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Robert E. Horton Memorial Lecture

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Design of Precipitation Networks [1]

Abstract

The knowledge of the temporal and spatial variability of precipitation is important to many aspects of our society. A review of the research that has been accomplished on precipitation variability is presented. This is coupled with a discussion of the state of the art in measurement and estimation of precipitation to evaluate the present ability to properly design precipitation networks.

1. Introduction

A knowledge of the temporal and spatial distribution of precipitation that occurs on the surface of the earth is very important to many aspects of our society. Use of such information ranges from application of climatological data for design and planning to predicting the occurrence of flash floods. The overall benefit derived from the application of precipitation information is vast and probably indeterminable. Even a very small incremental improvement in our ability to measure, estimate, or predict the temporal and spatial distribution of precipitation would be of great value. Improved ability for operational hydrologic forecasting alone could result in large savings. Currently the average annual loss from flooding is 200 lives a year and over two billion dollars in damages.

I would like to review briefly the research that has been accomplished on precipitation variability. For the purpose of this discussion I shall comment on long-term and short-term aspects of spatial and temporal variability. Long-term refers to those factors that are climatological, while short-term are those related with synoptic meteorology. Other factors that influence design of precipitation networks are measurement and estimation of precipitation, as well as benefits derived from such information. Finally, I shall present some comments on the design of precipitation networks.

2. Variability

Large-scale variations in time and space may greatly affect the availability of water for human activities. Only a few time series of precipitation data at selected points may be required to detect long-term trends; however, these time series must be consistent and of high quality.

Knowledge of the short-term spatial and temporal variation of precipitation is required when verification, monitorship, assessment, and prediction of water and water-related conditions are required on a real-time basis. Research on historically observed temporal and spatial variation can provide basic information that can be used to define required networks. A review of such research follows.

a. Long-term spatial variability

Isohyetal maps of the average seasonal or annual precipitation for a specified period are a common method of describing long-term spatial variability. For the areas of low relief in the more populated Midwest and eastern United States there is considerable information and the isohyetal patterns are relatively smooth. Our inability to adequately measure snowfall when wind is blowing often results in incorrect analyses of isohyetals for winter precipitation. Thus maps of winter precipitation for areas such as the north-central plains may be greatly in error.

In the mountainous areas of the western United States the spatial variability is much greater and data availability is much less. For these areas it is difficult to prepare representative maps even with a density of data considered adequate for other areas. Russler and Spreen (1947) were among the first to prepare topographically adjusted normal isohyetal maps. They used coaxial graphical methods to correlate the mean annual precipitation with topographic parameters. The method produced much-improved maps for western Colorado but was not applied widely because of the laborious processes required. The technique of using analysis of anomalies from precipitation-elevation relationships as a means of relating precipitation to topography was reported by Dawdy and Langbein (1960) and by Peck and Brown (1962). In this approach precipitation-elevation relationships are developed for the area under study for the seasons of the year that represent convective or summer (generally May–September) and winter (October–April) precipitation. These relationships for limited geographic areas with similar orientation to seasonal storm paths show that a major portion of the variation in seasonal precipitation is accounted for by elevation. In fact, the

