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RAINFALL MEASUREMENTS AT TAITA EXPERIMENTAL STATION, NEW ZEALAND

2 — Tilted Raingauges and Vectopluviometers

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ABSTRACT

The rainfall catches of two networks of raingauges, one network with gauges mounted vertically and the other with gauges normal to the slope, were compared over a 15-month period in a steep 4-ha scrub catchment. Measurements with vectopluviometers were used to classify the storms according to directional characteristics. In accord with the predictions from the data from the vectopluviometers the most important differences between the two networks occurred for strongly inclined rainfall from the north. For individual storms the mean catches of the two networks seldom differed by more than 10%, and for the whole period of observations the overall difference between the two networks was 3.2%. At individual sites few differences between paired tilted and vertical gauges exceeded 20% in storms of more than 25 mm. Local topography often produced severe modifications of rainfall direction within the catchment, and vectopluviometers exposed to the general wind flow over the catchment were unreliable for predicting the catch of individual tilted gauges.

INTRODUCTION

Rainfall may be considered as a vector, having direction as well as amount. The effective rainfall received at a site depends on both the topography of the site and the directional characteristics of the rainfall. Several investigators (reviewed by Corbett, 1967) have shown that on sloping ground a raingauge tilted so that its orifice is parallel to the underlying surface provides a more satisfactory measure of the rainfall received by the slope than does the conventional vertical raingauge. Where the gauge is part of a network for the determination of the rainfall received by a catchment, tilted gauges may be used to measure the rainfall on the various topographic facets that make up the catchment (Hamilton, 1954; Corbett, 1967).

When three orthogonal components of the rainfall vector are measured using a directional raingauge or vectopluviometer it is

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possible to calculate the expected rainfall on any slope of known aspect and inclination. Such calculations can be useful where direct measurements cannot conveniently be made, e.g. above the canopy of scrub or forest, or where access is difficult. However, the accuracy of the calculated value depends on the extent to which the data from a vectopluviometer apply to the slope in question, especially when this is some distance from the site of the vectopluviometer.

The Taita Experimental Station, which includes the four small catchments of the Taita IHD Experimental Basin, is situated on the hills to the east of the Hutt Valley (latitude 41°S, longitude 175°E). The land is finely dissected, valleys with steeply sloping sides being separated by rounded ridges and spurs. A mixture of scrub and forest covers the Station, although small areas of grassland occur on the lower slopes and on firebreaks. Rainfall is often accompanied by strong winds and may deviate considerably from the vertical so that the effective rainfall is expected to vary among the various topographic facets. A study was therefore made of the performance of vertical and tilted gauges in a small steep catchment (the Exotic Forest Catchment) and also of the reliability of calculations of the catch of tilted gauges from the data from vectopluviometers. Previous work by Aldridge (1967) in an adjoining catchment, using tilted storage gauges that were read monthly, had shown that good agreement between the observed and calculated catch of a tilted gauge was obtained at some but not at all sites. In the present work data were obtained for individual storms and an attempt made to explain some of the disagreements between the observed and expected behaviour of tilted gauges. The variability of catch of vertical gauges in the Exotic Forest Catchment and also over the Experimental Station as a whole has been reported earlier (Jackson and Aldridge, 1972).

METHODS

Sites of Gauges

The gauges were placed in and around the Exotic Forest Catchment (Fig. 1), which is 4.0 ha in area and ranges in altitude from 20 to 170 m above sea level. The catchment faces north-north-west and consists of a single valley which has steeply sloping sides and confining spurs with rounded crests. Similar hilly and steep land surrounds the catchment except to the north-west where the catchment opens on to the extensive flat land of the Hutt Valley. Level ground is almost completely lacking within the catchment while gentle slopes are confined to the bottom of the valley (near sites 6 and 7, Fig. 1), the lower part of a small basin at the head of the catchment (sites 3 and 5) and the crest of a short spur (site 8).

FIG. 1 – Aerial view of the Exotic Forest Catchment, Taita, showing the location of sites of rainfall measurements.

The rainfall measurements were made during the period from October 1965 to December 1966 while the vegetation in the catchment consisted of scrub, mainly gorse (*Ulex europaeus*), 0.5 m to 4 m tall, through which the young exotic trees, mainly pines, were emerging.

The sites in and around the catchment were selected to give a wide range of topography and also to give weighting according to the map area of the topographic facets. A brief description of each

TABLE 1 – Sites used for rainfall measurement in and around the Exotic Forest Catchment.

Site number	*Gauge type**	*Slope*		*Altitude (m)*	*Description of site*
		Inclination (degrees)	*Aspect (degrees)*		
1	VP	0	–	65	Climatological station; lawn on level crest of spur.
2	VP	0	–	20	Closely grazed pasture on floor of Hutt Valley.
3	VP	0	–	135	Cut gorse (0.6 m) in level area near head of catchment.
4	V	0	–	65	Lawn on level crest of spur.
5	V	0	–	140	Scrub and pines (1.5 m) in level area at head of catchment.
6	V	0	–	30	Rough grass (0.3 m) near valley mouth.
7	V	0	–	45	Broadleaf scrub (1.8 m) in valley bottom.
8	V	0	–	115	Sparse scrub (1m) on level crest of spur.
9	TV	20	014	55	Manuka scrub (4 m) on crest of spur.
10	T	18	024	30	Closely grazed pasture on concave footslope.
11	TV	29	030	100	Mixed scrub (0.6 m) on lower side-slope of valley.
12	TV	25	030	75	Dense gorse (2 m) at middle of side-slope of valley.
13	TV	32	030	50	Mixed scrub (1 m) on lower side-slope of valley.
14	TV	40	040	80	Dense gorse (3.5 m) at middle of side-slope of valley.
15	TV	40	245	100	Dense gorse (2 m) at middle of side-slope of valley.
16	TV	40	250	45	Scrub (1 m) on lower side-slope of valley.
17	T	28	260	60	Closely grazed pasture near crest of spur.
18	TV	35	280	85	Scrub and pines (1.2 m) on upper side-slope of valley.
19	T	22	320	75	Closely grazed pasture on crest of spur.
20	TV	22	335	150	Scrub (1.5 m) near apex of catchment.
21	TV	30	335	80	Gorse and pines (1.2 m) on crest of spur.

