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Some Errors in Precipitation Measurements

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The effect of gauge height, exposure and screening on systematic errors in rainfall estimation is investigated. Adhesion losses are found to be more than 2% of the annual precipitation, but for summer periods alone it can amount to over 5%. A statistical model using the square root of observations (corrected for adhesion) is found to be adequate to describe differences due to the aerodynamic effects. A correction formula is proposed.

Introduction

Since 1973, 19 gauges at four localities have been used for weekly observations of rainfall within and near to a forested area. The results are used in a systematic study of the most important errors involved in estimations of rainfall based on a single gauge. This study forms part of a larger investigation of the climate, hydrology and ecology of a forest area.

The Field Area

The field area is a gently undulating moraine plateau with slopes of less than 1%. A 1.5 km wide belt of forest runs across this plateau from East to West. Two stations (A and D) were established in orchards, one on each side of the forest belt. A third station (B) was placed in an open field near the northern station (A), and a fourth (C) in a 200 x 300 m² clearing in the centre of the wood. (See Fig. 1). The annual precipitation is about 650 mm/yr, and as a rule over 90% falls as rain.

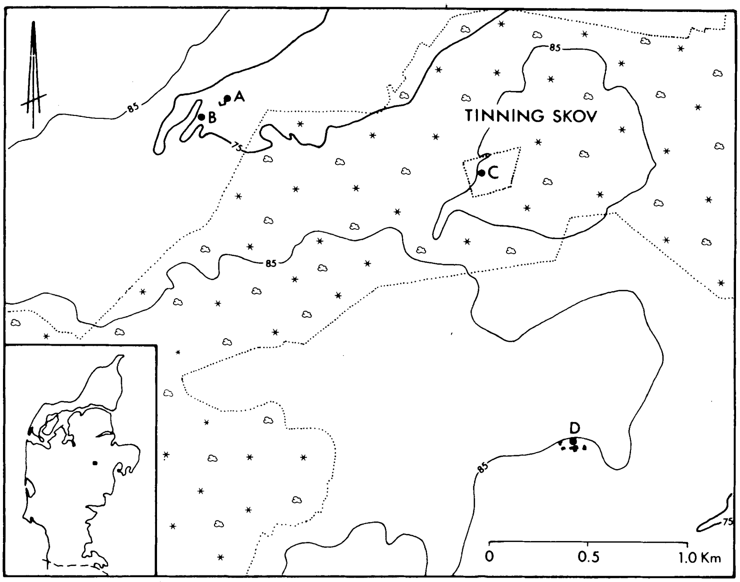

Fig. 1 Field area showing the location of stations A, B, C and D.

Instruments

A list of the instruments used at each station is given in Table 1. The following three types of gauge have been used:

a) Casella recorder (siphon type) with one revolution per week. This type is primarily used to give data on the duration and intensity of precipitation.

b) The Hellmann gauge, (Fig.2), hereafter also referred to as HG, has a standard opening of 200 cm². However, planimetry of paper impressions of the openings showed that 4 gauges were some 2% too large. Observations from these gauges are therefore corrected during data processing. After this correction the average opening is 200 cm², with a range of 0.8 cm². Readings are taken by means of measuring cylinders graduated to 0.1 mm precipitation. One of the two HG at station B was fitted with a Nipher screen, the other with an Alter Screen.

c) The PVC gauge, (Fig.2), hereafter also PG, is in principle similar to the HG. It is larger than the latter, but also satisfies the WMO (1965) criteria. The reservoir capacity is over 100 mm of rainfall and overflow is very unlikely, Rasmussen

Table 1

Station	Height above ground-level m	Hellmann-gauges (No.)	PVC-gauges (No.)	Angle from gauge to top of surroundings Directions N	NE	E	SE	S	SW	W	NW
A	0,0	13	5, 9*	21	25	19	21	22	28	19	24
A	1.5	11	6								
B	1.5	15, 16	18		<5	10	<5	<5	<5	<5	<5
C	0.0	10	1								
C	1.5		2, (19, 3, 4)**	35	32	40	13	35	20	30	30
D	0.0	14	7								
D	1.5	12	8	20	18	16	14	9	20	26	38

* No. 9 is the only gauge at ground-level not surrounded by an anti-splashing screen.