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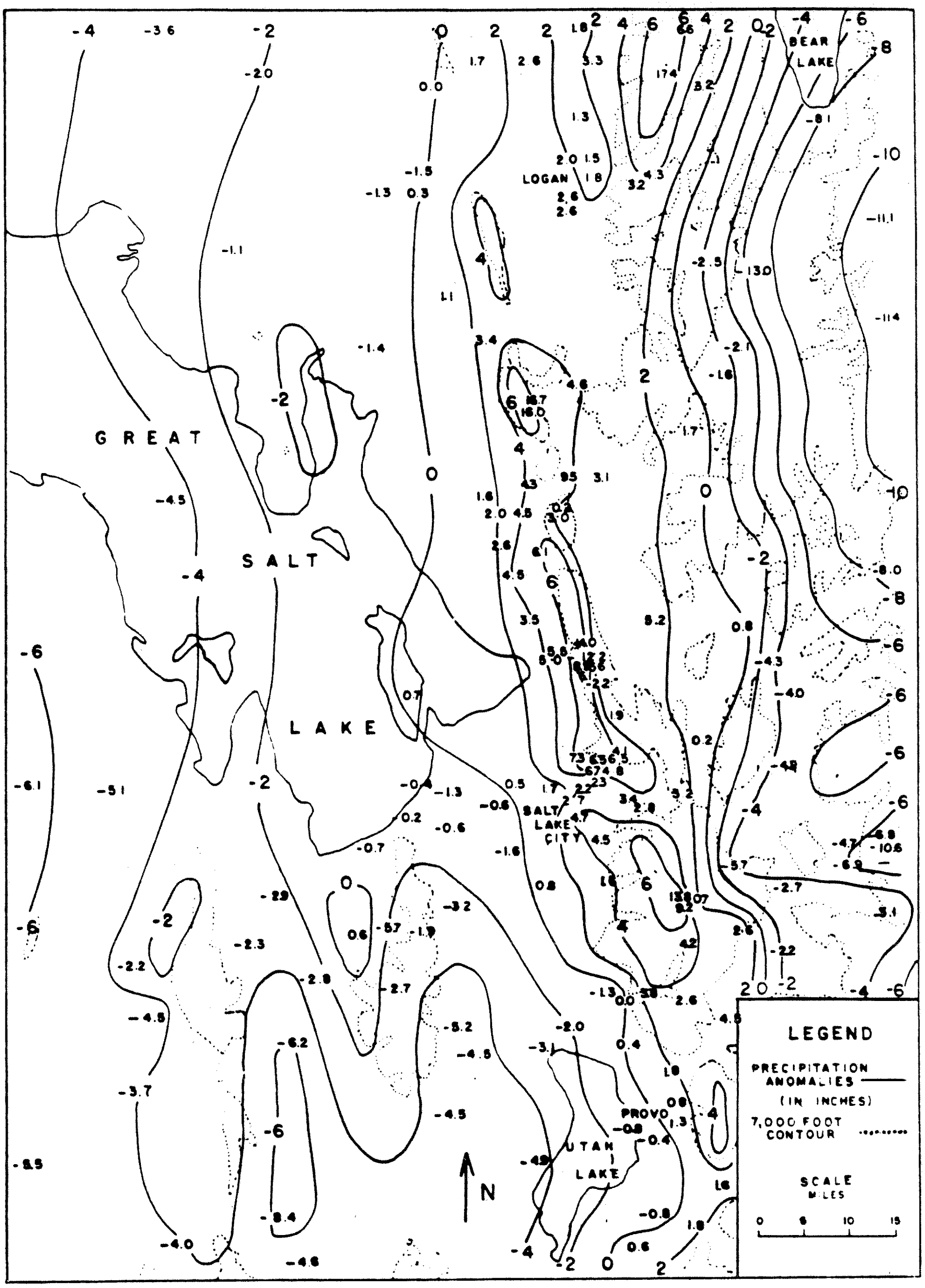

FIG. 1. Analysis of anomalies from mean October–April precipitation-elevation curve, Wasatch Front area of Utah.

coefficient of determination, r^2, for precipitation-elevation relationships for limited geographic areas is often on the order of 0.8–0.9. The plot of anomalies (deviations from a mean precipitation-elevation relation) on a map, as shown in Fig. 1, shows a good relation with the position and magnitude of topographic barriers in relation to the general storm movement. A reasonable analysis can be constructed even for areas with limited data. These analyses may then be used with a mean precipitation-elevation curve to compute values of precipitation for grid points used in the preparation of final isohyetal maps. Such maps have been produced for much of the southwestern portion of the United States (Miller, 1977).

Tor Bergeron (1973) of Norway and others (Ryden, 1972; Chang, 1973) have made comprehensive studies of the variability of precipitation in mountainous areas. Others (Longley, 1974) have made similar studies over areas of low relief such as the Canadian Prairies. Much work has been accomplished on analysis of the covariance fields of measured precipitation data. Sellers (1968) related intercorrelations with associated changes in the 700 mb flow patterns to describe the precipitation climatology of the western United States.

