Accuracy of Precipitation Measurements for Hydrologic Modeling

LEE W. LARSON AND EUGENE L. PECK

Hydrologic Research Laboratory, National Weather Service, NOAA, Silver Spring, Maryland 20910

The use of precipitation data as input for conceptual hydrologic models has enhanced the need for measurements more representative of 'true' precipitation. Precipitation input to continuous watershed models is generally some form of mean basin precipitation estimate based on point measurements. Each point measurement can have large catch deficiencies due to wind, especially for solid precipitation. A brief review is made of past results from studies concerned with these deficiencies. New curves based on current studies are presented for wind-caused gage catch deficiencies for both rain and snow. The results of using gage catch correction factors to adjust precipitation input to a conceptual hydrologic model are presented.

The use of precipitation measurements as a major input for conceptual hydrologic models has enhanced the need for point and areal measurements that are more representative of 'true' precipitation. Hydrologic modeling studies indicate that one of the most important factors in successful hydrologic simulation is reliable and representative precipitation data.

Raw precipitation data are often converted to some form of mean basin precipitation (MBP) estimate for use in a hydrologic model. Present hydrologic models to a large degree are limited by the accuracy of the MBP estimate. Many factors influence the estimate of MBP, including density and arrangement of the network, the particular site and gage characteristics at each location within the network, methods of areal analysis utilized, basin characteristics, storm characteristics, etc. For solid precipitation the most important of all these items, however, is the gage catch deficiency due to wind [*Peck*, 1972].

Many studies in the past have attempted to evaluate gage catch deficiencies in terms of the causes and magnitudes of the errors [*Green and Helliwell*, 1972; *Warnick*, 1956]. In this paper a brief review is presented of some of these past results. Recent relationships for wind-caused measurement errors for both liquid and solid precipitation are presented. Finally, the results of using precipitation correction factors based on these relationships as input for a conceptual hydrologic model and a calibrated watershed are presented.

Review of Previous Studies Concerned With Gage Catch Deficiencies

Literally hundreds of articles have been published on this subject from the mid-eighteenth century to the present. *Kurtyka* [1953], *Israelsen* [1967], and *Larson* [1971*a*] have each published comprehensive literature reviews containing a total of some 1600 references in the general field of precipitation measurements. More recently, the *World Meteorological Organization* [1973] has published an annotated bibliography in the same subject area.

Although most studies vary with one another as far as the magnitudes of gage catch deficiencies due to wind are concerned, they all reach the same general conclusions. That is, they all tend to agree that wind is the major cause of error in precipitation gage measurements. This error increases with gage site wind speed and is larger for solid than for liquid precipitation. A generally accepted theory is that in addition to site turbulence, much of the total measurement error is the result of turbulence and increased wind speed in the vicinity of the gage orifice resulting from the obstacle of the gage itself to the wind stream. As the air rises to pass over the gage, precipitation particles that would have passed through the gage orifice are instead deflected and carried further downwind, the result being gage catch deficiencies [*Peck*, 1972; *Robinson*, 1969; *Chou*, 1968; *Green and Helliwell*, 1972].

In order to minimize gage catch deficiencies, wind speed and eddy effects should be reduced in the vicinity of the gage [*National Oceanic and Atmospheric Administration*, 1972*a*]. To date, the most successful method of accomplishing this has been to place the precipitation gage in a well-protected natural site. A carefully selected natural site can reduce the adverse effects of wind in the vicinity of the gage considerably [*Brown and Peck*, 1962]. The Commission for Instruments and Methods of Observation of the World Meteorological Organization has stated that no single item is more important in the measurement of precipitation, especially snowfall, than the exposure or physical surroundings of the gage [*World Meteorological Organization*, 1969]. For good exposure a gage should have protection in all directions by objects of uniform height, the height of this protection varying from half the distance from the gage to the protection up to a height approximately equal to the distance from the gage to the protection. Care, however, must also be exercised to prevent 'overprotecting' the gage.

Much work has been done in the past to develop shields for gages that will compensate for the adverse effect of wind [*Weiss and Wilson*, 1957]. It has been shown that shields can have a beneficial effect on gage performance, especially for solid precipitation [*Warnick*, 1956]. Unfortunately, gage shields generally are not effective much beyond wind speeds of 20 mph (32 km/h). Gage shields generally function by directing wind currents down and around the gage, thus reducing the general turbulence and upward wind movement in the gage orifice vicinity. However, no combination of gage and shield will entirely eliminate the adverse effect of wind on gage catch.