* VP – vectopluviometer; V – vertical gauge only; T – tilted gauge only; TV – paired tilted and vertical gauges.

site used for measurement of rainfall is given in Table 1, and the location of each site is shown in Fig. 1. Sites close to trees projecting above the general level of the canopy were avoided, as were obviously over-exposed sites near the crests of the main spurs. At 10 sites, one of which (site 9) was in the adjoining Native Forest Catchment, a vertical gauge and a tilted gauge were mounted on masts about one metre apart so that the orifices of the gauges were just above the general level of the canopy. Data were also available from three sites (sites 10, 17, 19) on the grassed firebreaks on which tilted gauges only were used, and from eight level sites on which vertical gauges (sites 4–8) or vectopluviometers (sites 1–3) were used. The catches of the tilted gauges were converted to a map-area basis, i.e. depth of rainfall per unit area when projected on to a horizontal plane.

Storm Sampling

Measurements* were made over a period of 15 months from October 1965 to December 1966 and involved a total rainfall of approximately 1700 mm on 200 raindays. The networks of gauges were read on 74 occasions, giving data for 'storms' with rainfalls ranging from 0.25 mm to approximately 110 mm. In the present paper the term 'storm' is used to refer to all rainfall events for which data were obtained; many of these storms involved single periods of continuous rain but some combined several periods of intermittent rain or showers, while others combined two or more distinct periods of continuous rain that would have been separated if the breaks between the periods had occurred at a more convenient time. The grouping of the storms on the basis of the data from the vectopluviometers is discussed in a later section.

Measurement of the Direction and Inclination of Rainfall

Three vectopluviometers, similar to those described by Hamilton (1954, p. 31) were used. For measurement of the horizontal components of rainfall they have knife-edge rims 127 mm (5 in.) in diameter mounted vertically to face the four cardinal points of the compass; a fifth, horizontal, orifice serves as a vertical gauge. Their locations are given in Table 1 (sites 1–3). If, for a given storm, R is the catch in the vertical gauge of the vectopluviometer and R_n, R_s, R_e, R_w are the catches of the orifices facing north, south, east and west respectively, then the rainfall direction (bearing of rain measured clockwise from north) ω, and inclination (angle of deviation from vertical) i are given by:

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* All measurements were made to the nearest 0.25 mm (0.01 in.).

$$\tan \omega = (R_e - R_w) / (R_n - R_s) \quad (1)$$

$$\tan i = (R_n - R_s) / R \cos \omega = (R_e - R_w) / R \sin \omega \quad (2)$$

It is important to note that the direction and inclination are those of the *resultant* rain vector for the storm period contributing the measured quantities R_n, R_s, R_e, R_w and R. There may have been a considerable change of direction or inclination during the storm period without an instantaneous vector from the resultant direction or inclination. Van Heerdan (1961) showed that the inclination of the resultant rain vector is not the same as the *mean* inclination of the rainfall, which is nearly always greater than the former. This is important at Taita where the passage of a cold front may produce strongly inclined rainfall successively from the northerly and southerly quarters in a single storm period, giving a resultant that deviates only slightly from vertical and is usually from the west.

Calculation of Rainfall on Sloping Sites

The direction (ω) and inclination (i) of the resultant rain vector may be used to calculate the expected rainfall on a slope having aspect B and inclination (elevation above horizontal) A. Fourcade (1942) (cited by Hamilton, 1954) gave the equation in the form:

$$r = R + R \tan A \,.\, \tan i \,.\, \cos(B - \omega) \quad (3)$$

where r is the expected rainfall on the slope, expressed on a map-area basis.

It is often convenient to calculate r directly from the catches of the vectopluviometer, converting the Fourcade equation (3) to the form

$$r = R + a_1(R_n - R_s) + a_2(R_e - R_w) \quad (4)$$

where $a_1 = -\tan A \,.\, \sin B$

$a_2 = -\tan A \,.\, \cos B$

and the other symbols have the meanings already given.

Values for aspect and inclination of the sites of the tilted gauges are given in Table 1.

The calculated value, r, for the expected rainfall on the slope may be compared with the measured catch of a tilted gauge mounted with its orifice parallel to the slope. Good agreement between the calculated and measured values will be obtained if (a) the resultant rain vector is the same at the site of the tilted gauge as at the point where the horizontal and vertical components are measured, and (b) the exposure of the tilted gauge is such that the catch is in fact a good measure of the true rainfall received on the slope. Data obtained from a tilted gauge on a sloping site are subject to the same reservations as those from a vertical gauge on a horizontal site when used as a measurement of 'true rainfall' (Rodda, 1967; Green, 1970).

The vector method may also be used to calculate the mean rainfall for an entire catchment on the basis of the average slope and aspect. An equivalent plane surface can be derived (Lee, 1963) by taking from a contour map the co-ordinates of a sample of evenly spaced points on the perimeter of the catchment and then fitting a plane to these points by multiple regression. This procedure also provides for the equivalent plane the coefficients a_1 and a_2 required in equation (4). For the Exotic Forest Catchment the values obtained are:

$$a_1 = 0.1276; \qquad a_2 = -0.2685;$$
$$A = 16.5°; \qquad B = 334°.$$

The values of a_1 and a_2 for the fitted plane were very close to the corresponding means of the values at the 13 sites with tilted gauges. This resulted in good agreement (within 1% for each storm) between the calculated catch by the equivalent plane and the mean of the calculated catches at these 13 sites.

RESULTS

Storm Direction and Inclination

The 74 storms were grouped into four types on the basis of the values of bearing and inclination obtained from the three vectopluviometers. The distribution of direction and inclination of storms at site 1 (in the climatological station) is shown in Fig. 2, while the direction and inclination of the resultant vectors for the four types and for all storms are given in Table 2. These resultants were obtained from equations (1) and (2) using the totals of the catches R_n, R_s, R_e, R_w and R for all storms of a given type (cf. van Heerdan, 1961).

TABLE 2 – Characteristics of resultant vectors for storm types at three sites.

Storm type	*Site 1*		*Site 2*		*Site 3*	
	ω	i	ω	i	ω	i
northerly	352	18	330	9	340	29
weakly inclined	189	1	0	1	349	2
southerly	217	7	178	5	198	7
variable	240	7	173	3	161	5
All storms:	320	7	306	2	337	9

ω is rainfall direction, or bearing measured clockwise from true north (degrees).

i is rainfall inclination, or angle of deviation from vertical (degrees).