As a summary we can state that for those areas where there are sufficient data, reasonable analysis of the long-term spatial precipitation variability can be developed. Long-term values are well correlated with barrier orientation to moisture sources and with other topographic parameters. This is true for convective summer storms as well as general winter storms. Research on long-term precipitation anomalies and related meteorological patterns could provide information that would be useful in defining what observations would be of most value for increasing our understanding of long-term variability.

b. Short-term spatial variability

Short-term spatial variability of precipitation is much more difficult to model than is the long-term climatological variability. It has and should receive much more attention. Early work on the study of thunderstorms (Light, 1947; Byers and Braham, 1949) was primarily on circulation and structure of storms; however, it provided a large amount of information on precipitation originating from convective cells. Others (Linsley and Kohler, 1951; Osborn *et al.*, 1979) utilized data from dense networks to determine areal averages from point rainfall and the variability of such values.

The development of the theory of dynamic weather models by the Norwegians was a major step in being able to relate spatial variability with synoptic weather patterns. Since the Second World War considerable emphasis has been given to the measurement, analysis, and statistical characteristics of precipitation data.

Researchers in Europe as well as in the United States are beginning to stress the importance of understanding the meteorological processes as well as the statistical properties of the precipitation data. The paper by Canova and Maddox (1980) in this conference is a good example. In the United States many investigators are studying mesoscale weather systems in their efforts to develop improved quantitative precipitation forecasts. These studies indirectly are increasing our knowledge of short-term spatial variability. Many of these studies have been reported in the AMS Conferences on Hydrometeorology, on Flash Floods, on Severe Storms, and on Radar Meteorology.

Radar (Greene and Flanders, 1976) and satellites (Martin and Scherer, 1973) are providing vivid pictorial information on atmospheric water and clouds and have greatly broadened our appreciation of the potential value of these tools for analysis of spatial as well as temporal precipitation variability. The availability of digitized data from radar and satellite imagery offers a potential for studying short-term precipitation variability that is only just beginning to be appreciated (Hudlow, 1975).

Our knowledge of the relation of short-term precipitation variability to synoptic meteorology is very limited. Thus, it is still not possible to analyze adequately the spatial variability of precipitation. Future improvements depend upon an increase in our measurement capabilities and improved meteorological models of storms.

c. Long-term temporal variability

The occurrence of "runs" of wet and dry periods in long-term time series of precipitation records has fascinated scientists for years. The prospect of being able to explain and/or predict these "trends" has been the objective of many investigations. A better understanding of the statistical characteristics of precipitation data could have many applications for network design.

A good example of research that increased our knowledge was the analysis of wet and dry precipitation fluctuations by Yevdjevich (1963). The mathematical models developed showed that the sequence of wet and dry years is due largely to water carryover, evaporation from the river basin, and evaporation of rainfall in the air. Such knowledge is of considerable importance for stochastic hydrological analyses. The analysis of tree rings and lake deposits has also revealed interesting information on long-term temporal variation (Stockton and Fritts, 1971). The tree-ring data provide a much longer time series than either streamflow or precipitation records.

Sellers (1960) reported on trends in precipitation for the State of Arizona that clearly demonstrated the large temporal variability that occurs in the southwestern United States. The World Meteorological Organization defined normal precipitation as the average precipitation for a 30-year period. In general, a 30-year period tends to be sufficiently long to balance out the effect of abnormally wet and dry periods. However, substantial changes do occur in the average 30-year values of precipitation for semiarid areas when the period is changed by even 10 years. Such changes have been related to changes in the normal flow patterns.

Mandelbrot and Wallis (1968) proposed an interesting analysis of such anomalies in precipitation and their relation to hydrology. Those anomaly periods of extended duration were referred to as Joseph events and those of short-term extremes Noah events. Their approach used the concept of "self-similarity," which originated in the theory of turbulence. Simulations using their approach did produce simulations with "runs" of wet and dry years. However, they analyzed only precipitation records and did not relate the observed anomalies to meteorological conditions.

