An Application of the Dual-Gage Approach for Calculating "True" Solid Precipitation

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Abstract. The influence of wind on the catch of precipitation gages increases with wind speed. As an example, an unshielded gage measuring solid precipitation will catch fifty percent or less of the "true" catch at wind speeds of fifteen mph. The addition of a gage shield reduces the total wind caused error but does not eliminate it. A possible approach to calculating "true" catch has been proposed by W. R. Hamon of the Agricultural Research Service in Boise, Idaho. The dual-gage approach is based on the premise that a relationship exists between the catch of a shielded gage, an unshielded gage and "true" catch. The utilization of this approach requires solving for a calibration coefficient. The calibration coefficient is determined from data obtained at a research site in Vermont and then the dual-gage approach is applied to data from a research site in Wyoming. The results are presented and indicate that the dual-gage approach is encouraging for obtaining more reliable snowfall measurements.

Introduction

It has been well known for many years that wind causes an error in precipitation gage measurements (Abbe, 1887). This error increases with wind speed and is larger for solid precipitation than for liquid precipitation (Weiss, 1963). A generally accepted theory is that, in addition

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to site turbulence, much of the total measurement error is a result of turbulence and increased wind speed in the vicinity of the gage orifice resulting from the obstacle of the gage itself to the windstream (Robinson and Rodda, 1969) (Green, 1972). As the air rises to pass over the gage, precipitation particles which would have passed thru the gage orifice are deflected and carried further downwind thus resulting in a gage catch deficiency (Chou, 1968). The total deficiency in gage catch due to wind can approach 80 percent when the precipitation is in the form of snow (Wilson, 1954).

In an effort to improve precipitation measurements, especially for solid precipitation, prior researchers have tried various methods for eliminating or reducing the wind caused error (Kurtyka, 1953). Some of the earliest efforts were directed towards modification of the gage itself. The precipitation gage was made in nearly every conceivable shape and size and was tipped, gimbaled, and rotated. It was constructed of different materials, the orifice size was varied, and it was placed in varying heights and attitudes with respect to the ground. The net result of all this effort is that still no gage exists which is not subject to wind caused errors. An exception which should be noted is a properly installed pit gage which may, in certain circumstances, approach "true catch" for liquid precipitation only (Green, 1969).

In the middle 1800's research began to be directed towards developing gage shields to eliminate the wind error (Stevenson, 1842). Again a profusion of designs and ideas came forth. Shields were installed on the gage, in the gage, and at some distance from the gage. They were made of wood, metal, and canvas and were constructed flat, curved, stationary and swinging. This approach met with some success, however, because by the 1930's two shields had been developed which have been shown to be effective in reducing the wind caused error in precipitation measure-ments (Nipher, 1878) (Alter, 1937). These shields, the Alter and the Nipher, are in widespread use today with the Alter shield being generally preferred for situations where solid precipitation is likely to be encountered (NOAA, 1970). Even though these two shields reduce the wind caused error it is still evident that no combination of gage and shield exists which will entirely eliminate the wind caused error (Rodda, 1968).

The gage site or location has always been considered an important factor when obtaining reliable precipitation measurements. In fact, it is probably the single most important factor involved when obtaining precipitation measurements at anything approaching their true value. A well-protected precipitation gage is one which has surrounding uniform protection subtending angles of 20 to 45 degrees from the gage orifice (Brown and Peck, 1962). Israelsen (1967) states that in spite of its inadequacies, the most accurate method for measuring solid precipitation at this time is a simple can-type gage located on a well-protected site. Unfortunately, well-protected sites seldom exist where precipitation data arerequired or at sites where gages have often been located (airfields, rooftops, etc.).

In addition to considering gage design, shields, and location, researchers have also expended some effort towards developing correction factors to be used to minimize wind caused errors. Usually, gage readings are simply multiplied by some factor greater than unity to account for the measurement error. In some instances this adjustment factor has been considered to be a constant while in other instances it has been utilized as a function dependent upon other variables such as wind speed, temperature and gage configuration (Popov, 1967) (Gedeonov, 1966). One specific method of adjusting gages readings so as to minimize wind caused errors is the so called dual-gage approach. Hamon (1971), of the Agricultural Research Service in Boise, Idaho, has for the past five years conducted research on this method in connection with the research mission of the Northwest Watershed Research Center. The dual-gage approach is the subject of this paper and will be discussed in greater depth.