** Gauges 19, 3, 4 are placed at 40 m intervals along a line between gauge 2 and the western edge of the clearing. All gauges at ground-level are surrounded by mown grass to a distance of at least 2 m.

(1975). Each gauge is equipped with two bottles so that rainfall can be measured by weighing in the laboratory.

Planimetry showed that the average opening is 278.78 cm^2 with a range of 2.1 cm^2. Weighing errors are ± 5 mg so that the maximum error for the weight difference corresponds to $<<0.01$ mm precipitation.

To prevent splashing, a circular PVC screen with inclined strips was placed around the ground-level gauges.

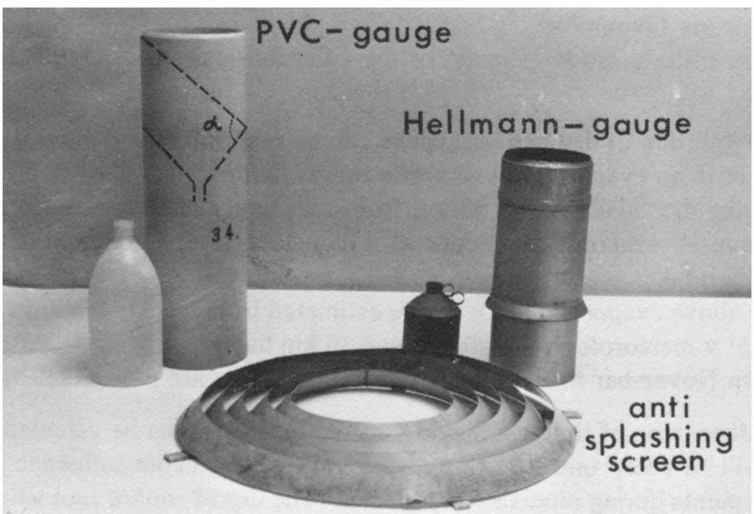

Fig. 2. Instruments used. The position of the funnel in the PVC-gauge is also shown.

Sources of Error

General

Since the true amount of precipitation is unknown, it is preferable to state the magnitude of error in terms of the range within which a given reading can fall.

Gross errors (e.g. booking errors) have been avoided by using fixed procedures and double checks wherever possible.

While some winter readings were discarded because they might have been affected by drifting snow, measurements were otherwise continued throughout the year, since snow plays a minor role even in winter.

Systematic Errors

Adhesion

After every rainfall, water adheres to the inner parts of the funnel and can evaporate. Golubev (1969) investigated this adhesion in the laboratory and found values in the range 0.03 mm – 0.20 mm, depending on gauge type. He also reports that for a well-cleaned gauge adhesion can be as much as twice that of a gauge that has been used for some time. We find that a value of 0.14 mm applies to well-cleaned HG, as well as PG, gauges.

Adhesion in the HG-reservoir is found to be less than 0.1 mm. Since it only occurs on emptying the gauge once a week, it is negligible in comparison with loss from the funnel, since this loss can occur after every rainfall if evaporation conditions are favourable.

We can make a crude estimate of the adhesion loss from a funnel, assuming that:

a) the duration of dry and wet spells can be read off on the pluviograph;

b) there is no evaporation loss while rain is falling;

c) during dry spells in the period from two hours after sunrise to two hours before sunset evaporation occurs at a constant rate; outside this period no evaporation takes place;

d) the above evaporation rate can be estimated from weekly readings from a 1/3 m^2 pan at a meteorological station some 10 km away;

e) from November to February evaporation losses are negligible.

For other parts of the year weekly corrections can thus be calculated, Fig. 3, and it will be noted that adhesion losses only have a major influence on rainfall measurements during relatively dry weeks. (The use of square root values will be explained later). When averaged the following losses expressed as percentages of total precipitation are obtained:

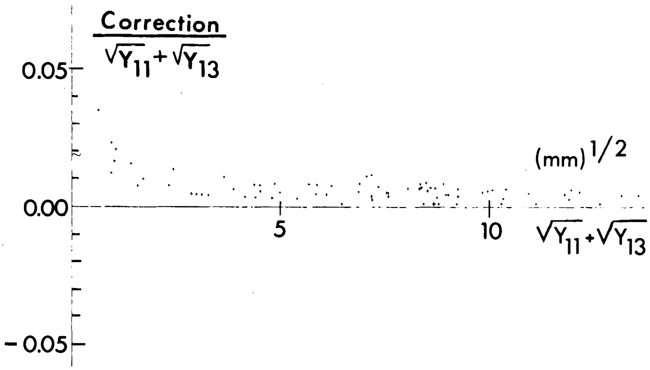

Fig. 3. Adhesion losses for the PVC-gauges at station A (all data).