In addition to the "runs" of wet and dry years that are observed in nature, there are other types of anomalies that have not received much attention. As an example, the distribution of precipitation in the western United States does not necessarily follow the same path of departure from normal at all locations. Seasonal precipitation at high elevations may often be normal or above while at lower elevations may be very much below normal. Changes in the ratio of high elevation to low elevation precipitation may greatly affect the use of any analysis or runoff prediction model developed using data from a period with vastly different ratios.

Peck (1964) has shown that the ratio of precipitation at a high elevation to that at low elevation varies considerably from one winter season (October–April) to another. For the Wasatch Mountains near Salt Lake City, Utah, he reported that during a 50-year period the high-low elevation ratios for individual winters ranged from 2.05 to 4.31. It is especially interesting to note that during the decade of the 1920s the average winter season high-low elevation ratio was 2.70, while during the decade of the 1950s it was 3.46. For those periods the ratios of high elevation to low elevation precipitation have been related to the persistence of closed circulation patterns (closed lows aloft) in the 1920s and a general lack of them during the 1950s. Data from our present networks are not sufficient to evaluate fully these variations.

Extremes of precipitation are of special interest because of the large impact the resulting floods and droughts have on our society. However, the occurrence of much above normal precipitation has received more attention than has much below normal precipitation. The droughts in the south-central and southwestern areas of the United States during the past few years have brought about an increased interest in the subject of droughts.

Most federal agencies use rainfall values in developing planning and design criteria for a wide variety of water control structures. These agencies have sponsored the efforts of the Water Management Information Division, Office of Hydrology, National Weather Service, to conduct hydrometeorological studies. These studies are to provide information on the temporal and spatial distribution of rainfall on a frequency basis. Another aspect is the investigations of the upper limit of rainfall, termed "probable maximum precipitation." These studies also indicate the temporal and spatial extent of the most extreme events nature can produce. A listing of these studies may be found in the publication by Miller (1977).

In general we must conclude that our understanding of long-term temporal variability in precipitation is inadequate. We do not have a good knowledge of either the underlying meteorological processes associated with major anomalies of precipitation or sufficient knowledge of the statistical characteristics of the precipitation data. Additional research on long-term temporal variability could be highly important for the understanding and assessment of water resources in the west.

d. Short-term temporal variability

The early studies on thunderstorms (Light, 1947) also provided much of the basic knowledge of short-term temporal variability. Likewise, the work of the Illinois State Water Survey (Huff, 1978) and the dense network studies by the Agricultural Research Service (now Science and Education Administration) have been very helpful.

The mesoanalysis studies of recent extreme precipitation events, e.g., at Johnstown, Pa. (Hoxit *et al.*, 1978), Kansas City, Mo. (Hales, 1978), and Big Thompson, Colo. (Maddox *et al.*, 1978), have provided a better understanding of some extreme cases of short-term temporal variability. However, even in nonextreme cases temporal variability is generally much greater than can be defined by present networks of precipitation gages. Even with the aid of information from satellites and radars our present ability to assess properly short-term temporal variability is limited.

The use of meteorological data for assessing short-term variability has received some attention. Elliott and Shaffer (1962) investigated the quantitative relation between orographic and air mass parameters and resulting precipitation in southern California. Williams and Peck (1962) used storm classification as an indication of the variability of precipitation in the mountain area of northern Utah. One of the first 2-dimensional models for predicting precipitation was developed by Myers (1962) in which he used an air flow model for prediction of precipitation in the Sierra Nevada Mountains of California.

Rhea (1977) developed a precipitation model for Colorado using only routinely available upper-air information, a fine mesh topographic grid, and a simple orographic model. The cumulative October–April precipitation from this model for 13 seasons compared very well with values from an isohyetal map developed by the anomaly technique (Peck and Brown, 1962). Elliott (1977) has developed a model for predicting the distribution of precipitation over a mountain range using only a valley precipitation measurement and data from an upper-air sounding.