Past studies have indicated a wide range of catch deficiencies for solid precipitation. *Black* [1954] stated that a precipitation gage at Barrow, Alaska, recorded 4 in. (10 cm) of annual precipitation while he estimated the true figure at 16 in. (41 cm) or more. Thus wind caused a catch deficiency of at least 75%. *Kurtyka* [1953] estimated gage catch deficiencies as high as 80% owing to exposure. *Sandsborg* [1972] estimated losses in the catch of snow at 40–50% for a gage at 1.5 m above the snow surface. *Warnick* [1956] estimated that for a wind speed of 20 mph (32 km/h) an unshielded gage could be expected to catch only 20% of 'true' catch. Warnick also estimated that the addition of a shield to the gage would increase its catch to 35% of true catch at 20 mph (32 km/h). *Larson* [1971*b*] has found that at wind speeds of approximately 12 mph (19 km/h) an unshielded gage would catch one third to one half of true catch and a shielded gage would catch two thirds to three fourths of true catch.

Gage catch deficiencies are much smaller for liquid than for solid precipitation. *Green* [1969] has estimated that for liquid precipitation, if wind speed at the gage orifice is 20–30% of that at a height of 6 ft (2 m), then the gage will catch within 1% of true catch. This usually corresponded to a wind speed of 12 mph (19 km/h) or less. *Linsley* [1958] shows gage catch deficiency for rain at 10 mph (16 km/h) to be approximately 15%. *Bratzev* [1963] has estimated the wind-caused measurement error for liquid precipitation to be about 5% per m/s (2 mph) of wind speed. *Struzer* [1968] has estimated the mean error due to wind for liquid precipitation at 10–20%. The use of shields on precipitation gages for liquid precipitation is less effective than it is for solid precipitation. *Chou* [1968] has reported an increase in rainfall catch of 2% when a shielded gage is utilized. *Larson* [1971*b*] reports no significant difference in rainfall catch between shielded and unshielded gages.

A fundamental problem underlying all of these types of studies is the determination of 'ground true.' All gage catch deficiency determinations depend upon this estimate. The care with which each of the various studies evaluated ground true to a large measure determines the value of the entire study. It is not too surprising that the comparison of results from various studies will result in a rather wide range of gage catch deficiencies for any given situation. The following general conclusions, however, will probably summarize most precipitation measurement error studies.

Point measurements of precipitation can have considerable deficiencies due to wind. These errors increase with wind speed and are much greater for solid than for liquid precipitation.

The most important factor in obtaining reliable precipitation measurements is proper site selection. A well-protected site can reduce measurement errors due to wind considerably.

Gage shields can reduce gage catch deficiencies; however, the shields are much more effective for snow than for rain. No combination of gage and shield will entirely eliminate the adverse effect of wind on catch. However, the shields themselves are not too effective at wind speeds above 20 mph (32 km/h).

CURRENT GAGE CATCH DEFICIENCY STUDIES

The Hydrologic Research Laboratory of the National Weather Service (NWS) has maintained for the past several years several precipitation research projects that have as one of their primary goals an evaluation of gage catch deficiencies (primarily for solid precipitation). One of the sites is located near Danville, Vermont, and is maintained and operated by the NWS. The second site is located near Laramie, Wyoming, and is maintained and operated by the Water Resources Research Institute of the University of Wyoming under contract with the NWS. The results obtained from these sites are considered to be quite reliable owing to the care that was exercised in establishing ground true. Both of these sites have been described in detail in other reports [*Larson*, 1971*b*, 1972*a*, *b*].

Gage catch deficiencies for solid precipitation have been

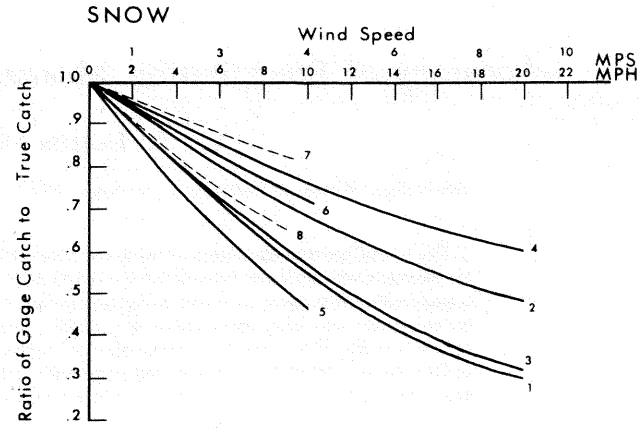

Fig. 1. Gage catch ratios versus wind speed for snow, where lines 1–4 represent Wyoming data and lines 5–8 represent Vermont data. Line 1 represents data from a nonshielded gage (1972–1973); line 2, from a shielded gage (1972–1973); line 3, from a nonshielded gage (1969–1971); line 4, from a shielded gage (1969–1971); line 5, from a nonshielded gage (1969–1972); line 6, from a shielded gage (1969–1972); line 7, from a shielded gage (1969–1973); and line 8, from a nonshielded gage (1969–1973). Lines 1–6 represent only snow, whereas lines 7 and 8 represent the winter periods November to March.

determined for shielded and unshielded gage configurations at both sites (Figure 1). For the Wyoming site it was found that at 10 mph (16 km/h) the gage catch deficiency was about 45% for solid precipitation and at 20 mph (32 km/h) it increased to about 70%. With the addition of a free-swinging Alter shield to the gage the deficiency at 10 mph (16 km/h) was reduced to about 28%, whereas at 20 mph (32 km/h) the deficiency was 45% for solid precipitation. For the Danville, Vermont, site an unshielded gage at wind speeds of 10 mph (16 km/h) also had a catch deficiency of about 45%. A shielded gage at this site at 10 mph (16 km/h) had a deficiency of about 24%. Data from the Danville site at wind speeds much beyond 10 mph (16 km/h) were not available.

