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LIMITATIONS OF HYDROLOGICAL TECHNIQUES IN THE EVALUATION OF WEATHER MODIFICATION STUDIES

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ABSTRACT

Hydrological techniques commonly used in evaluation studies of weather modification projects may not properly account for the large temporal and spatial variability of hydrological data. The causative factors (instrumental, observational, and climatological) for the variability and the limitations inherent in statistical evaluation studies are discussed. Emphasis is on the limitations of the techniques rather than on applications to specific weather modification studies.

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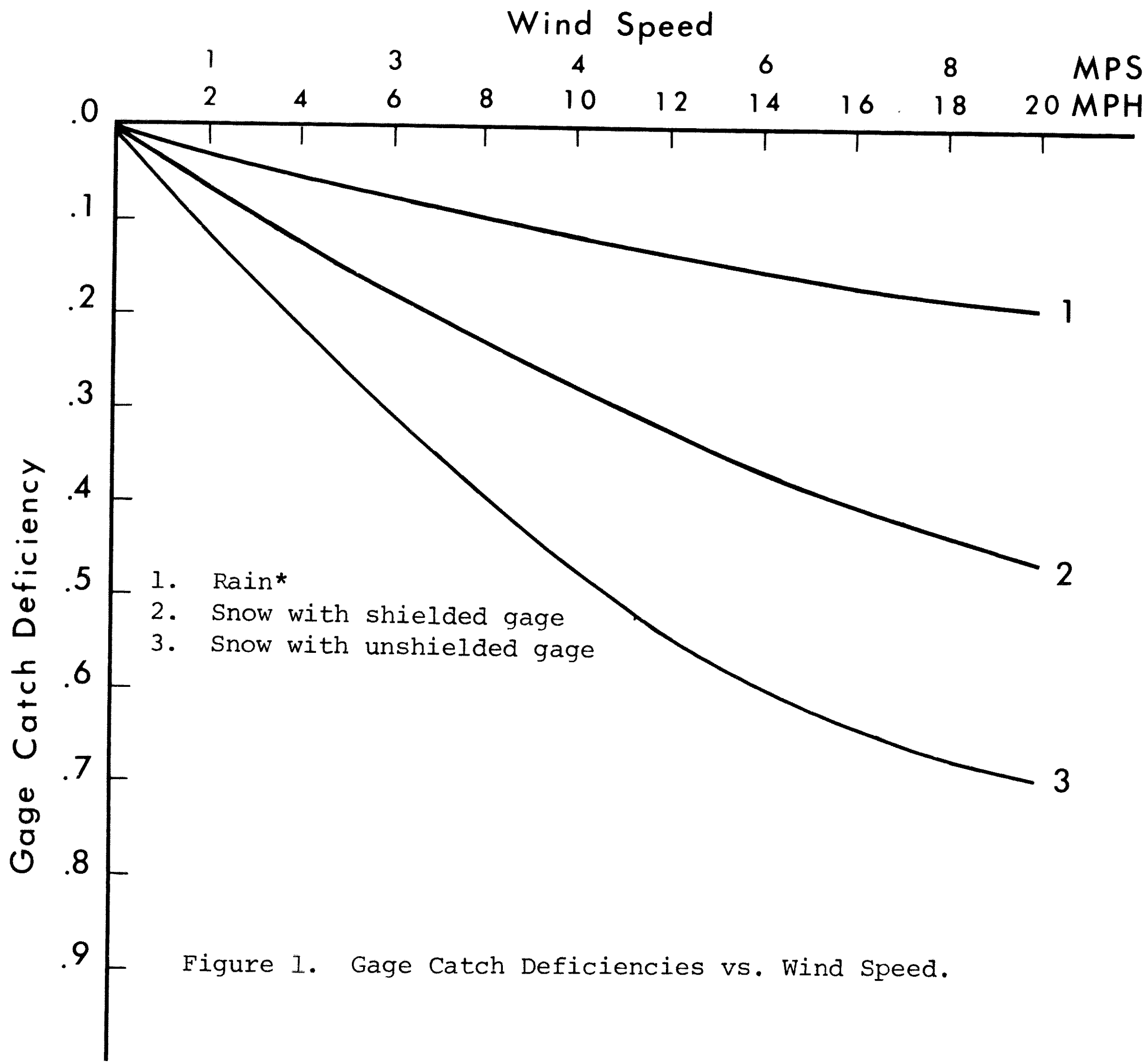

Figure 1. Gage Catch Deficiencies vs. Wind Speed.