The variation of precipitation over urban areas is of considerable importance for design and operation of municipal sewer and drainage systems. The METROMEX network (Huff and Vogel, 1977) operated from 1971 to 1975 around St. Louis, Missouri. This network provided considerable information on convective rainfall patterns and on the influence of urban areas on precipitation. A more recent study, Chicago Hydrometeorological Area Program (CHAP), also conducted by the Illinois State Water Survey (Changnon and Huff, 1977), includes more meteorological measurements associated with the urban storms and should provide additional insight into hydrometeorological relations.

Our ability to model short-term precipitation variability is extremely limited. Likewise, except for a few research areas equipped with a very dense network of gages, it is generally impossible to analyze the occurrence of precipitation over short time periods. Digitized Doppler radar could greatly enhance our knowledge of and ability to analyze short-term precipitation variability.

3. Other factors

Many factors must be considered in the design of precipitation networks besides a knowledge of precipitation variability. The quality of data depends upon the measurement errors, the analysis techniques, and the capability of sensors used in the network. In addition, economic, social, and political factors often included in benefit studies need to be given proper consideration. Brief discussions on the above subjects have been included to provide a more complete review.

a. Measurement errors

The basic technique for measuring precipitation has not changed materially since the 13th century when the Chinese used rain gages similar to the nonrecording gages of today (Needham and Ting, 1959). A book published in 1247 A.D. described the problems of improving the shape of the rain gage and methods to compute average precipitation for an area from the recorded observations. During the last 100 years the same problems have been the attention of many investigations (Israelsen, 1967). Basically, there has been little progress in measurement ability, especially for snowfall. The adverse effects of wind in reducing the catch in the gage is a major source of error in measurement compared with the "true" precipitation. As shown in Fig. 2, the reduction in catch is much greater for snowfall, with or without a windshield on the gage, than for rain (Larson and Peck, 1974). Even with wind speeds of 10 mi/h the gage catch deficiency begins to become significant for rain.

The errors in gage measurements and the bias that often occurs in measurement of snowfall (Rodda, 1968; McKay, 1972; Corbett, 1965) introduce problems in analysis of precipitation for hydrologic purposes and in the design of precipitation networks.

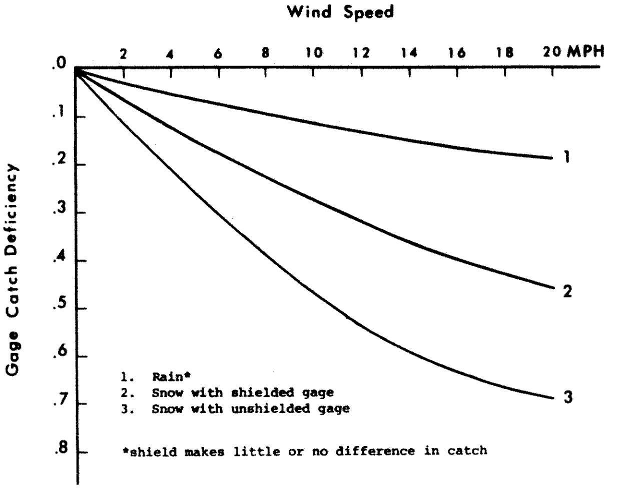

FIG. 2. Gage catch deficiencies vs. wind speed.

b. Areal estimation

An areal estimate of precipitation over a specific time period is a basic requirement for many hydrologic assessments or analyses. Many techniques have been developed to estimate areal precipitation. Various interpolation techniques have been used to derive areal estimations from gage data (Hatch, 1976; Rumyantsev and Shanochkin, 1973). More elaborate statistical techniques such as analysis of variance (Clarke and Edwards, 1972), correlation analysis, spectral analysis (Rhenals-Figueredo *et al.*, 1974), and multivariate estimation theory (Bras and Rodriguez-Iturbe, 1976) have been introduced during the last decade.

c. Radar data

A large number of techniques have been developed for using radar data for improving or optimizing rainfall estimates. One example is that by Rusin (1973) in the U.S.S.R.