Deficiencies in catch are much smaller for liquid than for solid precipitation (Figure 2). Data from the Danville site indicate that at wind speeds of 10 mph (16 km/h), deficiency in rainfall catch of about 10% can be expected. It was also found that the shielded gage caught little more rainfall than the un-

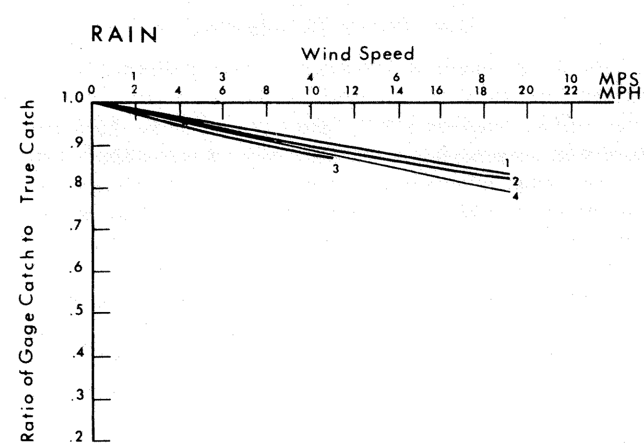

Fig. 2. Gage catch ratios versus wind speed for rain where line 3 represents Danville, Vermont, data. Lines 1, 2, and 4 are added for comparison purposes. Line 1 is from *Bogdanova* [1965], line 2 from *Green* [1969], and line 4 from W. R. Hamon (personal communication, 1972).

shielded gage at the wind speeds experienced at this site (about 1% more at 5 mph (8 km/h) of wind). Results from rainfall gage catch deficiency studies other than those at Danville are also shown in Figure 2. They indicate a rainfall catch deficiency of about 20% at wind speeds of 20 mph (32 km/h). There appears to be good agreement among all the studies shown in Figure 2.

A summary of gage catch deficiencies versus wind speed is presented in Figure 3. Curves are shown for liquid precipitation (the catches of shielded and unshielded gages are nearly equal), solid precipitation (unshielded gage), and solid precipitation (shielded gage). When precipitation is measured, the following approximate results can be expected.

For solid precipitation a 45% deficiency at 10 mph (16 km/h) and a 70% deficiency at 20 mph (32 km/h) can be expected. A shield can reduce solid precipitation measurement errors by about one third to one half.

For liquid precipitation a 10% deficiency at 10 mph (16 km/h) can be expected. A shield has little beneficial effect for liquid precipitation measurements.

NATIONAL WEATHER SERVICE RIVER FORECAST SYSTEM (NWSRFS)

The NWS is in the process of replacing empirical flood forecasting procedures with conceptual hydrologic models. The basic model that is being adopted is described in detail in two technical memorandums published by the *National Oceanic and Atmospheric Administration* [1972*b*; *Anderson,* 1974*b*]. These technical memorandums describe the entire system, including the conceptual watershed model, snow accumulation and ablation model, the processing of the basic data, and recommended calibration procedures.

The National Weather Service River Forecast System (NWSRFS) contains 33 parameters that must be calibrated in order to produce reasonable simulation results. Twenty of these parameters are in the soil moisture accounting and channel-routing routines, and an additional 13 are in the snow accumulation and ablation model. A number of these parameters can be determined from hydrograph analysis or by physical considerations.

Two parameters provide the flexibility for the model to adjust input precipitation. The first parameter is used to adjust

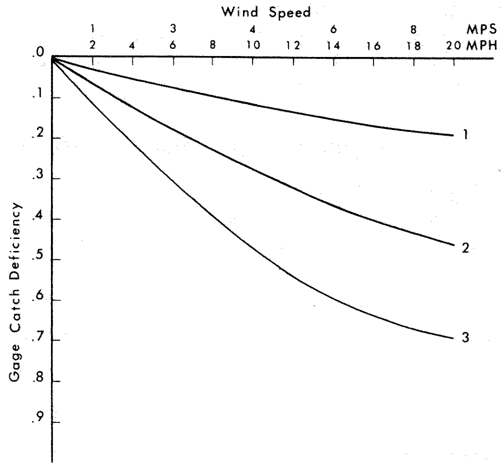

Fig. 3. Gage catch deficiencies versus wind speed. Line 1 is for rain (shield makes little or no difference in deficiencies), line 2 is for snow with a shielded gage, and line 3 is for snow with an unshielded gage.

all precipitation input to the model. This parameter, called K1 in the model, is the ratio of average areal precipitation to the precipitation input. Thus far, K1 has been found to be relatively unimportant if a good estimate is made of MBP and for most basins is set equal to unity. The second parameter, called the snow correction factor (SCF) in the model, is part of the snow accumulation and ablation model and adjusts only solid precipitation. The SCF is highly dependent pointwise on gage exposure, wind speeds, gage/shield configurations, storm type, etc. In NWSRFS, SCF is an areal adjustment and therefore must be a representative value for all the gages in the basin. *Anderson* [1974*a*] documented some of the effects of the parameter SCF in the Passumpsic River basin in Vermont. He found that SCF is quite sensitive, has a significant effect on snowpack runoff volumes, and in general is one of the more important snow model parameters.