*shield makes little or no difference in catch of precipitation could be made without error, areal estimates of precipitation averages would still be subject to large errors due to a non-representative gage location, the number of gages in the network, the distribution of gages within the network, and the algorithm utilized to calculate the areal mean.

Wilson (1954) has summarized many of the problems associated with obtaining both precipitation and snow cover measurements. He states that, on the average, solid precipitation measurements for his region of study (Central Sierra Snow Lab, USA) are about 15% low due almost entirely to the adverse effects of the wind. In addition, he points out that areal variation in precipitation measurements are due to many causes including storm, physiography, environment, site, and gage effects.

The reliability of precipitation as related to exposure has been documented by Brown and Peck (1962). This paper points out the real need for proper location of precipitation gages in order to obtain reliable and realistic precipitation records.

Snow Cover

Snow cover measurement errors have been documented by Vershiniva and Dimaksyan (1971). Errors in snow cover measurements are similar to precipitation measurement errors but in addition are complicated by wind transport of the snow, freezing and thawing of the snow cover, representatives of sample location, and nonuniform snow cover distribution.

Peterson and Brown (1975) have investigated the accuracy of snow cover measurements obtained by a sampling tube. They have estimated that this technique can overmeasure water equivalent at a point by as much as 12%, and the error seems to increase with snow density.

Kuzmin (1963) states that the representativeness of a snow survey depends upon the variation of snow reserves over the area, the correct selection of the traverse, its length, and the number of points sampled. He further states that it is impossible to select a short traverse that is representative of the whole vicinity and measurements at a single point are even less representative.

The problem of determining an areal average for snow cover, according to Kuzmin, is quite difficult because of the localized nature of data from the snow surveys and their territorial limitations. As an example, in the Oka basin, the estimated probable error in the calculation of areal snow cover is about 15% for basins of 30,000 to 40,000 km^2 and the error increases to 30% for smaller basins of about 15,000 km^2.

Streamflow

The most common streamflow observation is stage or water surface elevation. The stage record can be transformed to a discharge record by calibration. This calibration is accomplished by relating field measurements of discharge with simultaneous river stage measurements thus developing a stage-discharge relationship. The errors in streamflow observations are therefore not only subject to the usual instrument and observer errors but are also subject to errors from the stage-discharge relationship itself. The United States Geological Survey classifies their discharge measurements on a particular stream as good if the estimated error is less than 5%.

Annual streamflow measurements are generally reliable integrators of effective precipitation for producing runoff from large areas. However, since only a limited number of actual streamflow measurements are made during a year (the rest of the time the stage-discharge relation is used) the streamflow related to a single storm may not be as reliable.

Examples of contrasts in the variability in annual streamflow from rivers located in two semiarid regions in Anzaio (Tonto Creek), in a humid area on the western slopes of the Sierra Nevada in California (Merced River), and in the humid southeastern United States (Oconee River) are shown in table 1.

Table 1.--Variability of annual streamflow

	Standard Deviation % of mean	Lowest Water-year % of mean	Highest Water-year % of mean
Tonto Creek near Roosevelt, Arizona	78	14	358
Merced River near Yosemite, California	35	35	188
Oconee River near Milledgville, Georgia	32	44	167

Note: For 45-year period 1916-1960

Precipitation-runoff relations in humid regions generally have much higher correlations than those in arid regions. Correlations between annual precipitation, as observed at individual reporting stations, and annual or seasonal streamflow are often near 0.90. The coefficient of determination or the amount of the variability in the streamflow accounted for by the precipitation measurements is often between 80 to 90 percent. In the arid regions of the southwestern United States, even for streams from relatively high elevations, similar coefficients of determination are on the order of 0.40 to 0.70. Likewise, correlations between individual streamflow records or between precipitation records are also much greater for humid than for arid regions. The large variability in streamflow in arid regions is characteristic of the variability generally found for other hydrologic data in these regions.

HISTORICAL MEASUREMENT VARIABILITY

In arid and semiarid regions it is often difficult to obtain a reliable estimate of the available water resources from hydrologic records. In the more humid regions, simple analyses using such records may provide reliable quantitative estimates of the water resources. This difference is due in part to the fact that observation networks are generally sparser in arid and semiarid regions and hydrologic factors have greater temporal and spatial variability.