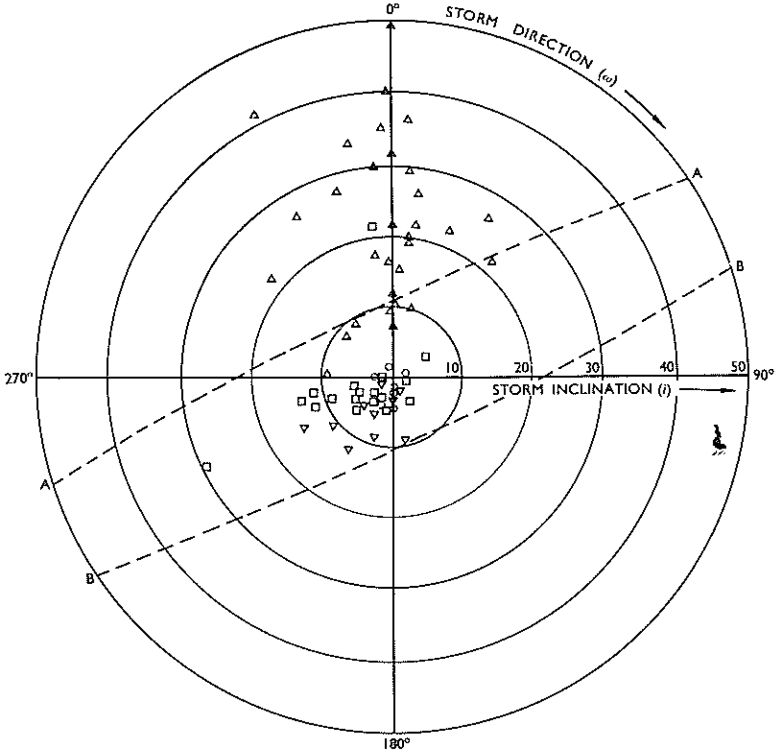

FIG. 2 – Distribution of storm direction (ω) and inclination (*i*) at site 1. The broken lines AA and BB define the combination of ω and *i* giving r/R equal to 1.05 and 0.95 respectively.
Northerly storms, △; weakly inclined storms, ○; southerly storms, ▽; variable storms, □.

Northerly storms were the most common during the period of the measurements and contributed 37% of the total rainfall. Of the 74 storms, 31 were of this type, including most of the strongly inclined storms (see Fig. 2). The three vectopluviometers showed good agreement in the values of rainfall direction for these storms, although the small variation among them was usually systematic. At the climatological station the majority of these storms came from directions within 20° of north (see Fig. 2) but at the head of the catchment (site 3, Fig. 1) there was a consistent shift to about 20° west of north, i.e. along the axis of the valley. There was also a clear tendency for the storm vectors to deviate more from vertical as the altitude of the vectopluviometer increased, probably as a result of an increase of wind speed with altitude.

Weakly inclined storms were recorded on 13 occasions, and contributed 10% of the total rainfall; they mostly involved small amounts of rainfall. Each storm had a resultant that deviated from the vertical by less than 5° at each vectopluviometer. Storms of this type produced very small catches in the horizontal gauges of the vectopluviometers, and the resultant directions obtained for individual storms varied considerably among the three vectopluviometers. The overall resultants for the type (Table 2) also vary, but this has no practical significance in view of the small deviation from vertical.

Southerly storms were recorded on 10 occasions and contributed 9% of the total rainfall. They were generally only moderately inclined. While all three vectopluviometers showed that these storms came from a southerly direction, they usually had a more westerly direction at site 1 – which is fully exposed to the air flow up the Hutt Valley – than at the other vectopluviometers. The absence of strongly inclined southerly storms is partly a result of the difficulty of separating them from a preceding northerly; however, comparison of the records from the vectopluviometer at site 1 with records from this site obtained since 1959 – including those used by Aldridge (1967) – indicated that strongly inclined southerly storms were less frequent in the period of this investigation than in other years.

Variable storms are those storms that showed a wide variation of direction among the three vectopluviometers and also gave considerable quantities of rainwater in more than two quadrants at each vectopluviometer, indicating a significant change in direction during the storm. The resultant vectors seldom deviated greatly from the vertical although, in contrast to the weakly inclined storms described above, instantaneous rainfall was often strongly inclined. Twenty storms of this type occurred in the period of this investigation and they contributed 44% of the total rainfall.

As can be seen in Fig. 2 and Table 2 the northerly storms were more strongly inclined than the other types, and many northerly storms were inclined at more than 10° from the vertical. For any given surface, defined by its slope A and aspect B, it is possible to use equation (3) to calculate the locus of the combination of storm inclination i and direction ω required to give a specified percentage difference, or ratio, between the rainfall on the slope (r) and that on a horizontal surface (R). When the values of A and B for the plane fitted to the perimeter of the catchment are inserted in equation (3) then the broken lines AA and BB in Fig. 2 are obtained as the loci of r/R equal to 1.05 and 0.95 respectively. It can be seen that most storms that are not northerlies lie between the two broken lines and are therefore expected to give differences less than 5% between r and R. Many northerly storms lie outside the broken lines and larger differences between r and R are expected.

Relation of Rainfall Inclination to Wind Speed

A strong deviation of rain from the vertical is usually associated with high wind speeds, although other factors, such as drop size, are undoubtedly involved (Hamilton, 1954; Lacy, 1951). Daily readings, taken at 9 a.m., of wind run at a height of 2 m were available for site 1, and the relation between inclination measured at this site and wind run was examined. When a storm continued on two or more days a mean wind run was obtained by weighting the run on each day according to the proportion of the total storm rainfall that fell on that day. Linear regression analysis gave the following relation for the 74 storms studied:

$$i = 0.108u_2 - 3.6\text{; correlation coefficient } 0.81$$

where i is the storm inclination (deviation of the resultant from vertical) in degrees, and u_2 is the daily wind run (km/day).

The correlation is satisfactory since the storm inclination is a resultant for an entire storm, and the wind run is a daily total whereas the rain usually falls for only part of a day. The northerly storms were almost always associated with a wind run in excess of 160 km per day (100 miles per day), but many of the storms of the other types were associated with lower wind runs. Three storms, all northerlies, were associated with a wind run over 320 km per day (200 miles per day).