The calibration of any hydrologic model is a lengthy and time-consuming procedure. *Monro and Anderson* [1974; *Anderson,* 1974*a*] have authored a recommended calibration procedure for NWSRFS. For this discussion it is sufficient to say that in the calibration process of the NWSRFS, two major programs are utilized. These are the verification and optimization programs. The verification program simulates an outflow hydrograph, plots observed and simulated hydrographs, calculates statistical summaries of comparisons between observed and simulated flows, etc. This program is utilized for trial-and-error calibration of the system parameters. The trial-and-error phase is normally a multirun process. The final calibration step is to utilize the optimization program. This program is a pattern search optimization scheme [*Monro,* 1971] that provides optimal values for the system coefficients.

INITIAL ESTIMATE OF SCF

The SCF was of particular interest for this study. Two approaches were utilized in order to make a reasonable estimate of the value of this parameter prior to the calibration process.

The first approach was to compare the precipitation catch of shielded and unshielded gages in or near the Pemigewasset River basin. Only one shielded gage existed in the basin above Plymouth (Warren, New Hampshire). A second shielded gage was located just south of the basin (Bristol, New Hampshire). Two unshielded gages in similar orographic locations and at comparable elevations were then chosen for catch comparison with the shielded gages. One of the unshielded gages is located in the basin (Woodstock, New Hampshire), and the second is just south of the basin (Lakeport, New Hampshire). Figure 4 is a plot of the sum of the monthly precipitation catch for the shielded gages versus the sum of the monthly precipitation catch of the unshielded gages for the calibration period (1964–1971). It is apparent that during the predominantly solid precipitation months (i.e., November to March) the shielded gages catch more precipitation than the unshielded gages. During predominantly liquid precipitation months (i.e., April to October) the monthly plots are close to or slightly below the 45° line.

In order to estimate a value for SCF a comparison was made between the winter catches (November to March) for the pairs of shielded and unshielded gages. The total winter catch for these shielded gages was 260.72 in. (662.22 cm), whereas the unshielded gages caught 229.15 in. (582.04 cm). Figure 3 shows that a shield reduces the solid precipitation measurement error of an unshielded gage by one third to one half. Thus the difference between the total winter catches of the pairs of gages

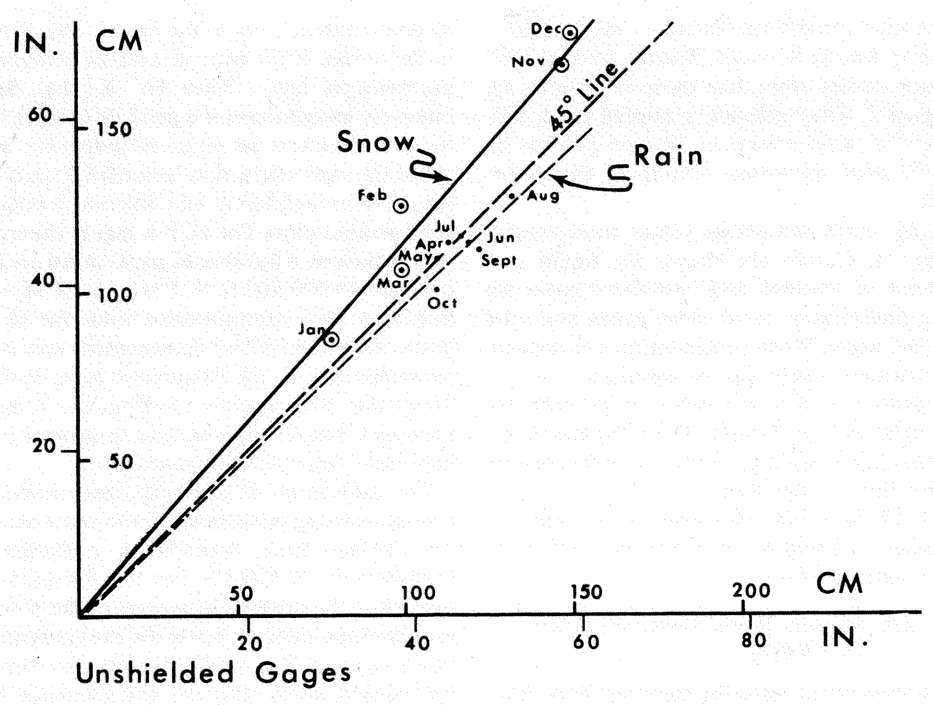

Fig. 4. Total monthly precipitation catch of shielded and unshielded gages for the period 1964–1971. The shielded gage data are from Bristol and Warren, New Hampshire, (average elevation of 615 ft), and the unshielded gage data are from Woodstock and Lakeport, New Hampshire (average elevation of 625 ft). Data from months November to March are considered predominately for snow, and data from months April to October are considered predominately for rain.