The Dual-Gage Approach

Many studies have shown that a plot of the ratio of gage catch to "true catch" and wind speed will generally follow an exponential type curve (Warnick, 1956). This relationship has prompted many researchers to develop correction factors for precipitation measurements based on wind speed. It has also enabled several researchers to develop correction factors based on the relationship between the catch of shielded gages, unshielded gages, and "true catch" (Hamon, 1971) (Struzer, 1969). An approach outlined by Hamon is essentially as follows. A plot of the catch of an unshielded gage (u) and "true catch" (A) versus wind speed (w) can be represented by an exponential equation of the form.

$$\frac{u}{A} = e^{-bw} \qquad (1)$$

where b is coefficient dependent upon temperature. A plot of the catch of a shielded (rigid) gage (s) and "true catch" versus wind speed is represented by an equation of the form

$$\frac{s}{A} = e^{-aw} \qquad (2)$$

where a is a temperature dependent coefficient. These two equations can be utilized to develop an equation relating the catch of unshielded and shielded gages.

$$\frac{u}{s} = e^{w(a-b)} \qquad (3)$$

Equations 1 and 3 can then be represented in logarithmic form as follows.

$$\ln\left(\frac{u}{A}\right) = -bw \qquad (4)$$

$$\ln\left(\frac{u}{s}\right) = w(a-b) \qquad (5)$$

If the shielded and unshielded gages are located close enough to each other so that they are subjected to essentially the same wind movement, but do not interfer with each other, then w can be eliminated by simultaneous solution of equations 4 and 5.

$$\ln\left(\frac{u}{A}\right) = \frac{b}{b-a} \ln\left(\frac{u}{s}\right) \qquad (6)$$

$$\ln\left(\frac{u}{A}\right) = B \ln\left(\frac{u}{s}\right) \qquad (7)$$

Thus, "true catch" (A) can be determined from equation 7 if precipitation data from adjacent shielded and unshielded gages are available and if an appropriate value for B has been determined. Data from shielded or unshielded gages can also be corrected to "ground true" by using equations 1 and 2 but this necessitates knowing windspeed and the coefficient a or b for each case. The advantage of the dual-gage approach and equation 7 is that B may be considered a constant which has been shown to be essentially independent of temperature and windspeed.

The Dual-Gage Analysis and Application

The National Weather Service, in cooperation with the Agricultural Research Service, has for the past six years operated several snow research studies in the Sleepers River Basin of northern Vermont. Several precipitation gage sites at this location have provided data which are suitable for use in evaluating the coefficients and constant in equations 6 and 7. Site X-4, which was chosen for use in this study, has shielded (both rigid and Alter) and unshielded gages at a height of 15 feet above the ground. The rigid shield is a standard Alter shield, with the leaves constrained at 30 degrees with the vertical. All gages used in this study are weighing-recording gages with 8 inch orifices. Other meteorological data such as wind speed and temperature are also available at this site. A well-protected site to obtain "ground true" precipitation (A) was established just east of site X-4 by cutting a 30 foot diameter opening in a dense coniferous forest. This opening was encircled by a 10 foot high polyethylene wind screen. A weighing-recording precipitation gage was installed inside this enclosure along with a totalizing anemometer.

The B constant for use in equation 7 was determined by finding the best fit regression line through the origin where $X = \ln (u/s)$ and $Y = \ln (u/A)$ for 36 storms of the 1969-72 period (Figure 1). The data for s was from the rigid shielded gage. This resulted in a B value of 1.76 with a correlation coefficient of .83 and a standard error of .09. The B value was also determined by finding an average value for the coefficients a and b for these storms and utilizing the following relationship between a, b, and B.

$$B = \frac{b}{b-a} \qquad (8)$$

A best fit regression line through a plot of ln (s/A) and ln (u/A) versus wind speed resulted in a value for a of -.033 and a value for b of -.075 for the same 36 storms previously used (Figures 2 and 3) but quite low correlation coefficients were noted in both cases. B calculated from equation 8 results in a value of 1.78 which checks quite closely with the previously determined value of 1.76. Other preliminary studies have found B values ranging from 1.73 to 1.8 (Hamon, 1971) (Larson, 1972).