Differences Between Tilted and Vertical Gauges

The mean catch of the network of vertical gauges and the mean of the catches (each expressed on a map-area basis) of the tilted gauges were calculated for each storm. In Fig. 3 the difference between the two means is shown in relation to the mean from the vertical gauges, with the type of storm indicated as in Fig. 2. Since the catchment faces north, the northerly storms were expected to give a larger mean catch in the tilted gauges than in the vertical gauges, and this usually occurred. For individual northerly storms differences of 5% to 10% between the two networks were common, and when all northerly storms were combined the total mean catch of the tilted gauges was 7.5% greater than that of the vertical gauges (see Table 4). For the other types of storms no consistent difference between the tilted and vertical networks was found, in accord with the distribution of points in Fig. 2 which shows that few storms that are not northerlies deviate sufficiently from the vertical to give much difference between the two networks. Over the whole period of measurements the total catch of the network of tilted gauges was 3.2% greater than that for the vertical gauges.

The differences between the network means illustrated in Fig. 3 must be compared with the variation within the networks for their significance to be assessed. The results of these comparisons are summarized in Table 3, in which the data have been grouped by type and size of storm. The storm types were defined by vectopluviometer records as discussed earlier, and the five classes of size of storm were chosen on the basis of long-term records from the

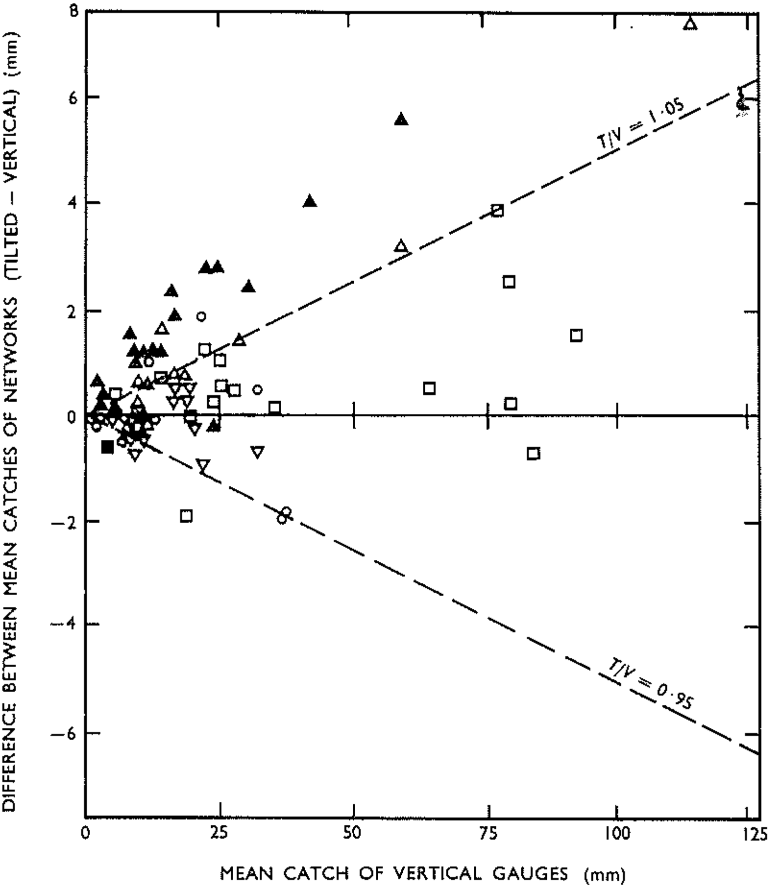

FIG. 3 – Differences between the mean catches of networks of vertical and tilted raingauges in relation to storm size. For key to storm types see Fig. 2. Storms lying between the broken lines in Fig. 2 are shown open, others solid.

TABLE 3 – Average values, for size classes and storm types, of mean and standard deviation of catches of networks of vertical and tilted gauges.

*Size class** *(mm)*	*Vertical gauges* *Mean (mm)*	*Vertical gauges* *Std. Devn. (mm)*	*Tilted gauges* *Mean (mm)*	*Tilted gauges* *Std. Devn. (mm)*	*Diff. between means (Tilted – Vertical)*	*No. of storms in size class*	*No. of storms with significant diff. between means†*
Northerly Storms							
0– 7.5	3.1	0.38	3.4	0.48	0.3	4	1
7.6–15.1	10.2	1.20	10.9	1.14	0.7	14	5
15.2–22.8	16.5	1.47	17.9	2.08	1.4	4	2
22.9–43.2	29.3	2.70	31.5	2.72	2.2	6	4
>43.2	77.1	3.28	82.8	4.09	5.6	3	3
Weakly Inclined Storms							
0– 7.5	2.6	0.23	2.4	0.30	–0.2	8	2
7.6–15.1	11.3	1.17	12.3	1.12	1.0	1	1
15.2–22.8	21.8	2.62	23.8	1.91	1.9	1	1
22.9–43.2	35.6	2.31	34.5	3.40	–1.1	3	0
>43.2	–	–	–	–	–	0	–
Southerly Storms							
0– 7.5	5.8	1.09	5.5	0.91	–0.3	2	0
7.6–15.1	9.6	1.24	9.0	1.22	–0.6	2	0
15.2–22.8	18.5	1.32	18.7	2.21	0.3	5	0
22.9–43.2	31.9	3.38	31.2	2.79	–0.7	1	0
>43.2	–	–	–	–	–	0	–
Variable Storms							
0– 7.5	4.3	0.51	4.2	0.51	–0.1	2	2
7.6–15.1	12.4	1.04	12.5	0.84	0.1	3	0
15.2–22.8	20.9	1.75	20.5	2.44	–0.4	4	1
22.9–43.2	27.8	2.18	28.3	2.36	0.5	5	0
>43.2	79.9	5.18	81.2	6.99	1.3	6	0

* Boundaries between classes were originally 0.30, 0.60, 0.90, and 1.70 inches.
† Difference between means significant at 0.05 level of probability.

climatological station (site 1). Daily rainfalls in these size classes contribute equal proportions of the total rainfall, but in Table 3 there is a rather high frequency of storms in the two largest size classes (greater than 22.8 mm) as a result of the combination into a single storm of rain that fell on two or more consecutive days. Most of these prolonged storms are of the 'variable' direction type, since they are the result of the passage of a cold front which produced large amounts of rain at first from the north and later from the south or south-west; such storms give relatively small, non-significant differences between the mean catches of the two networks. In contrast the northerly storms in the two largest size classes usually give significant differences between the two means.