4.6.1973 – 25.11.1973	2.3%
26.2.1974 – 25.11.1974	2.4%
3.3.1975 – 9.6.1975	5.1%

Actual losses may be increased by very light showers which are not recorded on the pluviograph. It should also be noted that for gauges 1.5 m above ground-level the actual losses probably exceed the calculated ones, partly because assumption a) does not hold, and partly because of the »oasis effect« generated by a freestanding wet object.

The real losses could therefore be greater than given above. Thus Golubev (1965) finds a loss of 8% (2.4 mm) for a summer period. It has not, however, been possible to measure such deviations, and the same corrections have therefore been used for all gauges.

Condensation Errors

A freestanding metal object can collect considerable amounts of dew at times when effective terrestrial radiation losses are great. More dew will collect in a gauge at a height of 1.5 m than on the ground below. Conversely, a gauge set into the ground receives heat by conduction from the soil and therefore collects less condensation than the surface of the soil or the vegetation. Dew falls in Denmark are rarely over 0.1 mm. Because of adhesion they can therefore usually not be detected in the gauges. Station 3, which is well protected against wind, is particularly subject to marked radiative temperature drops. Here, on two occasions, 0.15 mm rainfall was measured at a height of 1.5 m while other gauges remained dry. These anomalies might be due to condensation.

Evaporation Errors

In most gauge types the funnel is connected to the reservoir by means of a cylindrical spout with a diameter of less than 1 cm, thus reducing evaporation losses. As further precaution the neck of the reservoir in the PG is made to fit tightly around the spout.

Both of the gauge types used in the present study were tested under very effective drying conditions in the laboratory (RH 55%, temp. 22°C, artificial ventilation). The measured evaporation losses were:

HG 0.01 mm/day
PG 0.02 mm/day

Using a similar type of Hellmann gauge at an exceptionally exposed site in Switzerland, Sevruk (1974) measured evaporation losses of the order of 0.05 mm/day (exceptionally 0.1 mm/day). It therefore seems reasonable to ignore evaporation losses.

Splashing

Both of the gauge types used comply with the WMO recommendation (1965) that α in Fig. 2 should be at least 90°. Splashing from the gauges has presumably thus been avoided. Splashing from a hard, wet surface is restricted to a height of 1 m, Ashmore (1934). It follows that only the ground-level gauges had to be screened against splashing from outside. A circular PVC screen with sloping louvres was used for this purpose, see Fig. 2. Sandsborg (1968) considers a 45 x 45 cm^2 screen to be adequate, but Green (1970) uses 90 x 90 cm^2. Since a tight carpet of closely cropped grass gives rise to very little splashing, a diametre of 70 cm was thought to be adequate in the present study.

Aerodynamic Effect

Criteria for Optimum Shelter

In most countries gauges are placed with their openings above ground-level, and the gauges are therefore exposed to wind. Wind-tunnel experiments have shown that wind speeds may increase as much as 30% over the opening, Robinson and Rodda (1969). Some drops are therefore taken past the gauge and precipitation will be underestimated. This error, called the aerodynamic effect, can for rainfall in exposed localities reach 20% or more – see for example Madsen (1972) and Berggren (1970). This error can only be avoided by placing the gauge in completely open terrain and by ensuring that the opening is below the height of the local roughness constant. But this exposes the gauge to the risk of snow drifting.