can be used to obtain an estimate of the true winter catch. In this case, the estimate of the true precipitation would range from 292 in. (742 cm) to 324 in. (823 cm). The resulting correction factor for unshielded gages would range from 1.27 to 1.41. This analysis, of course, assumes that the exposure of all four sites is similar and that the differences in the catches are due primarily to the shields and not some site peculiarity.

A second approach to estimating a value for SCF was to utilize basin wind speeds. This approach makes several important assumptions. First, it assumes that mean point wind is indicative of mean areal wind. Second, it assumes that the precipitation gages are exposed to mean areal wind. Third, it assumes that mean wind is indicative of storm wind. The second assumption is primarily dependent upon the site or location of each individual gage. Gages with poor exposure may be exposed to higher than average winds, whereas gages with good exposure may be exposed to less than average winds. In order to minimize the effects of these types of assumptions it would be preferable to have storm wind data from many points in the basin. In addition, it would be desirable to be aware of the location and exposure of each precipitation gage utilized in the analysis.

In this particular study, the nearest available wind data were from Concord, New Hampshire, south of Plymouth, New Hampshire. During the winter months the mean wind speed at this location and at gage orifice height was estimated to be approximately 5.5 mph (2.5 m/s). This corresponds to an SCF of about 1.37 for unshielded gages and solid precipitation (Figure 5). This estimate of SCF is in the range of SCF values previously determined by gage catch comparisons. Thus a reasonable estimate of SCF based on both gage catch comparisons and wind speed measurements would be a value in the range of 1.27–1.41.

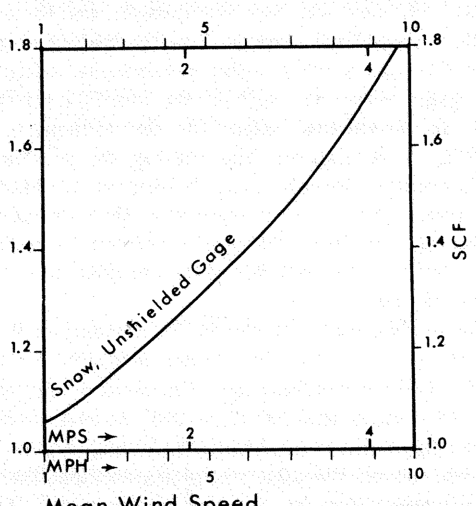

Fig. 5. Mean wind speed versus SCF.

APPLICATION OF NWSRFS TO THE PEMIGEWASSET RIVER

The Pemigewasset River basin is located in east central New Hampshire. The portion of the basin fit by NWSRFS for this paper was upstream of Plymouth, New Hampshire, an area of approximately 622 mi² (1611 km²). Streamflow data were available from U.S. Geological Survey records at Plymouth, and hourly and daily climatological data (precipitation and temperature data) were available for several stations in the basin from the National Climatic Center at Asheville, North Carolina. The meteorological data necessary for calculating daily potential evapotranspiration were available from local climate publications.

The following is background information on the watershed at the Pemigewasset River, Plymouth, New Hampshire. The

TABLE 1. Calibration Results From a Multiyear Statistical Summary

Run	Observed Mean Flow, ft³/s/d	Simulated Mean Flow, ft³/s/d	rms	Correlation Coefficient	Percent Bias
2	1228.0	1162.5	1064.2	0.82	−5.3
7	1228.0	1195.2	813.6	0.90	−2.7
11	1228.0	1205.9	762.9	0.91	−1.8
12*	1228.0	1213.9	699.8	0.93	−1.2
13†	1228.0	1231.8	637.1	0.94	+0.3
14‡	1228.0	1221.9	636.2	0.94	−0.5
A§	1228.0	1201.7	708.1	0.92	−2.1

* Parameters were optimized on first 50 months.
† Parameters were optimized on last 50 months.
‡ Mean of both sets of optimized parameters was utilized.
§ 'Best' simulation results were obtained with SCF set equal to unity.

area is 622 mi² (1611 km²). The mean elevation is 1811 ft (533 m). The elevation range is 457–5249 ft (139–1600 m). Six stations were utilized to compute mean basin precipitation, the elevation range of precipitation stations being 457–810 ft (139–247 m). Three stations were utilized to compute mean basin temperature, the elevation range of temperature stations being 457–720 ft (139–220 m). The mean annual values for the test period 1964–1971 are given below.