Sources of variability in hydrologic records include those caused by changes in measuring techniques or locations of sensors, frequency and/or time of observations, site characteristics, and by man's activities in the environment. Such historical changes have been described by Kazmann (1964). He refers to records which contain such changes as being "dirty" data in that the records do not represent a consistent measurement of the same hydrologic regime. Such changes may greatly affect statistical studies and may result in the assignment of significance to the effectiveness or noneffectiveness of weather modification activities that may be entirely opposite to the real physical effect. In particular, the consistency, continuity, and usefulness of historical hydrologic data can be altered seriously by any of the above factors.

Historical "dirtiness" in hydrologic data affect the statistical significance of hydrologic relations for humid and arid regions to about the same degree. However, natural variance, which is related to the climatic variations, is much greater for arid regions than for humid regions. For this reason, it is important that these variations be understood if we are to have an understanding of the possible magnitude and variation in hydrologic records.

CLIMATIC VARIABILITY

As background for a better understanding of how climatic variations may affect important hydrologic variables such a streamflow, a brief example of the synoptic climatology of the arid and semiarid regions of the southwestern United States may be pertinent. The area involved includes the States of Nevada, Arizona, New Mexico, most of Utah and Colorado, and parts of Wyoming and California.

Moisture moves into the southwest from several sources and precipitation occurs with a variety of storm types. During the summer months the principal flow of moisture generally comes from the Gulf of Mexico. Occasionally, the flow from the Gulf does extend as far west as the major ridge of the Sierra Nevada in California at which time the entire arid and semiarid areas of the southwest may be under its influence. The total precipitation amounts over the major portions of the region are greatest (more rainy days) when the center of the moisture flow is west of its normal position.

A second source of summer moisture is derived from the Pacific Ocean. This moisture movement occurs when tropical storms move inland from the west or southwest and are often associated with hurricanes which move inland through Baja, California. These storms occur during summer and fall and the associated precipitation is often widespread and intense. For the very arid regions of the lower Colorado River basin, a few of these occurrences in a 30-year period account for a fairly large percentage of the normal precipitation for the months of August and September.

During the winter period, October through April, much of the moisture which moves into the area comes from the Pacific Ocean. Although most of the storms move into the area from the west or northwest, some originate in the area. The most intense storms are usually associated with deep troughs or "closed lows" in the upper-air circulation pattern. Those having upper-air closed circulation patterns are generally "cold lows."

The amount of precipitation in the arid regions is fairly well divided between the winter and summer periods. In the summer, however, the rainfall produces relatively little runoff because of large evapotranspiration losses. Nevertheless, large volumes of streamflow may occasionally be caused by the intense storms associated with hurricanes during late summer and early fall.

The major portion of streamflow is normally associated with precipitation during the October through April period. Most of the runoff comes from higher elevations and the distribution of precipitation with elevation is an important factor. Jorgensen, Klein and Korte (1966) demonstrated that a substantial portion of the winter precipitation in the arid areas is associated with storms of the "closed low" type. These storms generally have much greater areal extent of precipitation than do other types of winter storms. In addition, these storms are longer in duration, often lasting two to three days.

The distribution of precipitation is primarily related to the degree of lifting induced by the three basic causes (orographic, convective, and dynamic). If a storm has widespread dynamic lifting, as assembled with "closed lows," the ratio of precipitation amounts at high elevations to that at lower elevations is small compared to the same ratio for storms where orographic lifting is the most important factor. A low ratio of precipitation is probably also true for convective showers in the intermountain area of the Western United States.

Sellers (1960) has demonstrated that the average magnitude of observed precipitation in Arizona did not change significantly during the 50-year period 1910-1959. However, there have been several series of years which have had considerably more or less precipitation than the long-term mean. A study was made by Peck (1964) to determine if there were variations in the high-low elevation ratios during the year. It was found that the ratio of observed october-April precipitation from a high level (2,654 m, msl) to a low-level station (1,296 m, msl) did vary considerably over fairly long periods of time. For example, during the 1920 decade the average ratio was 2.70, while for the 1950 decade it was 3.46. This significant change in the ratio with time is probably associated with changes in the number of "closed lows." This apparent variation with storm type could be of considerable hydrologic importance, especially as it relates to weather modification projects.