Further, for practical reasons one must often place the gauge near to the residence of the observer. As alternatives one can try to define suitable shelter criteria or to estimate the necessary correction. Obviously, the screen should interfere as little as possible with the general wind pattern. Jensen (1955) examined the shelter provided by various natural and artificial screens and finds that the best shelter is provided by screens with 30-50% perforation area and up to a distance of some three to four times the height of the screen. (More solid obstructions create complex eddies which can be quite violent). Further, Jensen finds that below 0.4 times the screen height wind speeds are everywhere reduced by the same percentage. For a gauge height of 1.5 m a screen with the necessary perforations should thus be some 4 m high and placed some 10 to 15 m upwind. It should be noted that such a screen will not intercept rainfall even if it falls at an angle of 75^0 to the vertical. Andersson (1965) claims that the aerodynamic effect can be almost entirely eliminated by measuring precipitation in a forest clearing. Since the forest acts as a solid screen, however, the gauge must be placed at some distance from the edge of the clearing so as to avoid large eddies. If Jensen's results can be directly applied then we can conclude that an ideal clearing must have a diameter of some 6-8 times the tree height. We should note Anderssons warning, however, that the greater aerodynamic roughness of the forest might lead to more rain falling in the forest area than in the surrounding open country. Further research is required to clarify this point.

Using Jensen's results we can conclude that the best shelter conditions are to be found at station A. The height and distance of the screening is ideal, apart from a few buildings some 25 m west of the gauges. At D our shelter criteria are not satisfied since the screening is too high and too solid (height 6-8 m, perforation 0%). Finally, station C is placed in an almost ideal clearing, while at B there is no shelter whatsoever.

Shelter conditions are frequently expressed in terms of the vertical angles to the highest surrounding objects (e.g. Brown and Peck 1962, Berggren 1970, Madsen 1972). These angles were compared by means of vertical photographs with a fish-eye lens. Contour lines for the shelter at A are shown in Fig. 4. The vertical angles derived from photographs at A and D vary for the most between 15^0 and 25^0, at C they are some 30-35^0 while at B all angles are lower than 5^0 (se Table 1). These values are within the limits prescribed for Danish conditions by Madsen (1972).

Estimating the Aerodynamic Effect

In order to achieve greater homogeneity we have divided our data into two groups: May-October (summer, deciduous trees in leaf) and November-April (winter, deciduous trees bare). At this stage we are primarily interested in the differences between individual readings rather than the recorded totals. The differences depend largely on wind speed and direction, but these cannot be

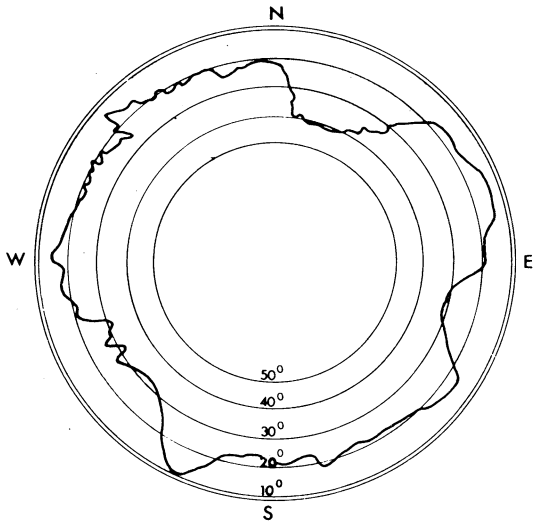

Fig. 4. Vertical angles to surroundings at station A based on a fish-eye photograph.

satisfactorily described on a weekly basis and they are not included in the present analysis.

In Fig. 5 we illustrate systematic differences as well as the variation of the gauge data, by plotting differences between two gauges against the sums of their readings. The figure shows that the variation of the differences increases with the arithmetic sum of the readings, (Fig.5a), that the opposite is true for the logarithmic data, (Fig.5c), and that there is no such pattern in the square-root data, (Fig.5b).

The square root transformation also destroys the connection between systematic difference and rainfall total. A probit analysis (Fig.6) shows that the square root differences for gauges can be well described by a normal distribution. The same applies to all other gauge pairs.

If we define

Y_{iu} = precipitation in mm for gauge i in week u

$X_{iu} \equiv (Y_{iu})^{1/2}$

then for $i \neq j$ we can assume that

$$X_{iu} - X_{ju} \sim N(\alpha_i - \alpha_j\ ,\ \sigma^2_{ij})$$

$$\mathrm{Cov}(X_{iu} - X_{ju}\ ,\ X_{iv} - X_{jv}) = 0 \text{ for } u \neq v$$

Here, $N(\alpha, \sigma^2)$ denotes the normal distribution with mean α and variance σ^2, and Cov (X, Y) denotes the covariance of the variates X and Y.