An application of the dual-gage equation (equation 7) was then made to data previously collected from an installation in Wyoming. The University of Wyoming is conducting snow research studies, under contract with the National Weather Service, NOAA, at a site located in southeastern

Wyoming (Larson, 1971). Precipitation gages numbered 6 and 7 at this site are paired shielded and unshielded gages with no natural site protection which provide the necessary input to equation 7. A carefully selected "ground true" site is located near gages 6 and 7 and provides data necessary to compare a measured or assumed "ground true" catch with a calculated "ground true" from equation 7. A total of one hundred storms from the two winters of 1969-70 and 1970-71 were available for analysis. Utilizing a B value of 1.76, the calculated "true catch" values were determined. These results are given in Table 1 and show that for these data the unshielded gage catches 56 percent less than the assumed ground true; the Alter shielded gage catches 34 percent less than the assumed ground true; and the dual-gage approach underestimated the assumed ground true by 5 percent. The percent of assumed ground true obtained here for the unshielded and shielded gages checks quite closely with data published by previous researchers (Weiss and Wilson, 1957). It seems that for the wind speeds encountered during this study (12 mph storm average) the unshielded gage could be expected to catch about 50 percent and the shielded gage about 70 percent of "true catch".

In order to test the hypothesis that the mean storm catch of assumed ground true, calculated ground true (dual-gage), the unshielded gage, and the shielded gage are all equal, the two-way classification analysis of variance was used. The F test showed that the null hypothesis (i.e. mean storm catchs are all equal) had to be rejected. The test statistic for the gages was 43.66 which exceeded the critical value at a significance level of .05 with 3 and 297 degrees of freedom. To identify which storm means within the group of four had no significant difference in performance, the

Duncan multiple range test was used (Miller, 1965). This test indicated that there was no significant difference between the mean storm catch of the dual-gage calculated ground true and assumed ground true but that there was a significant difference in performance between the unshielded gage, the shielded gage, and the group containing the calculated and assumed ground trues.

A linear regression analysis of measured ground true catch on the calculated ground true catch from the dual-gage approach resulted in a slope of 1.08 indicating nearly a 1:1 relationship. The slope for the best fit linear regression line for the unshielded gage was 1.79 and for the shielded gage was 1.46. A plot of the ratio of storm precipitation catch (i.e. unshielded, Alter shielded, and dual-gage) and measured ground true versus wind speed resulted in the exponential curves shown in Figure 4. The detrimental effect of wind on an unshielded gage is readily apparent from this graph along with the change in the gage ratio with wind speed caused by the addition of an Alter shield and the use of the dual-gage approach.

A plot of storm errors (i.e. assumed ground true - calculated ground true using dual-gage) versus wind speed resulted in a very wide scatter of points with a best fit linear regression line having a slight positive slope (0.01) and a correlation coefficient of 0.21. An examination of the mean error per storm resulted in values of 0.16, 0.10, and 0.01 inches respectively for the unshielded gage, the shielded gage, and the dual-gage while the standard deviations were 0.22, 0.17, and 0.16 inches respectively.

The constant (B) and coefficients (a,b) used in this study will no doubt be refined in the future as more data are accumulated and as results from other researchers are published. All are dependent on "ground true" measurements which, of course, are subject to error. It is felt, however, that the value of $B \cong 1.8$ is reasonable and will probably not change radically in the future (Larson, 1972). Figures 2 and 3 show the great variability in individual precipitation-wind measurements and might suggest that this approach may have greater applicability with longer time periods. An examination of the dual-gage method applied to storm data and then to monthly data showed a much smaller range of relative errors for the latter.