The results discussed above (Table 3 and Fig. 3) were obtained from the complete networks of 13 tilted and 18 vertical gauges. A comparison of the two networks was also made using only the 10 sites at which there were paired tilted and vertical gauges. The results were very similar to those discussed above, although there was a tendency for northerly storms to give larger differences between tilted and vertical gauges when only the paired gauges were considered than for the complete networks. This was mainly a result of the lower catches by vertical gauges on windward slopes than on level sites, reported in Jackson and Aldridge (1972).

It can be seen from the values of the standard deviations given in Table 3 that the variation within the two networks is very similar, although it was expected that the variation among tilted gauges would be in part systematic as a result of the orientation of the gauges. When the values of the difference in catch between tilted and vertical gauges ($T-V$) at each of the 10 sites with paired gauges were examined it was found that they often did not show the expected relation to site orientation, as is discussed in the next section. For individual storms the standard deviation of the values of ($T-V$) obtained at the 10 sites was almost always equal to or a little greater than the standard deviations of the two networks (these were approximately equal – see Table 3), indicating a low correlation (the correlation coefficient was 0.5 or less) between the members of the pairs and no significant overriding rainfall pattern or site effects. The largest measured difference between any pair of gauges was 30.0 mm (26%) at site 14 in the storm of 114 mm which also produced the largest difference between the network means (see Fig. 3). For storms greater than 25 mm no site ever had a difference between the two gauges of more than 40% and differences greater than 20% between a pair of gauges were seldom recorded at more than one site.

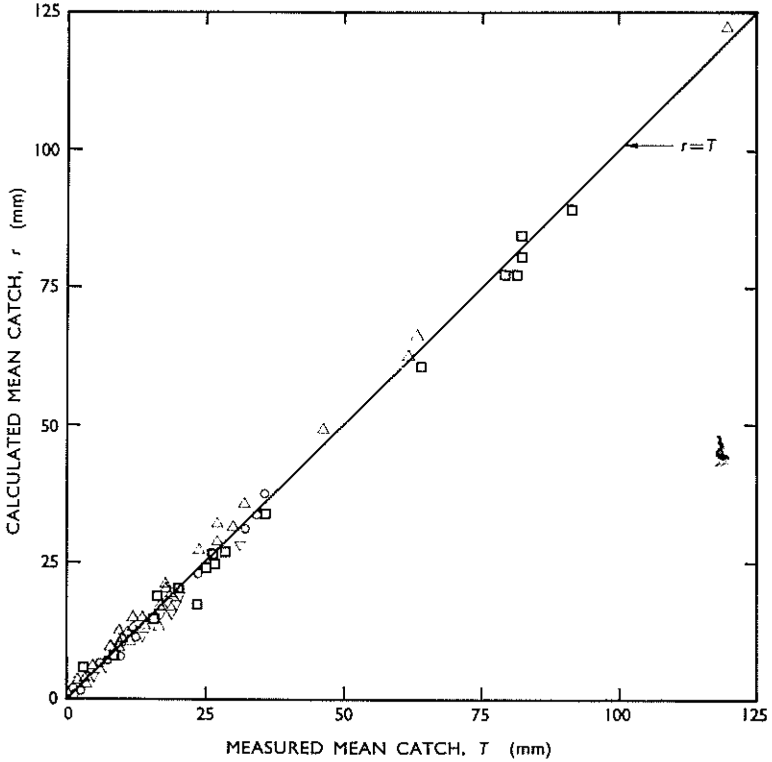

FIG. 4A – Calculated vs measured mean catch of network of tilted gauges.

Quantitative Use of Data from Vectopluviometers

For the data obtained from the vectopluviometers to be considered quantitatively useful there are two tests to be applied. The Fourcade equation (3) must be able to predict the rainfall received on a slope from the data measured at the vectopluviometer site, i.e. the calculated value, r, should be compared with the measured catch of a tilted gauge, T, placed on the slope, as in Figs. 4A, 5A and 6A. However, a more significant test is obtained by examining to what extent the vectopluviometers predict the relative behaviour of vertical and tilted gauges. This can be done by a comparison of the second term on the right-hand side of equation (3), which represents the contribution of the horizontal components of the rainfall vector, with the difference $(T-V)$ between corresponding values from tilted and vertical gauges, or alternatively by comparing the ratios r/R and T/V. Three vectopluviometers were used (sites 1, 2 and 3 in Fig. 1) and the mean catches of the networks of tilted

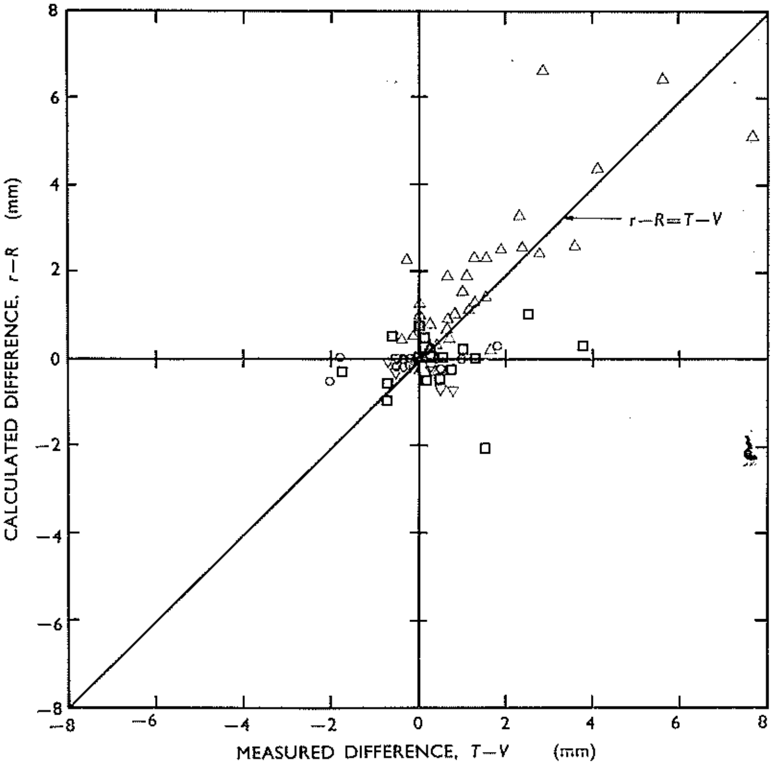

FIG. 4B – Calculated vs measured difference between mean catches of tilted and vertical gauges. For key to storm types see Fig. 2.