Discharge	26.8 in. (68.2 cm)
Precipitation	48.9 in. (124.2 cm)
Snowfall	16.2 in. water equivalent (41.2 cm)

The calibration of the Pemigewasset watershed involved several verification and optimization runs to arrive at the 'optimum' parameter values. The optimization scheme in NWSRFS is limited to 50 months of data. Therefore the final step in the calibration procedure was to optimize first on the initial 50 months of data and second on the last 50 months. The mean of the two sets of optimized parameters was then used in the final verification run. A multiyear statistical summary of some of these runs is presented in Table 1. The final simulation run of the calibration period resulted in a correlation coefficient of 0.94 and a bias of −0.5% between observed and simulated daily flows. A comparison between observed and simulated annual spring runoff (March to May) was made, and the results are shown in Figure 6. It is apparent that there is a good relationship between the two sets of data with a correlation coefficient of 0.99. In addition, all data points are grouped closely around the 45° line.

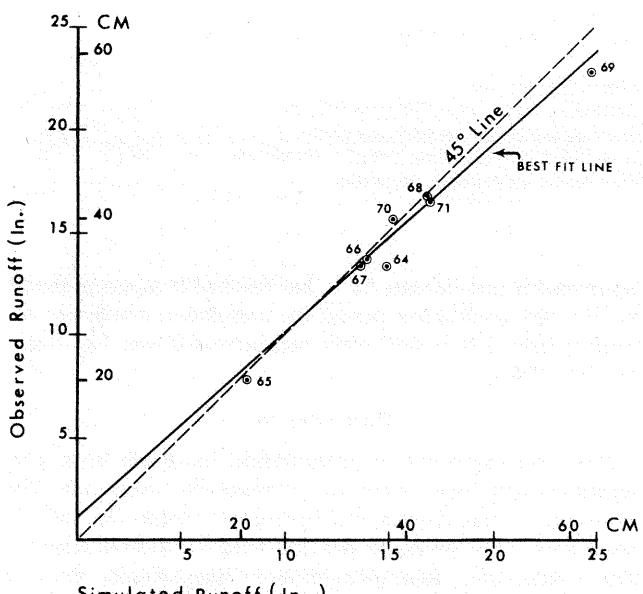

Fig. 6. Spring runoff comparisons of the Pemigewasset River at Plymouth, New Hampshire, for the months March to May, 1964–1971. The best fit regression line is represented by the equation $Y = 0.90X + 1.02$ and has a correlation coefficient r of 0.99.

The calibration procedure was begun with an initial SCF of 1.15. This value was chosen because it would be a reasonable minimal starting value for calibrating any watershed with winter snow cover if no other data (i.e., wind or shielded/unshielded gage comparisons) were available to make a more definitive judgment. The calibration process ultimately resulted in a final optimized value for SCF of 1.30. This is in the range of values previously established for SCF on the basis of the two approaches used. Thus it would seem that a good initial estimate of SCF can be made prior to the calibration process by using available wind and/or solid precipitation records.

SCF SENSITIVITY

After the model was fit satisfactorily to the Pemigewasset basin, the sensitivity of SCF was investigated. The first step was to hold all parameters at their optimized values while SCF was varied from 1.0 to 1.5. Some of the results of this process are presented in Figure 7. It can be seen that a minimum root mean square (rms) and a maximum correlation coefficient r occur with an SCF ≐ 1.3. The percent mean snowmelt period bias (March to May) increases steadily from a large negative bias with SCF = 1.0 to a large positive bias with SCF = 1.5. A zero monthly bias is achieved with SCF ≐ 1.27, whereas at the optimized value of SCF ≐ 1.3 a slight positive bias exists (approximately +2.5%).

A natural question that might arise is whether or not an SCF is actually necessary in a complete conceptual hydrologic model. That is, can other parameters in the model be adjusted to compensate for the wind-caused solid precipitation measurement errors that occur during the snow accumulation process? To answer this question, parameter SCF was fixed at unity. The model was again optimized on the initial and final 50 months of the calibration period. Sixteen parameters were allowed to readjust themselves to compensate for the lack of an SCF. Of these parameters, five were concerned with evaporation, two with moisture storage, three with moisture distribution, four with snow ablation, one with input data ad-