It would seem that the dual-gage approach has at least three possible advantages which should be considered. First, the correction factor B is essentially independent of windspeed and temperature thereby eliminating the need for such data in order to make the calculations for "true catch". This is not true for most other correction methods which usually require at least a measure of storm wind speed. Struzer (1969) has concluded that his version of the dual-gage approach is at least as accurate as correction methods which require wind data for precipitation corrections. Second, the dual-gage installation should be installed at a site which is exposed to the prevailing wind movements so that a distinct catch differential will be generated between the shielded and unshielded gages. The only major siting requirements are that the dual-gages be installed at the same relative heights so that the two gages are subjected to the same wind movements, high enough so as not to be affected by blowing snow, and since the procedure basically assumes a horizontal wind movement the dual-gage sites should be located in relatively smooth areas so as to avoid updrafts and downdrafts induced by roughness (Peck, 1972). Thus, if it is concluded that a natural well-protected site is not available at a particular location, the installation of a dual-gage site could perhaps eliminate the subjective judgements involved in deciding which of the available sites have the best natural shielding and what is their classification in terms of protection. Third, in windy areas the dual-gage site could permit easier comparisons of data between sites because it is perhaps easier to establish sites open to the prevailing winds at two different locations than it is to establish two naturally protected sites each having an equal amount of protection.

Conclusions

In areas where both solid precipitation and high winds can be expected and where well-protected natural gage sites are not available, the dual-gage approach for improving precipitation measurements seems to hold some promise. The percent relative error in precipitation measurements over the two year period of this study was reduced from 56 percent for the unshielded gage and 34 percent for the shielded gage to 5 percent for the dual-gage approach. A multiple comparison test showed that for these data, there was no statistically significant difference between the mean storm catch of assumed ground true and the mean storm catch calculated using the dual-gage approach. This does not mean that the dual-gage method is the ultimate and universal answer for solving all the problems associated with measuring precipitation. However, it does seem that in certain circumstances the dual-gage method more closely approximates "true catch" than either a shielded or unshielded precipitation gage by itself.

In recent years it has become evident that one of the limiting factors in further developments of conceptual water models, water budget studies, rainfall-runoff relationships, etc. is an inability to accurately measure precipitation either on a point or areal basis. It has been pointed out that the most critical factor in watershed simulation is the input from raingage networks (Crawford and Linsley, 1966) and that in hydrologic simulation an error of 10 percent in precipitation input can result in an error of 50 percent in the residual of excess rainfall (McGuinnes and Vaughan, 1969). It does seem important, therefore, that a continued effort should be made towards improving and developing current and new methods of measuring precipitation.