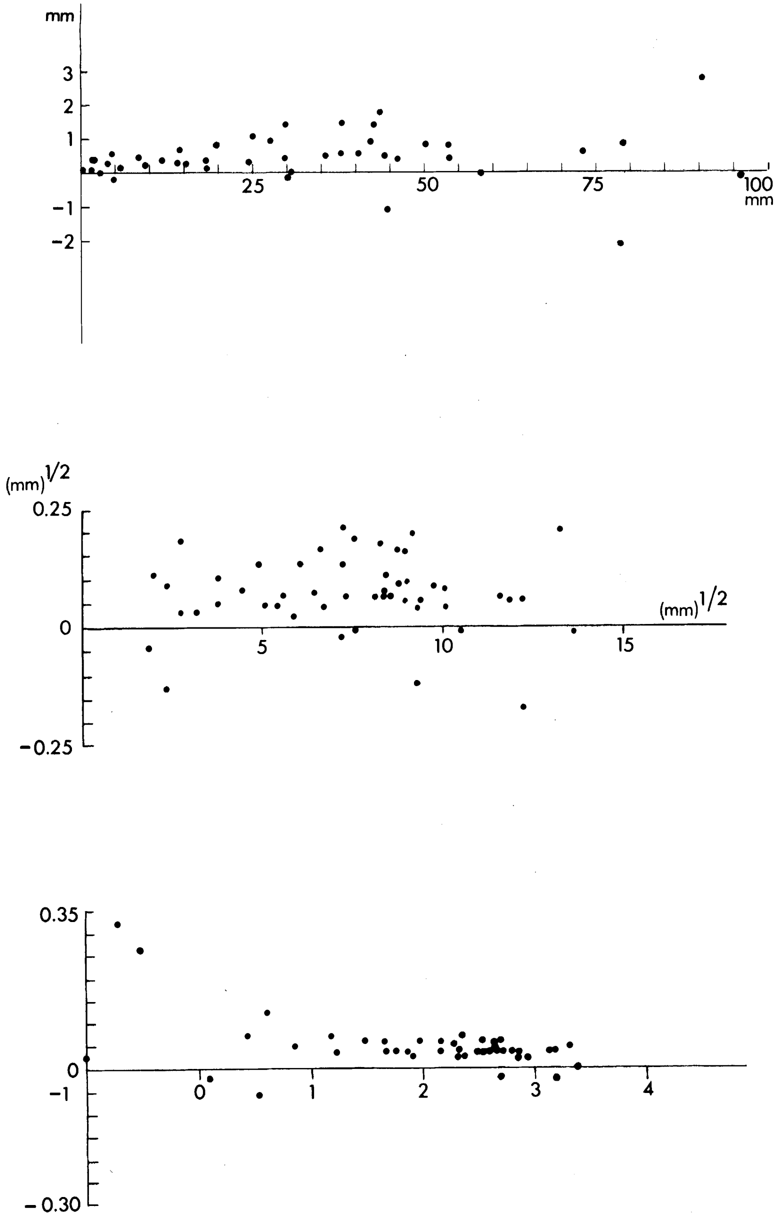

Fig. 5. Comparison of readings from gauges 11 and 13 (station A, summer data)

a. Difference (11-13) plotted against sums (11 + 13) of readings.

b. Square root differences ($\sqrt{11} - \sqrt{13}$) plotted against sums ($\sqrt{11} + \sqrt{13}$) of readings.

c. Log-differences ($\log_{10}11 - \log_{10}13$) plotted against sums ($\log_{10}11 + \log_{10}13$) of readings.

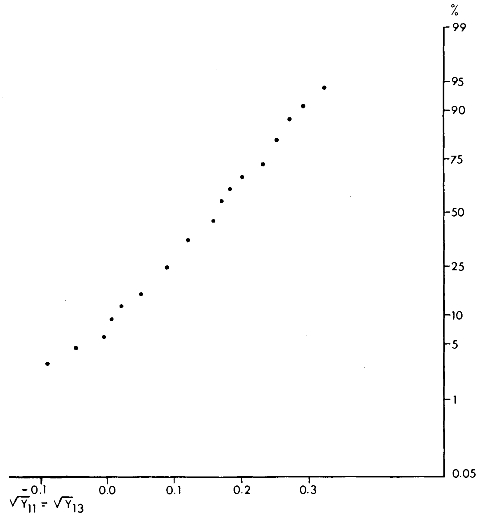

Fig. 6. Distribution of square root differences ($\sqrt{11}$ - $\sqrt{13}$)
(station A, summer data).