Unfortunately, precipitation variability with elevation does not appear to be consistent over the entire west. Figure 2 shows graphs of how the high elevation-low elevation precipitation ratios vary during the months of October-April for a number of station sets over the western United States. It is evident that the patterns are not consistent. These patterns may not be uniquely related to occurrences of storm types but they are undoubtedly related to the variation in the lifting processes which produce the precipitation in each section. The magnitude of variations in the ratios from month to month is greatest for the more arid regions and is an additional indication of the greater variability in hydrologic parameters in these regions.

HYDROLOGICAL LIMITATIONS OF STATISTICAL APPROACHES

Many investigators in recent years have attempted to develop statistical techniques for evaluating weather modification projects. The great variability in time and space for all hydrologic parameters, especially precipitation and streamflow, has made the development of these statistical techniques very difficult - if not impossible. In addition, the use of "dirty data" can introduce spurious correlations among hydrologic parameters. The final worth of any statistical technique for evaluating weather modification projects will depend primarily upon the quality of the input data.

Huff, et al. (1969), investigated the natural time and space characteristics of 1 minute rainfall rates in the north-central United States and the potential utilization of these rate measurements in

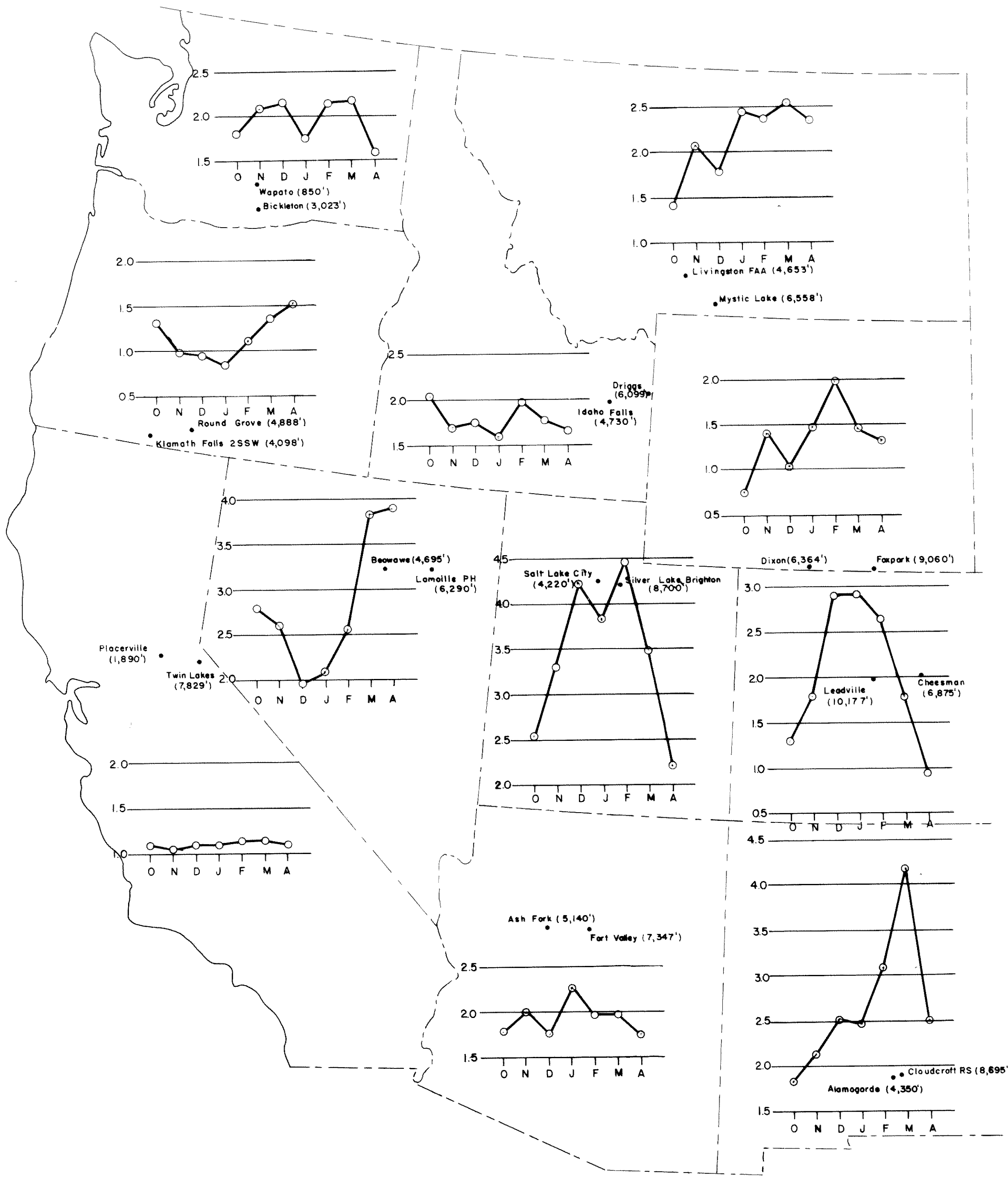

Figure 2. Diagrams showing variations in the ratios of monthly precipitation (Oct-April) for pairs of selected high-low elevation stations in the eleven western states. (Peck, 1964)

the verification of cloud seeding effects. Attention was given to the effects of rain type, storm type, and other parameters of the time-space distributions. Overall, it was concluded that rainfall rate may be a useful tool in weather modification evaluations, but by itself it is not effective unless very large and pronounced changes in the rate structure are produced by seeding.

Weisbecker (1974a and 1974b) discusses winter orographic snow cover augmentation in great detail for the Colorado River of the western United States. He states that it is not easy to show how much snow results from cloud seeding due to the great variability of natural precipitation. Weisbecker states that two sets of precipitation measurements are required, one from a seeded area and one from a non-seeded area. If enough measurements are taken, the natural variability for the two sets of data will be similar so any other difference will be due to cloud seeding. The trick of course is to have the two sets of measurements taken under similar conditions. This would seem to be a difficult proposition at best.