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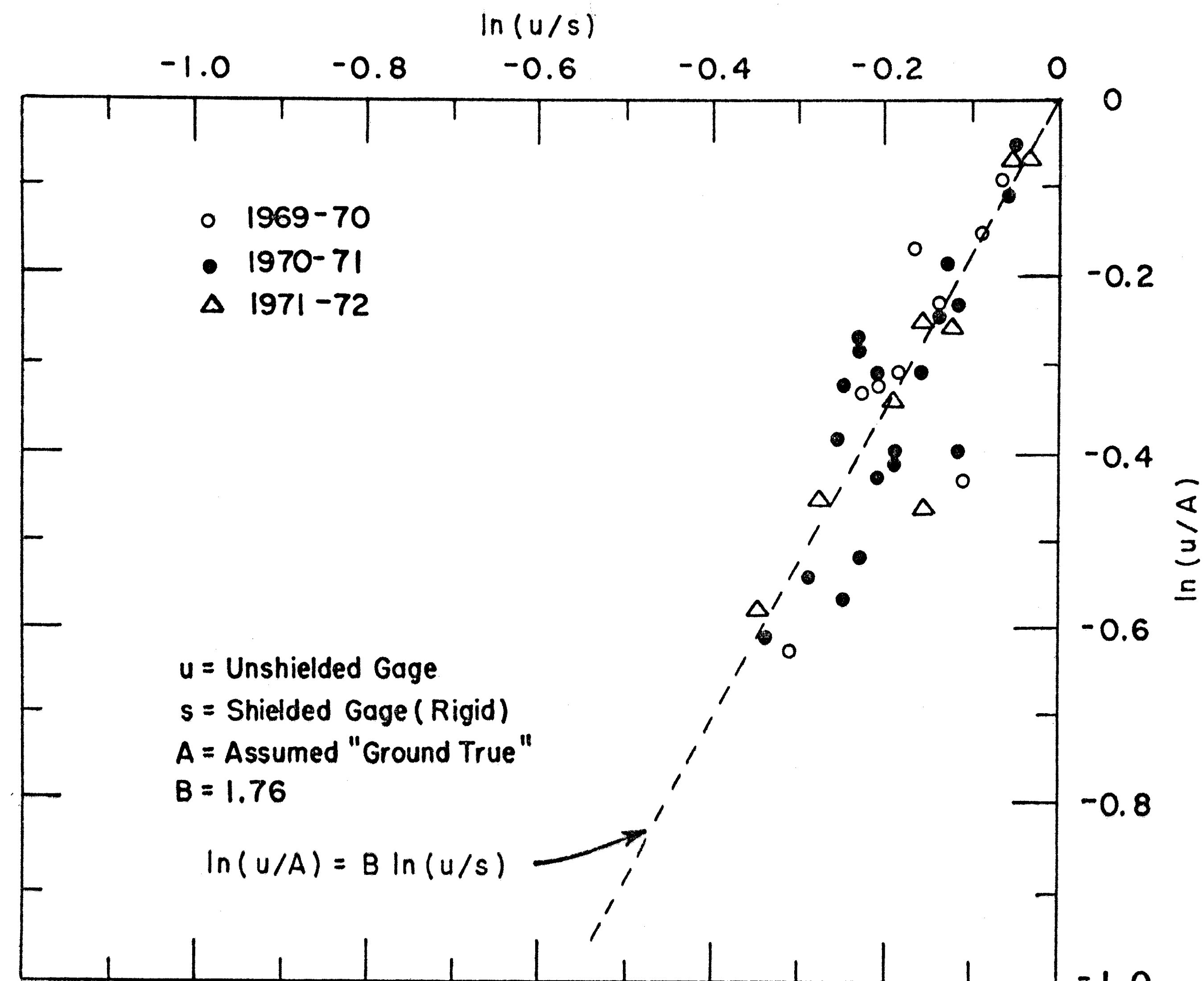

Figure 1. Precipitation Ratios, Site X-4, Danville, Vt.

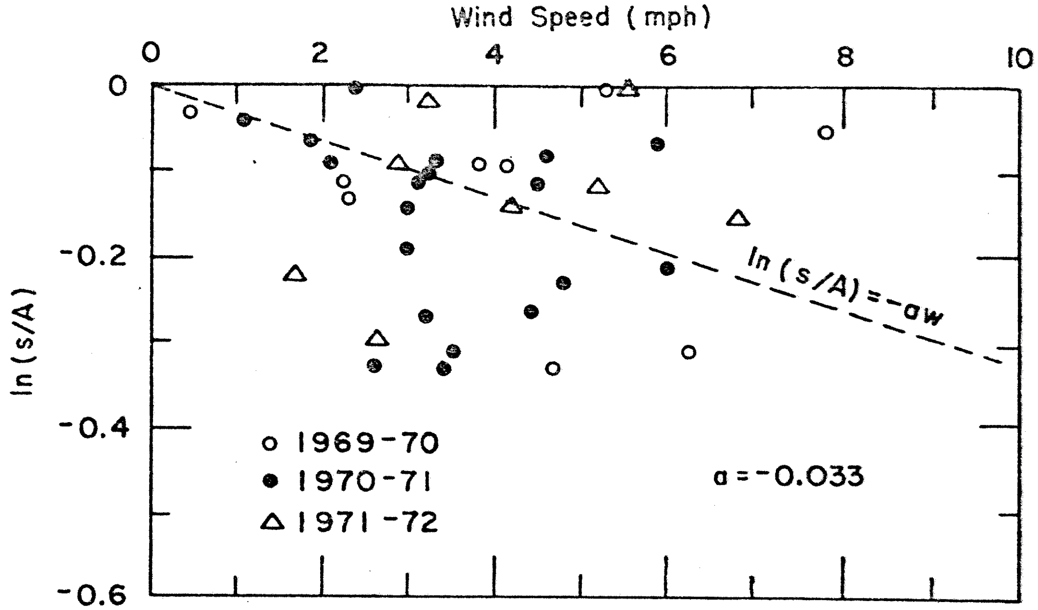

Figure 2. Precipitation Ratio versus Wind Speed,
Site X-4, Danville, Vt.