In the following particular attention will be paid to the parameter (α_i-α_j).

The analysis would be much easier if the covariance between gauges could be described more simply, for example:

$X_{iu} \sim N(\alpha_i + \beta_u \,, \tau_i^2)$ and independent

but it has not been possible to make a reduction of this kind. Thus the correlation between

$(X_{iu} - X_{ju})$ and $(X_{ku} - X_{lu})$, $u = 1 \,, \ldots, n$

is found to differ significantly from zero.

We have therefore chosen to use simple estimators and testors with known distributions, even though these are based on partial data – and may thus be inefficient.

In comparing two gauges, i and j, placed at different heights at the same place, we will estimate the difference α_i-α_j, and, in particular, see whether it is significantly different from 0.

In weeks for which we have observations from both gauges, we can define

$$Z_u = X_{iu} - X_{ju}$$

It follows that

$$Z_j \sim N(\alpha_i - \alpha_j \,, \sigma_{ij}^2)$$

and thus we can estimate the difference $(\alpha_i\text{-}\alpha_j)$ and the variance σ^2_{ij} by the average and standard error

$$\bar{\bar{Z}} = \frac{1}{n} \sum Z_u$$

$$s^2 \equiv \frac{1}{n-1} \sum (Z_u - \bar{Z})^2$$

The hypothesis $\alpha_i = \alpha_j$ can therefore be tested by judging Student's t-testor

$$t = \frac{\bar{\bar{Z}}}{s} \sqrt{n}$$

in the t-distribution with $f=n$-1 degrees of freedom. A comparison of gauge pairs, (i-j) and (k-ℓ), in estimating whether height differences are more significant at one station than another must be based on an estimation of

$$(\alpha_i - \alpha_j) = (\alpha_k - \alpha_l)$$

Here the same method is used, except that we use

$$Z_u \equiv (X_{iu} - X_{ju}) - (X_{ku} - X_{lu})$$

which could be calculated for those weeks during which all four gauges were in operation.

Comparison of PVC and Hellmann Gauges

The two gauge types are compared in Table 2. For winter conditions there seems no reason to prefer one gauge to the other. The summer values are more varied, however, and the fact that the t-values are all positive should be noted. There is no clear reason why the PVC gauge should give smaller readings, but suspicion must fall on both adhesion and condensation. The latter is particularly likely in view of the different materials the gauges are made of – a view which is supported by the fact that the largest differences occur at station C where the terrain favours marked temperature inversions.

Shelter Conditions at the Stations

A comparison of stations A, C and D shows that C, in the clearing, is preferable to the others. (See Table 3). For winter data t is significant at the 1% level, and the summer values are also high. A comparison of D with A is more difficult. The values of t are not alarmingly high, but they are all negative, suggesting that A is preferable to D. These results confirm – though less clearly than expected – our introductory comments on the suitability of the stations. In particular, station C is much better sheltered than A, though the geometric configurations are otherwise similar. The total summer rainfall measured at these two stations differs less than

Table 2 Comparison of different gauges at stations A, B, C and D. p is the probability of having a t-value larger than the measured one if there is no difference between the compared gauges.