Weisbecker also states that this approach is not suitable for evaluations of full scale operational precipitation augmentation programs. In this situation, enough knowledge about the physical processes would have to be available so that a precipitation model could be developed which would compute expected precipitation. A comparison of the expected precipitation with measured precipitation would result in an estimate of the amount of augmented precipitation. The problem here is that the current state-of-the-art in meteorological modeling of atmospheric processes has not progressed to the point where this type of approach can be accomplished.

Morel-Seytoux and Soheli (1973) have investigated the use of streamflow for evaluating weather modification experiments. They determined that if precipitation is augmented by 10% for a period of 5 years, there is only a 50% chance of detecting this change from streamflow records.

Some research has related precipitation distribution in mountainous areas to meteorological parameters. In the future, it may be possible to include these meteorological parameters in the analysis of weather modification projects. Peck (1972) published a paper that deals with correlating the geographic distribution in a mountainous area with upper-air meteorological parameters. The parameters selected were those that are related to instability, dynamic lifting, and the moisture content of the air masses. Also, wind speed and direction were included as an indication of the effects of orographic lifting. The results indicated that there were two distinct and different populations in the precipitation data. One group was found to be associated with low values of the high level-low level precipitation rations. The second group was associated with the high values of the same ratios.

GENERAL COMMENTS

The most important characteristic of hydrologic parameters is the large temporal and spatial variability. This great variability introduces a tremendous problem in trying to establish the significance of relations that may be used for evaluation of weather modification efforts.

Any successful attempt to prove the effects due to weather modification must depend on a thorough understanding of the variabilities in data that may occur. The best solution would be to have a complete knowledge and extensive measurements of all factors and parameters involved. This is not possible with the present state-of-the-art or by known observational techniques. Evaluation methods incorporating the relationship between meteorological parameters and hydrologic events may prove more successful than analyses using only hydrologic measurements of precipitation or streamflow.

Even highly significant correlations among meteorological and hydrologic parameters are subject to limitations, however. There is no adequate way to determine, for example, if weather modification has also changed the meteorological conditions sufficiently to alter the synoptic situation and thus make any conclusions subject to possible error.

Future efforts of weather modification evaluation should make full utilization of radar and satellite observations as well as improved meteorological and hydrological measurements.