In the United States there has been considerable activity as evidenced by the large number of papers presented at the AMS Conferences on Radar Meteorology. I would like to mention the objective analyses programs by Brandes (1975) and by Crawford (1978), which have demonstrated the operational feasibility of providing much-improved rainfall estimation using radar information and ground measurements.

d. Satellite data

The use of satellite imagery for estimating precipitation has also received considerable attention. Barrett (1970) presented analyses that gave fairly good estimates of monthly precipitation. Since then the techniques developed by Scofield and Oliver (1977) and by Griffith *et al.* (1978) have shown ability to estimate (at least for convective storms) areal precipitation for daily periods for areas of 10^4 km^2. For major precipitation events the National Environmental Satellite Service (NESS), using the Oliver and Scofield technique for affected counties, provides operational estimates to field offices of the National Weather Service for use in weather and river forecasting.

e. Meteorological data

The use of meteorological data to assist in determining areal estimates of precipitation has received less attention than the approaches discussed earlier in this report. A few papers that are representative of some of the contributions to obtain better areal estimates of precipitation are: Kessler and Russo (1963), statistical properties of radar imagery; Wilson (1966), study of movement of radar echoes; Epstein and Pitcher (1972), stochastic analysis of meteorological fields; Eddy (1973), objective analysis of atmospheric structure; and Mehia and Rodriguez-Iturbe (1973), characteristics of rainfall patterns.

Meteorological information could play an important role in the design of networks. It would be of greatest value for short-term spatial and temporal analyses. It has been demonstrated that the spatial correlation of precipitation is related to storm type, as is the coefficient of variation within a given storm. The use of meteorological information with observed data should improve the areal and spatial variations analyses.

Orographic lifting is an important factor in increasing the amount of precipitation, but storm-induced lifting also plays an important part. Meteorological parameters can be used to help account for the lifting from general convergence (Peck, 1972). Local mesoscale or microscale measurement of circulation patterns by Doppler radar or other indirect measures could be used to estimate the amount of lifting due to local conditions.

The Prototype Regional Observing Forecasting Service (PROFS), as proposed by the Environmental Research Laboratories, NOAA, would incorporate multisensor measurements for populated areas and could provide much more definition of mesoscale and microscale phenomena (Beran, 1978).

f. Benefit studies

Although precipitation information has many uses, most studies on benefits have been in the field of hydrology. Jacobi and Dawdy (1973) concluded from studies of rainfall-runoff models with different precipitation data input that the ability to model rainfall-runoff has outrun our ability to collect data accurate enough to evaluate the models. The same year Grayman and Eagleson (1973) used objective analysis and a rainfall-runoff model for designing a network for a flood warning service. They recognized the stochastic nature of the rainfall-runoff relations to study the errors in discharge prediction and their relation to data collection procedures. Davis *et al.* (1979) used risk calculations and statistical decision theory to evaluate the efficiency of the data collection subsystem, the response subsystem, and the overall information response system of a flood warning program. Jettmar and Young (1979) also reported on an evaluation of networks for operational river forecasting by relating the lead time of forecasts to the benefits of the forecast service. The economic data for this study were from a comprehensive analysis of damage from flooding experienced in the Susquehanna River Basin in Pennsylvania (Day, 1970). Dawdy (1979) has pointed out the need for simplicity in evaluating benefits while recognizing that the hydrological network provides only part of the information for water resources planning and management decisions. Social, political, and economic factors also play an important part.

4. Availability of network data

The Office of Water Data Coordination of the Department of Interior's U.S. Geological Survey (Langford and Kapinos, 1979) has the responsibility to design a national water data network. This agency coordinates with more than 30 federal and numerous nonfederal organizations on installation of various gages to avoid duplication and enhance the overall value of the data. However, precipitation gages are not a part of the national water data network and no agency has a similar responsibility to plan, design, or coordinate the installation of precipitation gages.