and vertical gauges are considered first to show the extent to which the values calculated from the three vectopluviometers differ. In Table 4 the total mean catches of the networks are given for the four types of storm for which the corresponding resultant storm vectors were given in Table 2. For the northerly storms an increase in inclination of rainfall with altitude was found (Table 2), and this produced the variation of the calculated ratio r/R for these storms seen in Table 4. For the other storm types the vectopluviometers agree quite well in the calculated values of r/R. There is, however, a rather wide variation in the calculated mean catches as a result of the differing catches of the vertical gauges at the three vectopluviometer sites. The vectopluviometer at site 1 showed the closest overall agreement of calculated values with measured values, and for this reason it is the only one usually considered in the analysis of the behaviour at the individual sites which follows.

TABLE 4 – Measured totals, for storm types and all storms, of mean catches of vertical gauges and of tilted gauges and their ratio, with corresponding values calculated from vectopluviometers.

	Northerly	*Weakly inclined*	*Southerly*	*Variable*	*All storms*
Number of storms	31	13	10	20	74
Mean catch of vertical gauges V (mm)	628	161	155	748	1692
Mean catch of tilted gauges (mm):					
Measured (T)	675	159	154	756	1744
Calculated (r) —					
Vectopluviometer 1	719	158	141	737	1755
Vectopluviometer 2	687	148	136	714	1685
Vectopluviometer 3	761	180	170	774	1885
Ratio of mean catch of tilted gauges to mean catch of vertical gauges:					
Measured (T/V)	1.075	0.990	0.992	1.012	1.032
Calculated (r/R) —					
Vectopluviometer 1	1.092	0.995	0.984	0.997	1.033
Vectopluviometer 2	1.049	1.002	0.977	0.985	1.008
Vectopluviometer 3	1.162	1.010	0.972	0.976	1.047

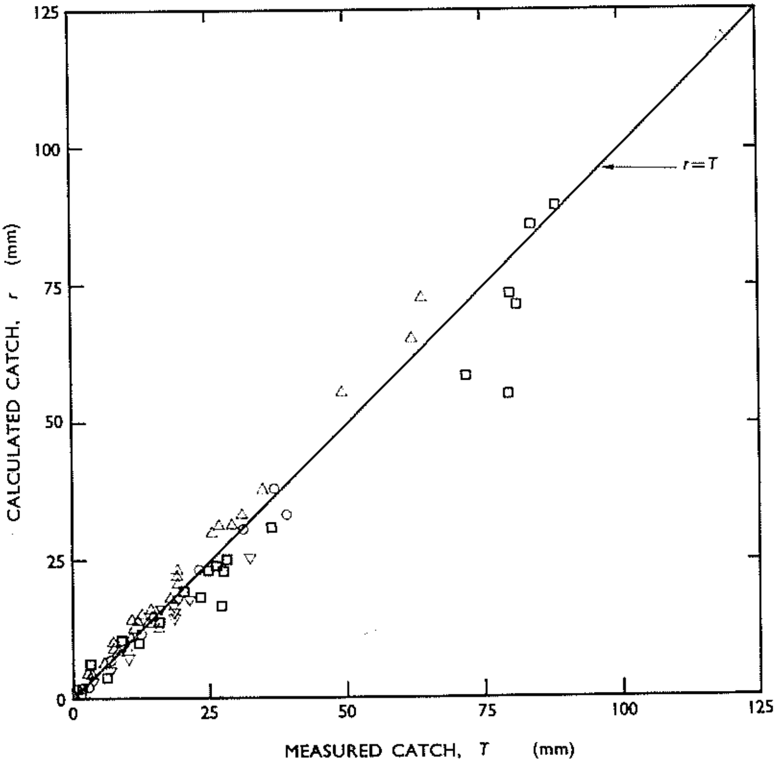

FIG. 5A – Calculated vs measured catch of tilted gauge at site 13.

In Fig. 4A for each storm the mean catch of the network of tilted gauges is compared with the value calculated using the data from the vectopluviometer at site 1, while Figs. 5A and 6A show the results for sites 13 and 15, respectively – these are two of the 10 sites having paired gauges. As these figures illustrate there was a close relation between the measured and calculated catches of the tilted gauges. Correlation coefficients were greater than 0.97 for all combinations of each of the three vectopluviometers with each of the 13 tilted gauges. However, scatter about the regression line was relatively large, and the standard deviations from the regression were between 2.5 mm and 6.5 mm, which are greater than most of the differences between paired tilted and vertical gauges.

The measured $(T-V)$ and calculated $(r-R)$ differences between tilted and vertical gauges are compared using network means in Fig. 4B and data from sites 13 and 15, respectively, in