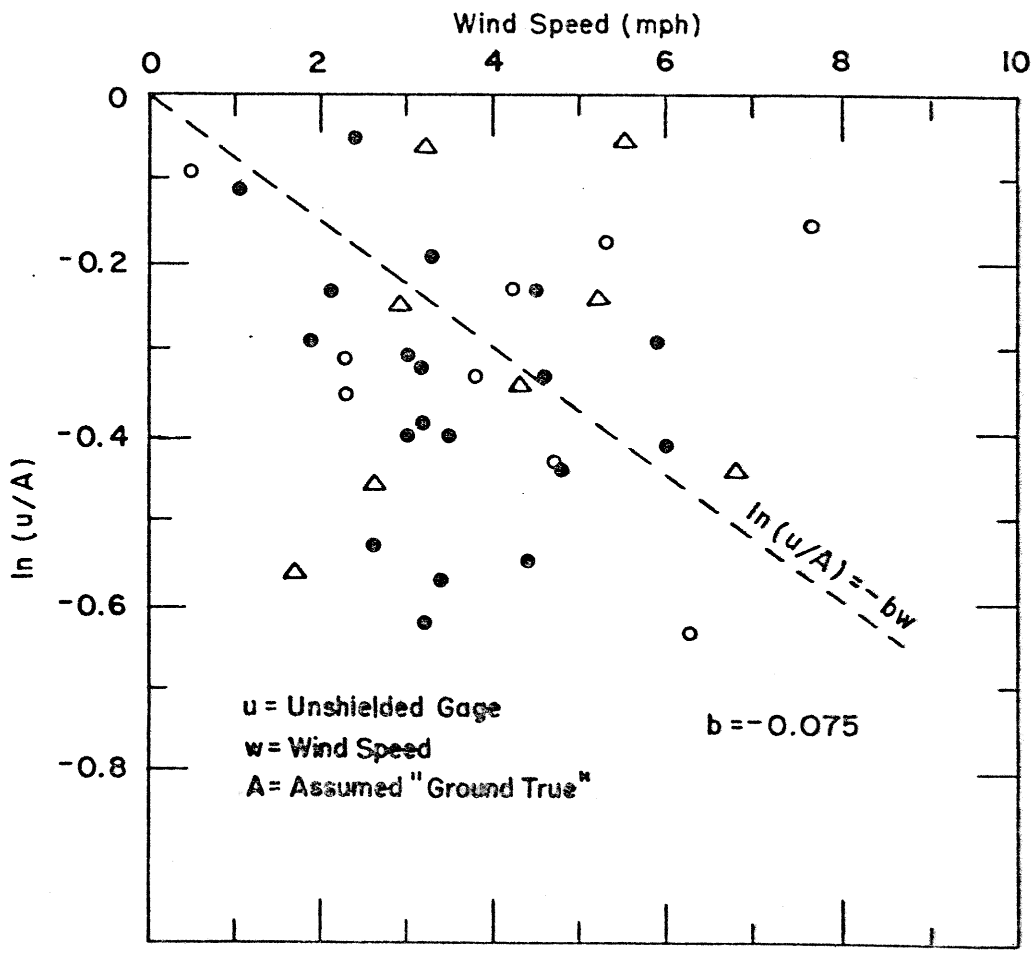

Figure 3. Precipitation Ratio versus Wind Speed,
Site X-4, Danville, Vt.