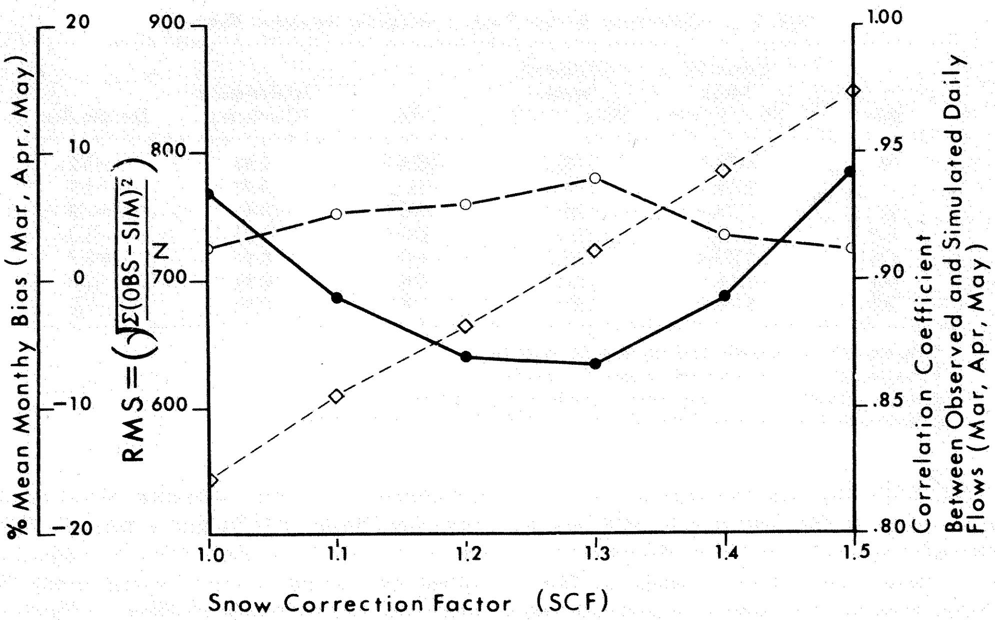

Fig. 7. SCF versus rms (solid circles), correlation coefficient (open circles), and percent monthly bias (squares). This SCF sensitivity plot is based on observed and simulated daily flows.

TABLE 2. Optimized Parameters

Parameter	With SCF	Without SCF	Purpose
UZSN	0.250	0.407	Nominal upper-zone storage
CB	0.22	0.255	Infiltration index
POWER	2.08	1.88	Exponent in infiltration curve
KV	1.00	1.61	Weighting factor for variable groundwater recession rates
K24EL	0.171	0.198	Percent of watershed in stream surfaces and riparian vegetation
A	0.045	0.057	Percent impervious area
EPXM	0.350	0.457	Maximum interception storage
K1	1.0	1.027	Ratio of areal precipitation to precipitation input
K3	0.1700	0.1756	Evaporation loss for lower zone
MFMAX	0.028	0.022	Maximum nonrain melt factor
MFMIN	0.0085	0.0068	Minimum nonrain melt factor
SI	14.3	18.1	Areal water equivalent above which 100% snow cover always exists
DAYGM	0.010	0.0069	Daily melt at snow-soil interface
EHIGH	1.15	1.07	Maximum adjustment factor for evapotranspiration
NEP	180	203	Day when evapotranspiration reaches maximum
NDUR	60	53	Number of days at which evapotranspiration is maximum
SCF	1.30	1.00	Snow correction factor for precipitation gages

justments, and one with groundwater recession. The mean optimized values for these parameters with and without SCF along with a short explanation of the function of each parameter is given in Table 2. The optimization scheme, in an attempt to compensate for reduced input from winter precipitation with SCF = 1.0, adjusted parameters to increase upper-zone storage capacity, reduced both maximum and minimum snowmelt factors, reduced summer evapotranspiration, and increased the adjustment factor for all precipitation measurements (K1) from its normal 1.000 to 1.027. A general redistribution of runoff from summer, fall, and winter months to the spring runoff months occurred. The statistical results of the final verification with SCF fixed at unity are listed in Table 1 under run A. It can be seen that eliminating SCF, even though other parameters were reoptimized to compensate for it, has resulted in a poorer model fit. For the verification period the correlation coefficient decreased from 0.94 to 0.92 while rms increased over 10% (from 636.2 to 708.1).

Conclusions

Point measurements of precipitation, especially solid precipitation, can have errors of considerable magnitude due primarily to wind. Conceptual hydrologic models that include snow-accounting processes provide better simulation results if this wind-caused solid precipitation measurement error is eliminated or reduced through the use of an SCF. An estimate of a reasonable SCF can be made from available wind data (Figure 5) or through a comparison of precipitation data from shielded and unshielded gages (Figure 3).

Acknowledgments. The authors would like to thank Eric A. Anderson and John C. Monro for their advice and guidance and Robert Tubella and Michelle Scott for their technical assistance. This paper was presented at the 55th Annual Meeting, AGU, Washington, D. C., April 8-12, 1974.

REFERENCES

Anderson, E. A., Conceptual streamflow forecasting model applied to northern New England rivers, paper presented at 31st Eastern Snow Conference, Ottawa, Ont., Feb. 7-8, 1974*a*.

Anderson, E. A., National Weather Service river forecast system, Snow accumulation and ablation model, *NOAA Tech. Memo. NWS Hydro-17,* chap. 1-5, Nat. Oceanic and Atmos. Admin., Silver Spring, Md., 1974*b*.

Black, R. F., Precipitation at Barrow, Alaska, greater than recorded, *Eos Trans. AGU, 35*(2), 203-207, 1954.

Bogdanova, E. G., Relationship of readings of the Tret'yakov gage to wind speed, *Sov. Hydrol. Selec. Pap. 1,* 59-67, 1965.