It does not require much imagination to envision how large variations in hydrologic records might affect the validity of analyses related to weather modification evaluation. In order to take properly into account all possible effects of variation in time and space, a very long and extensive set of measurements are required for the pre- and post-modification periods. The magnitude of hydrologic variation is not as great for nonarid areas, and evaluation may, therefore, not be as subject to such criticism. However, for arid regions such as the southwestern United States, the limitations of data, the short records, and the great variability in hydrologic parameters make it difficult to assign a high degree of significance to statistical analyses, using only basic hydrologic measurements.

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Master

INTRODUCTION

Following the early cloud-seeding experiments which were initiated about 1950, there were many papers published on the evaluation of the effectiveness of weather modification programs. In a large number of these evaluations streamflow records were used as the basis for determining whether the modifications were effective. The approach often was a simple statistical comparison of the streamflow records prior to and following the cloud-seeding operations for target area versus one or more control areas. A basic assumption was that the streamflow records were significant enough to reveal any change related to the weather modification. It was also assumed that the weather modification was effective only over the target area.

Other evaluations used precipitation or snow survey records in similar statistical comparisons. In many of these studies it was assumed that the precipitation gage measurements represented the true precipitation and that the average precipitation over a basin could be defined from point values.

As these early evaluations were subjected to review and criticism, it became evident that the simple statistical methods were often not adequate for evaluating the significance of possible changes produced by weather modification efforts. Several reports (for example, Markovic 1966) have discussed the relative merit of using streamflow or precipitation records in evaluating weather modification. There are, however, problems in using basic hydrologic data of which one of the most important is natural variability in the factors.

The value of a statistical relation for determining future changes in a relation is dependent not only on the degree of correlation but also on how well it represents the true population. In general, it may be stated that as the natural variability increases, a longer period of testing is required to determine the significance of any change.

LIMITATIONS RESULTING FROM OBSERVATIONS AND/OR NATURAL VARIABILITY

Systematic, random, and chaotic errors all influence observations made in conjunction with hydrologic studies. Systematic errors include instrumental errors, environmental errors, or observer errors. Chaotic errors often are very large and may be due to gross instrument or observer errors. These can generally be corrected or eliminated. Random errors are all the remaining derivations of measurement from some unknown "true" value (Velikanov, 1965).

PRECIPITATION

Errors in precipitation measurements have been well documented. Peck (Feb. 1972), WMO (1973), and Kurtyka (1953) are but a few references. In general, large negative errors in precipitation measurement exist due to wind, evaporation, wetting of the gage, observer errors, instrument errors, and sitting problems. Errors in the measurement of solid precipitation are considerably larger than for liquid precipitation.

Rodda (1971) documents many of the errors associated with the measurement of precipitation. He states that errors in point precipitation measurements could be as high as 80% primarily due to poor gage exposure. He also states that "it is a fallacy to suppose that it is simple to measure rainfall" and that "measurements of precipitation --- have invariably been assumed to be accurate. This assumption is not valid, however, ----."

Larson and Peck (1974) point out that most of the deficiency in precipitation catch is due to turbulence near the gage orifice resulting from the obstacle of the gage itself to the windstream. Thus, gage catch deficiency generally increases with wind speed. For liquid precipitation a deficiency of about 10% at 4mps can be expected for the Universal gage of the USA. For solid precipitation, a deficiency of about 50% for the same gage and wind speed is reported.

Rusin (1971) has reported on measurement errors due to wind for the Tretyakov gage of the USSR. He reports errors of 30-40% when measuring low intensity rain and errors of 100-200% when measuring solid precipitation.

It has been shown many times that the use of a gage shield can reduce wind caused measurement deficiencies (Kurtyka, 1953; Alter, 1937). For example, the use of an Alter shield on a Universal gage reduces the deficiency in catch for solid precipitation from 50% to about 30% at 4mps (fig. 1). Similar results have been reported for shields used in the USSR with the Tretyakov gage.

It is apparent that point measurements of precipitation, either solid or liquid, are subject to large deficiencies in catch due primarily to wind caused turbulence. The process of determining areal estimates of average precipitation from point measurements therefore is also subject to errors of large magnitude.

Again, many researchers have studied the problem of estimating areal precipitation. For example, it was shown that for a basin of 21,000 km^2 the standard error of precipitation areal estimates for a network of 160 gages is 8% but for a network of 80 gages it is 20% (Linsley, *et al.*, 1958). It is obvious that even if point measurements