TABLE 1

Precipitation Totals

Location: Wyoming

Period: Sept. 1969 - May 1971 Storms: n = 100 (snow)

Gage	#6 unshielded	#7 Alter shield	* calculated ground true	** assumed ground true
Total precipitation	12.48"	18.45"	26.71"	28.15"
Mean precip. catch per storm	.12"	.18"	.27"	.28"
% of standard	44%	66%	95%	100%
Variance	.03	.05	.09	.13
Standard deviation	.18	.23	.31	.37

* Based on dual-gage approach
** Used as standard or measured ground true

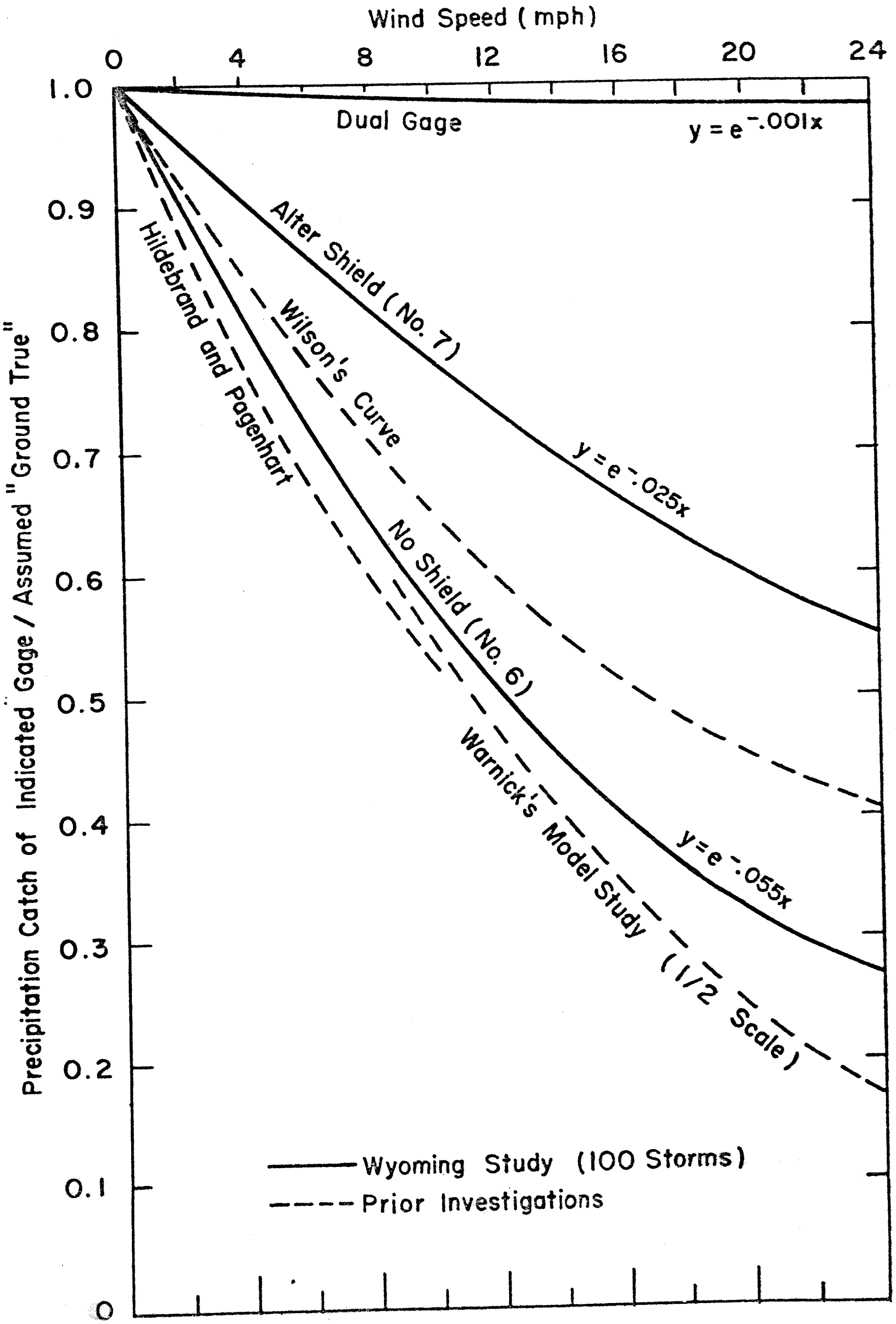

Figure 4. Precipitation Ratios versus Wind Speed, Wyoming Site.