Bratzev, A. P., Influence of wind speed on the quantity of measured precipitation, *Sov. Hydrol. Selec. Pap. 4,* 414-417, 1963.

Brown, M. J., and E. L. Peck, Reliability of precipitation measurements as related to exposure, *J. Appl. Meteorol., 1*(2), 203-207, 1962.

Chou, K. C., Research and discussion on definite precipitation measurements, *Sci. Rep. 5,* pp. 48-65, Dep. of Geogr. and Meteorol., National Taiwan Univ., Tai-Pei, Formosa, June 1968.

Green, M. J., Effects of exposure on the catch of rain gauges, *Tech. Pap. 67,* pp. 1-28, Water Res. Ass., Medmenham, Marlow, Buckinghamshire, England, July 1969.

Green, M. J., and P. R. Helliwell, The effect of wind on the rainfall catch, report, pp. 1-7, Water Res. Ass., Medmenham, Marlow, Buckinghamshire, England, Feb. 1972.

Israelsen, C. E., Reliability of can-type precipitation gage measurements, *Tech. Rep. 2,* pp. 1-74, Utah Water Res. Lab., Utah State Univ., Logan, July 1967.

Kurtyka, J. C., Precipitation measurements study, *Rep. Invest. 20,* pp. 1-178, State Water Surv. Div., Urbana, Ill., 1953.

Larson, L. W., Precipitation and its measurement, A state of the art, *Water Resour. Ser. 24,* pp. 1-74, Water Resour. Res. Inst., Univ. of Wyo., Laramie, June 1971*a*.

Larson, L. W., Shielding precipitation gages from adverse wind effects with snow fences, *Water Resour. Ser. 25,* pp. 1-161, Water Resour. Res. Inst., Univ. of Wyo., Laramie, Aug. 1971*b*.

Larson, L. W., Approaches to measuring 'true' snowfall, paper presented at 29th Eastern Snow Conference, Oswego, N. Y., Feb. 3-4, 1972*a*.

Larson, L. W., An application of the dual-gage approach for calculating 'true' solid precipitation, paper presented at 53rd Annual Meeting, AGU, Washington, D. C., April 1972*b*.

Linsley, R. K., et al., *Hydrology for Engineers,* p. 29, McGraw-Hill, New York, 1958.

Monro, J. C., Direct search optimization in mathematical modeling and a watershed model application, *NOAA Tech. Memo. NWS Hydro-12,* pp. 1-52, Nat. Oceanic and Atmos. Admin., Silver Spring, Md., April 1971.

Monro, J. C., and E. A. Anderson, National Weather Service river forecasting system, *J. Hydraul. Div. Amer. Soc. Civil Eng., 100*(HY5), 621-630, 1974.

National Oceanic and Atmospheric Administration, Substation observations, *Weather Bur. Observ. Handb. 2,* pp. 16-37, Data Acquis. Div., Office of Meteorol. Oper., Silver Spring, Md., 1972*a*.

National Oceanic and Atmospheric Administration, National Weather Service river forecast system forecast procedures, *NOAA Tech. Memo. NWS Hydro-14,* chap. 1-7, Hydrol. Res. Lab., Silver Spring, Md., Dec. 1972*b*.

Peck, E. L., Snow measurement predicament, *Water Resour. Res., 8*(1), 244-248, 1972.

Robinson, A. C., and J. C. Rodda, Rain, wind and the aerodynamic characteristics of rain-gauges, *Meteorol. Mag., 98,* 113-120, 1969.

Sandsborg, J., Precipitation measurements with various gauge installations, *Nordic Hydrol., 3,* 80-106, 1972.

Struzer, L. R., et al., Correction of precipitation normals (in Russian), *Tr. Gl. Geofiz. Observ., 215,* 3-15, 1968.

Warnick, C. C., Influence of wind on precipitation measurements at high altitude, *Eng. Exp. Sta. Bull. 10,* pp. 1-63, Univ. of Idaho, Moscow, 1956.

Weiss, L. L., and W. T. Wilson, Precipitation gage shields, *Int. Ass. Sci. Hydrol. Publ. 43, 1,* 462-484, 1957.

World Meteorological Organization, Guide to meteorological instrument and observing practices, *WMO 8TP3,* chap. 7, pp. 1-20, Geneva, 1969.

World Meteorological Organization, Annotated bibliography on precipitation measurement instruments, *Rep. 17, WMO-343,* pp. 1-278, Geneva, 1973.

(Received April 16, 1974;
accepted April 19, 1974.)

Reply

LEE W. LARSON AND EUGENE L. PECK

National Weather Service, Silver Spring, Maryland 20910

The points raised by Storr are well documented in the literature and recognized by the authors.

The paper was an attempt to summarize the problems associated with the nonrepresentativeness of point measurements for areal precipitation and to present techniques to adjust precipitation input data for hydrologic modeling. The generalized curves in Figure 3 are useful for this purpose.

No statement or implication was made to indicate that the curves could be used to estimate ground truth values for any specific climate or time period.