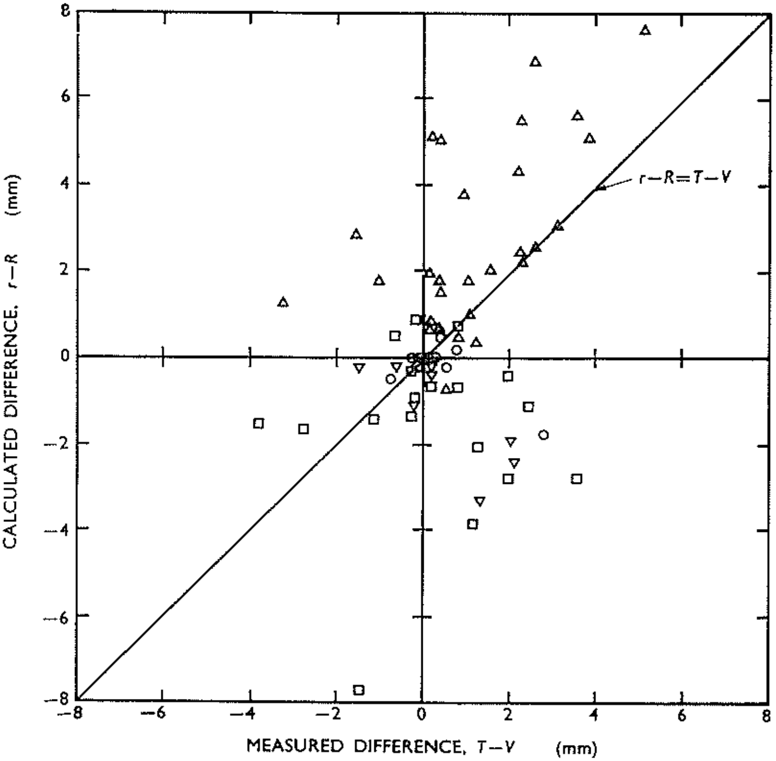

FIG 5B – Calculated vs measured difference between catches of tilted and vertical gauges at site 13. For key to storm types see Fig. 2.

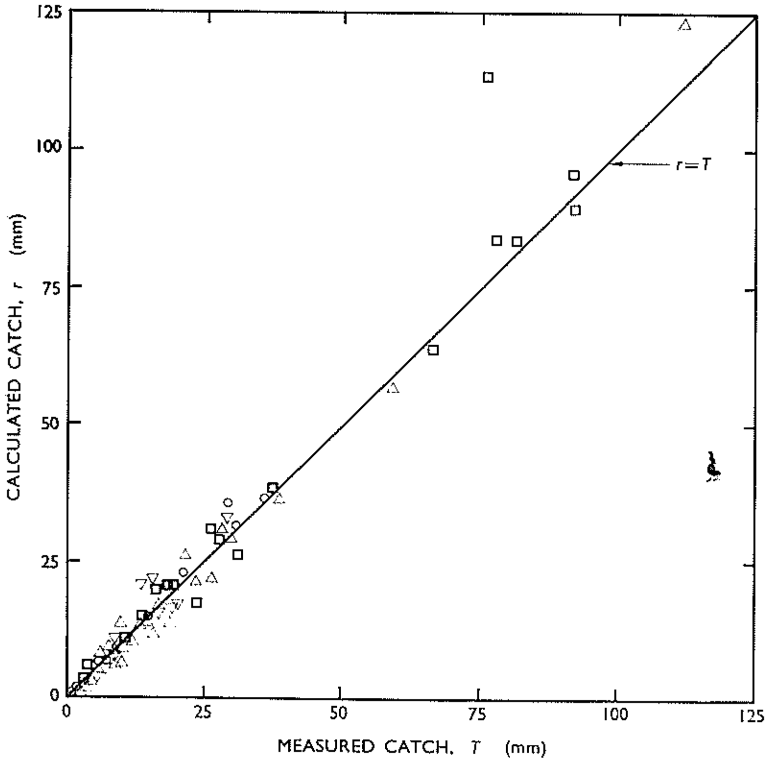

FIG. 6A – Calculated vs measured catch of tilted gauge at site 15.

Figs. 5B and 6B. Qualitatively the results in Fig. 4B are reasonably satisfactory, since most of the calculated differences between the means of the two networks are of the same sign as those observed, but quantitatively agreement is poor and errors of ±100% of the observed difference are common. At the sites illustrated in Figs. 5B and 6B there is obviously a systematic failure to predict the sign of the difference between the two gauges. For northerly storms most sites showed behaviour similar to site 13 (Fig. 5B), the expected higher catch by tilted gauges than by vertical gauges being observed. However, even at sites 15 (see Figs. 6A, B) and 16, which are the sites with the most southerly aspects (Table 1), the catch of the tilted gauge was higher than that of the vertical gauge in northerly storms although the opposite was expected. A similar reversal of behaviour occurred for many storms from the south-west for which sites facing north-east (e.g. site 13, Fig. 5B) gave higher catches in tilted than in vertical gauges, while site 15 (Fig. 6B), which faces south-west, gave a lower catch in the tilted gauge than in the

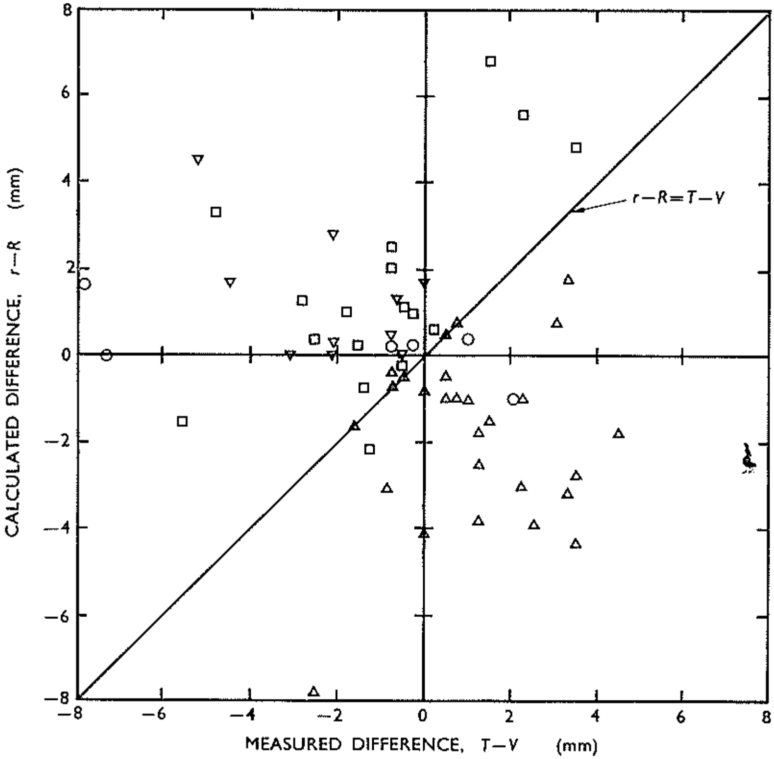

FIG. 6B – Calculated vs measured difference between catches of tilted and vertical gauges at site 15. For key to storm types see Fig. 2.

vertical gauge. It appears that local topography has sufficient effect on rainfall direction within the catchment for the data from vectopluviometers exposed to the general flow over the catchment to be unreliable in prediction of behaviour at individual sites.