			SUMMER					WINTER				
Sta- tion	ht.above ground- level	Compared gauges	$\bar{Z}$	s	f	t	p	$\bar{Z}$	s	f	t	p
C	0.0 m	10;1	0.020	0.0039	44	2.11	2-5%	-0.008	0.0072	32	-0.53	60%
A	0.0 m	13;5	0.014	0.0065	44	1.15	20-30%	0.001	0.0032	32	0.10	90%
D	0.0 m	14;7	0.003	0.0039	44	0.32	70-80%	-0.009	0.0090	32	-0.53	60%
A	1.5 m	11;6	0.013	0.0072	44	1.01	30-40%	-0.001	0.0064	32	-0.07	90%
D	1.5 m	12;8	0.011	0.0057	44	0.96	30-40%	-0.007	0.0192	32	-0.29	70-80%
C	1.5 m	1;2	0.011	0.0010	15	1.30	20%	0.072	0.0083	25	3.88	<1%
C	1.5 m	1;19	0.059	0.0011	15	6.56	<1%	0.037	0.0070	25	2.17	2-5%
C	1.5 m	1;3	0.031	0.0015	15	2.96	1%	0.067	0.0052	25	4.55	<1%
C	1.5 m	1;4	0.084	0.0102	15	3.11	<1%	0.218	0.0566	25	4.49	<1%
A		13;11	0.055	0.0072	44	4.26	<1%	0.163	0.0086	32	9.77	<1%
D		14;12	0.063	0.0028	44	7.88	<1%	0.183	0.0211	32	7.02	<1%
A		5;6	0.054	0.0063	44	4.48	<1%	0.161	0.0076	32	5.91	<1%
D		7;8	0.072	0.0051	44	6.59	<1%	0.184	0.0230	32	6.76	<1%
C		1;2	0.022	0.0025	44	2.90	<1%	0.067	0.0069	32	4.50	<1%
A		5;9	-0.022	0.0072	44	-1.72	5-10%	-0.013	0.0050	32	-1.03	~30%

1%, and there is no visible seasonal variation in the comparative data. These results thus support Andersson's view that clearings are ideal gauge sites.

In order to determine the ideal size of such a clearing, three extra gauges (Nos. 19, 3 and 4) were placed at intervals of 40 m along a straight line from the middle of the clearing at station C to within 8 m of the western edge. (Elevation angle for gauge 4: about 70^0. All gauges at 1.5 m above ground level). An East-West orientation was used because of the dominant westerly winds. In Table 2 the three gauges are compared with gauges 1 and 2. The summer data from the three extra gauges – but not gauge 2 – differ significantly (1% level) from gauge 1. During the winter all of the gauges differ significantly (5% level) from gauge 1. For gauges 2, 19 and 3 the values of $\bar{Z}$ and s^2 are very similar, but at gauge 4, $\bar{Z}$ is about twice as large, and s^2 a full order of magnitude greater. In other words, the distance of the gauge from the windward edge of the clearing makes little difference as long as it is some two to four times the tree height, but at a distance somewhere between half and twice the tree height, major discrepancies occur.

Table 3 Comparison of different pairs of gauges at stations A, B, (and D). p is the probability of having a t-value larger than the computed one if there is no difference between the compared gauges.

			SUMMER					WINTER				
Station	ht.above ground-level	Compared gauge pairs	$\bar{Z}$	s	f	t	p	$\bar{Z}$	s	f	t	p
A/D	0.0 m	(5,6);(7,8)	-0.0170	0.0099	44	-1.14	20-30%	-0.0227	0.0132	32	-1.12	20-30%
A/C	0.0 m	(5-6)-(1-2)	0.0320	0.0086	44	2.29	10-20%	-0.0941	0.0093	32	5.53	<1%
A/D	0.0 m	(13,11); (14,12)	-0.0081	0.0067	44	-0.66	50-60%	-0.0198	0.0225	32	-0.75	40-50%
A/B	1.5 m	(13,15); (13,16)	0.1915	0.0569	15	3.11	<1%	0.4331	0.1050	25	6.68	<1%
B	1.5 m	(18,15); (18,16)	-0.0426	0.1241	15	-1.48	10-20%	-0.0332	0.0768	25	-0.61	~60%

Correction for Aerodynamic Effect

We have seen above that the differences between two gauges are best described by a square-root transformation. Therefore any correction cannot take the form of either straight addition or multiplication.

We can most conveniently estimate gauge reading Y_i on the basis of an observed rainfall Y_j (from another gauge) by calculating

$$Y_i = [(Y_j)^{\frac{1}{2}} + (\alpha_i - \alpha_j)]^2$$

Using $\bar{Z}$ as an estimator of $\alpha_i - \alpha_j$ the value of $\delta = (Y_i - Y_j)$ is illustrated in Fig. 7. From the data given in Table 2 we can also calculate 95% confidence limits:

$$\bar{Z} \pm \sqrt{\frac{s^2}{n}}\, t_{0.975\ ,\ f}$$

It should be noted that this correction can only be applied to the sample period used. We cannot, for example, use it for monthly totals, since the actual deviation from a given total will be greater if the rain occurs evenly distributed over the weeks than if all of it comes in one week.