The current activities of NOAA could help make presently observed precipitation data available to more users. The Hydrologic Rainfall Analysis Project (HRAP), being conducted by the Hydrologic Research Laboratory of the National Weather Service (NWS), NOAA (Greene *et al.,* 1979), is in support of the NWS river and flood forecasting service. The objective is to accomplish the research and development to produce reliable operational rainfall data using surface, radar, and satellite reports. The program will include techniques for preprocessing, quality control, and operationally merging the data into computer files.

A special use of the precipitation data is by the Quantitative Precipitation Branch of the National Meteorological Center, NWS. Quantitative Precipitation Forecasts (QPFs) are of value for operational hydrology. The amount of precipitation to occur in the next few hours is often more important than how much occurred in the past. The amount of rainfall that has occurred, however, can also be of importance for preparing the forecast of additional rainfall. The files of all precipitation data collected by the River Forecast Centers of the NWS are now available on a real-time basis to the Quantitative Precipitation Branch.

5. Design of precipitation networks

The papers presented at the AGU Chapman Conference in Tucson, Arizona, in December 1978 (AGU, 1979) provide an excellent overview of the current status of network design for the field of hydrology. For precipitation, techniques based on statistical analyses of observed data are probably the most advanced but still must be considered in the development stage. There has been very little practical use of any of the proposed approaches for the actual design of networks.

The primary controlling factor for design of a precipitation network is the need for the data; secondly, can the proposed network actually provide reliable and accurate data with the resources available?; and thirdly, the question of whether the network should be operated independently or integrated into a larger or national network.

It is evident that current ground measurements cannot provide sufficient information on the temporal and spatial distribution of precipitation needed to meet the many uses for these data. Network plans for the future must take advantage of the capability of all methods and techniques that can be used to increase our ability to define the occurrence of precipitation. The plan must consider the use of precipitation gages, pulse and Doppler radar, remote sensors on satellites, and even streamflow data where appropriate.

Each sensor should play a different but important part in defining the final estimate of the precipitation. Ground gages provide a fair measurement, at least for rainfall at a point. Various means can be used to arrive at areal values, but an obvious choice is to jointly use radar information with the gage data. When the gage data are used to calibrate the radar measurement the primary value of the radar data is to obtain an improved knowledge of the areal variability as it relates to the gage data. Satellite data could be used in a similar fashion. However, data from satellite observations could add other information.

The best estimate of the actual precipitation can be obtained if the information content of all data sources are fully utilized. It should be recognized there is a large amount of redundant information when gage, radar, and satellite data are all available. Objective techniques must be employed that explicitly take account of the error of each measurement. Various methods are available to accomplish this. One is estimation theory, which represents a recipe for combining measurements and predicted values to obtain a best estimate of the state vector. Kalman filter, a special case of estimation theory, was the subject of an AGU Chapman Conference (Chiu, 1978). Combing the various methods requires a knowledge of the uncertainty of the independent variables. Thus, it is essential that the radar techniques for calibration be objective. In addition, estimation of precipitation or measurements of variables from satellites must also be such that the uncertainty of the measurements can be evaluated.

6. Conclusions

A decision to use a multisensor (gage, pulse radar, and satellite) network to obtain improved estimates of precipitation will require much more than the installation and operation of the data collection network. Detailed studies of the uncertainty of each measurement and the development of an objective analysis for combining the data will be necessary. The incorporation of additional measurements (for example, Doppler radar) or meteorological information (for example, an index of lifting by convergence) would necessitate the same knowledge of uncertainty and development of a revised objective analysis for combining the variables. Other approaches such as physical models will also require considerable research and development.

There is a need for cooperation among federal and nonfederal agencies to plan, design, and coordinate the installation of precipitation gages in the United States. In such a program consideration should be given to:

1) Obtaining data for all purposes (recognizing that one network will not meet all requirements).
2 Using multisensors (ground gages, pulse and Doppler radar, satellites, etc.) and meteorological measurements and knowledge.
3) Developing objective analyses methods to maximize information from the network.
4) Coupling information with other networks (streamflow, groundwater, etc.).

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