DISCUSSION

For the whole period of measurements the overall difference between the networks of tilted and vertical raingauges in this catchment is small (3.2%) and is close to the difference (3.3%) calculated from the data from the vectopluviometer in the climatological station (site 1). Data on daily wind run at 2 m above ground at this site have been obtained since 1963 and these show that the 15-month period of these rainfall measurements had a low average wind run (127 km/day) compared with annual averages around 160 km/day in most other years. Similarly, the resultant rain vector at this site

(site 1) was less strongly inclined ($i=7^\circ$, Table 2) than in most other years over the period that measurements have been made (1959–1971). The average annual resultant rain vector for these years ($\omega=320^\circ$, $i=11^\circ$) would give a calculated catch by the tilted gauges 5.6% higher than by the vertical gauges.

Three vectopluviometers were used during the comparison of tilted and vertical gauges, and – although they did not always agree particularly well for individual storms – the calculated overall differences between tilted and vertical gauges for the whole period are reasonably consistent (3.3%, 0.8%, 4.7%: Table 4). Certainly there is nothing to indicate a difference between networks of tilted and vertical gauges as large as the 19% found at San Dimas (Hamilton, 1954).

The results of Aldridge (1967) for the Native Forest Catchment, which adjoins the Exotic Forest Catchment used in the present work, show that four tilted gauges caught, on average, 11% more than the vertical gauge in the climatological station.[*] Vertical gauges were not used within the Native Forest Catchment but it has been shown (Jackson and Aldridge, 1972) that the catch of this vertical gauge in the climatological station differs by only 0.4% from the mean of the network of vertical gauges used in the Exotic Forest Catchment, and it is also likely to be a sufficiently close estimate for the Native Forest Catchment for the 11% higher catch by tilted gauges to be regarded as significantly greater than the difference of 3.2% found in the present work. The lower wind speeds and less strongly inclined rainfall during the period of the present work are partly responsible, but selection of sites is also a factor. The four sites used by Aldridge (1967) overestimate the effective slope of the catchment and correspond to $A=24^\circ$, $B=333^\circ$ compared to the values $A=16.5^\circ$, $B=334^\circ$ for the Exotic Forest Catchment. With the former slope parameters and the resultant rainfall vector $\omega=310^\circ$, $i=13^\circ$ the expected average difference between tilted and vertical gauges is 9.4%, in reasonable agreement with the observed 11% difference.

Individual storms associated with daily wind runs (at 2 m) less than 160 km/day were usually inclined at less than 10° from the vertical and gave very small differences between the two networks.

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[*] In Table 1(b) in Aldridge (1967) the vertical catch for the period 1959–64 should be 203.05 in., not 214.31 in. as given there. It should also be noted that the values given under Mean Storm Direction and Mean Storm Inclination are averages of monthly values over the periods specified, not resultants. The resultants for both periods used by Aldridge have direction (ω) 310° and inclination (i) 13°.

The largest differences occurred for northerly storms, which were usually inclined more than 10° from vertical and associated with daily wind runs in excess of 160 km/day, and the mean catch of the tilted gauges was 5 to 10% greater than that of the vertical gauges. Differences between the means of the two networks seldom exceeded 10% except in very small storms. At some of the sites with paired gauges large differences occurred between the tilted and vertical gauge, but in storms greater than 25 mm these differences seldom exceeded 20%. In contrast, the results of Hamilton (1954) show differences between paired gauges for storms greater than 25 mm that average about 20% and are often greater than 40%. Hamilton also found that vertical gauges nearly always caught less rain than tilted gauges, whereas at Taita at some sites the tilted gauge often caught less than the vertical gauge (e.g. Fig. 6B).

For individual storms the vectopluviometers gave an indication of the type and magnitude of the difference between paired tilted and vertical gauges on windward slopes well exposed to the storm. But on lee slopes, and other slopes within the catchment, the rainfall direction was strongly modified by the local topography, and the relative performance of tilted and vertical gauges on these sites could not be predicted from the measurements with vectopluviometers.

The main value of vectopluviometers is for characterizing the rainfall over the catchment to indicate whether inclination of rainfall is likely to be a problem in measuring rainfall. Thus at San Dimas, the results of Hamilton (1954) indicate that strongly inclined southerly storms make a major contribution to the rainfall and it is for this reason that when networks of tilted and vertical gauges were compared in a south-facing catchment the tilted gauges nearly always caught more than the vertical gauges. At Taita significant amounts of rainfall are received from various directions and these tend to compensate so that the long-term resultant rainfall vector does not deviate greatly from vertical and a much smaller difference between networks of tilted and vertical gauges is found than at San Dimas. The difference between the two networks is a function of the slope and aspect of the catchment and it is only in small, steep catchments that the overall slope (which can be satisfactorily characterized by the multiple regression procedure of Lee, 1963) is likely to be sufficient for the use of tilted gauges to be necessary.

CONCLUSIONS

1. Data from vectopluviometers provide a means of classifying rainstorms by their direction and inclination. When combined with

the slope and aspect of a site or of a catchment the vectopluviometer data allow prediction of the possible differences between tilted and vertical gauges.

2. For the Exotic Forest Catchment at Taita only northerly storms inclined at more than 10° from the vertical were expected to give more than 5% difference between the mean catches of networks of vertical and tilted gauges, and this was confirmed by measurements over a 15-month period.

3. Rainfall inclination was strongly correlated with wind speed, and storms with rainfall inclined at more than 10° from vertical were associated with wind runs of more than 160 km per day.

4. Differences between the mean catches of the networks of tilted and vertical gauges seldom exceeded 10% except in very small storms. Over a long period storms from various directions compensate and the mean catch of the tilted gauges was only 12% greater than that of the vertical gauges.

5. For paired vertical and tilted gauges on the same site the difference between the two gauges seldom exceeded 20% in storms greater than 25 mm.

6. When the whole series of storms was considered, the catch of each individual tilted gauge was very strongly correlated with that predicted from the vectopluviometer data using equation (3). However, vectopluviometers did not give satisfactory prediction of the differences between the tilted and vertical gauges at sites with paired gauges because rainfall direction within the catchment was strongly modified by local topography. In spite of this failure at individual sites the vectopluviometers characterize the flow over the catchment sufficiently well to give satisfactory prediction for the catchment as a whole.

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