It is very likely, however, that this kind of analysis of other periods would yield similar forms of corrections applicable to each of these periods.

This has not been done in the present paper, since the number of observations is too small.

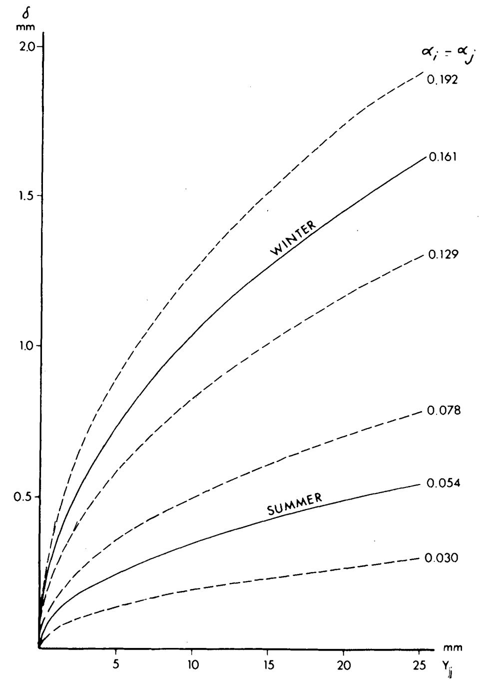

Fig. 7. Correction $\delta = (Y_i - Y_j)$ and 95% confidence limits (---) based on gauges 6 and 7.

Gauges Fitted with Screens

Rainfall can be measured very accurately if the gauge opening is placed at ground-level. Unfortunately, solid precipitation cannot usually be measured with the same gauge. Various aerodynamic screens have therefore been developed to improve the accuracy of gauges above ground level (see e.g. Golubev 1969, Green 1970, Berggreen 1972 and Madsen 1972).

One Nipher screen (on gauge No. 15), an Alter screen (on gauge No. 16) and one PVC gauge (No. 18) without any screen were established at station B.

The above gauges are compared with the ground-level gauge No. 13 at station A. As a rule both gauges with screens have given smaller readings than gauge 13, but slightly larger ones than the gauge without a screen. Further, we have found that a square-root model can be used in the analysis. Since only small differences between the two screened gauges have been measured, we have chosen to carry out our analysis as follows:

1) t-test, gauges 13, 15 and 16: use of screen compared with gauge at ground-level.

2) t-test, gauges 18, 15 and 16: gauge without screen as against gauge with screen.

The results are given in Table 3. It is obvious that for periods where precipitation is solely in liquid form there is little advantage in using screens of the Alter or Nipher types. Perhaps we should add that because gauge 18 was set up very late, the number of degrees of freedom in the two tests is small, thus weakening the conclusions.

The Importance of Splashing

We have already mentioned that gauges at ground level were fitted with plastic guards to reduce splashing. For comparison a PVC gauge at A was placed inside an iron pipe with a 3 cm greater radius. Apart from that provided by the grass, no screening was provided. Results in Table 2 suggest that grass can lead to some splashing into the gauge, though the effect is small. It is greatest in summer, which is what we would expect in view of the larger rain drops and greater rainfall intensities during this season.

Conclusions

The present paper shows that the main errors in measuring precipitation with a Hellmann gauge (tightly closed to prevent evaporation) are due to adhesion and the aerodynamic effect. Evaporation and condensation errors lie within the accuracy of instrumental readings. The analysis has shown that it is necessary to make a better estimate of the adhesion error, especially to establish whether there are major differences between gauges at different heights. This could be done by continous weighing of the precipitation gauge, rather than using a pluviograph which only registers rainfall exceeding the adhesion loss. The aerodynamic error as examined at four locations seems to be independent of gauge type. The proposed square root model seems adequate for describing differences between gauges, and can lead to a reasonable estimate of the correction for gauges at other than ideal locations. We can point out that a model using a logarithmic transformation for the relation between two gauges, (Madsen 1972) cannot be used, since our observations include values <1 mm, which, in a log-transformation, would produce a major skewness.

A study of the relationship between the measured differences and the different geometric configurations at the stations shows that shelter does play a role. We hope to examine this further so as to establish quantitative methods for estimating shelter effects.

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