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FOURCADE

SOME NOTES ON THE EFFECTS OF THE INCIDENCE OF RAIN ON THE DISTRIBUTION OF RAINFALL OVER THE SURFACE OF UNLEVEL GROUND.

By H. G. Fourcade.

(With six Text-figures.)

(Read June 18, 1941.)

I. Precipitation on Slopes.

Consider a rain-gauge set at an inclination α towards the direction from which rain is falling at an inclination i to the vertical. Let R be the rainfall recorded by a gauge horizontally set. In fig. 1, BC is the

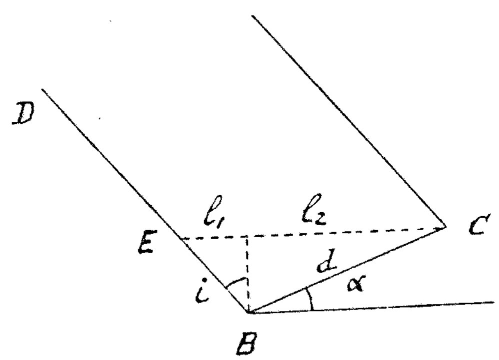

Fig. 1.

gauge, of diameter d, and BD the direction of the rain. The catch C of the gauge will be equal to the rainfall over an ellipse with horizontal axes CE and d. We have

$$l_1 = d \cos \alpha,$$
$$l_2 = d \sin \alpha \tan i.$$

The area of the ellipse will then be

$$A = \frac{\pi}{4} d(l_1 + l_2)$$
$$= \frac{\pi}{4} d^2 (\cos \alpha + \sin \alpha \tan i).$$

The horizontal area of the gauge is

$$\frac{\pi}{4}d^2 \cos \alpha,$$

so that **the rainfall received by the gauge per unit of its horizontal area is**

$$r = R + R \tan \alpha \tan i = \frac{C}{a \cos \alpha},$$

where a is the actual area of the gauge.

When **the direction ϖ from which rain is falling is at an angle $(\beta - \varpi)$ from the aspect β of the slope of the gauge,**

$$r = R + R \tan \alpha \tan i \cos (\beta - \varpi).$$

$$\text{If} \quad (\beta - \varpi) = 90^\circ, \qquad \cos (\beta - \varpi) = 0,$$

that is, the catch on a slope of aspect at right angles to the direction of the rain is independent of the inclination of the rain.

The influence of the inclination of rain on the rainfall over a slope has been noted before, as by Horton (1) in 1919, and already by the present writer as far back as 1889 (2), but its implications do not appear to have been followed up in sufficient detail.

Set up a composite gauge with four vertical apertures facing N., E., S., and W., and one horizontal aperture. Let a be the area of each vertical aperture, i_n and i_e the N. and E. components of the inclination i of the rain, and ϖ, reckoned from N. by E., the direction in azimuth from which rain is falling. The rainfall R is given by the horizontal gauge. We have

$$\tan i_e = \frac{R_e}{R}, \qquad \tan i_n = \frac{R_n}{R},$$

$$\tan \varpi = \frac{R_e}{R_n} = \frac{\tan i_e}{\tan i_n},$$

$$\tan i = \frac{R_n}{R \cos \varpi} = \frac{R_e}{R \sin \varpi}$$

$$= \frac{\tan i_n}{\cos \varpi} = \frac{\tan i_e}{\sin \varpi}.$$

When i_n and i_e are both positive the catches in the N. and E. vertical gauges of area a will be

$$C_n = Ra \tan i_n \quad \text{and} \quad C_e = Ra \tan i_e.$$

Substituting C_n/Ra and C_e/Ra for $\tan i_n$ and $\tan i_e$,

$$r = R + \frac{\tan \alpha}{a} (\cos \beta C_n + \sin \beta C_e).$$

For another period in which the rainfall is R' and the vertical catches C'_n and C'_e,

$$r' = R' + \frac{\tan \alpha}{a} (\cos \beta C'_n + \sin \beta C'_e).$$

Adding

$$r + r' = R + R' + \frac{\tan \alpha}{a} [\cos \beta (C_n + C'_n) + \sin \beta (C_e + C'_e)].$$

The result is therefore the same whether we deduce the total equivalent rainfall from the sum of equivalent falls computed separately, or directly, from the aggregate catches of each gauge. The partial catches of the vertical gauges are therefore strictly additive for each, irrespective of the directions or inclinations of the intermediate rains.*

When C'_n and C'_e are negative they become C_s and C_w. Finally, then, **the equivalent rainfall on a slope is given by**

$$r = R + \frac{\tan \alpha}{a} [\cos \beta (C_n - C_s) + \sin \beta (C_e - C_w)],$$

with

$$\tan i_n = \frac{C_n - C_s}{Ra}, \qquad \tan i_e = \frac{C_e - C_w}{Ra}.$$

Example.

Over a period with a precipitation of 19·70 in. there is collected in vertical gauges of 10 sq. in. area

$$C_n = 0{\cdot}67 \text{ c. in.}$$
$$C_e = 4{\cdot}50 \quad ,,$$
$$C_s = 14{\cdot}00 \quad ,,$$
$$C_w = 80{\cdot}00 \quad ,,$$

$$\tan i_n = \frac{0{\cdot}67 - 14{\cdot}00}{197} = -0{\cdot}0677, \qquad i_n = -3^\circ\ 50',$$

$$\tan i_e = \frac{4{\cdot}50 - 80{\cdot}00}{197} = -0{\cdot}383, \qquad i_e = -21^\circ\ 0',$$

$$\tan \varpi = \frac{-0{\cdot}383}{-0{\cdot}0677} = 5{\cdot}67, \qquad \varpi = 260^\circ\ 0',$$

$$\left.\begin{aligned} \tan i &= \frac{-0{\cdot}383}{-0{\cdot}985} = 0{\cdot}389 \\ &= \frac{-0{\cdot}0677}{-0{\cdot}1736} = 0{\cdot}390 \end{aligned}\right\} \qquad i = 21^\circ\ 20'.$$

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* This result follows at once from the rule for the addition of vectors.

The equivalent rainfall on slopes of N. and S. aspects, and inclination a, would then be

$$19\cdot7 \mp 1\cdot33 \tan a.$$

On slopes of E. and W. aspects,

$$19\cdot7 \mp 7\cdot50 \tan a;$$

or, for particular values of a, and more aspects,

$a=$	10°	20°	30°	40°
N.	19·5	19·4	18·9	18·6
N.E.	18·6	17·4	16·1	14·4
E.	18·4	17·0	15·4	13·4
S.E.	18·9	18·1	17·2	16·0
S.	19·9	20·1	20·5	20·8
S.W.	20·8	22·0	23·3	25·0
W.	21·0	21·4	24·0	26·0
N.W.	20·5	21·3	22·2	23·4

Another method of determining the inclination and direction of rain consists of the use of four inclined gauges set to face the cardinal points.

For the two opposite gauges, each of area a, of a pair we have catches

$$C_1 = Ra(\cos a + \sin a \tan i_1),$$
$$C_2 = Ra(\cos a - \sin a \tan i_1),$$

whence

$$C_0 = Ra\frac{C_1 + C_2}{2\cos a},$$

$$\tan i_1 = \frac{C_1 - C_2}{C_1 + C_2}\cot a = \frac{C_1 - C_2}{2C_0 \cos a}.$$

Two values i_e and i_n are obtained from the complementary pairs E.W. and N.S. Then, as before,

$$\tan \varpi = \frac{\tan i_e}{\tan i_n} \quad \text{and} \quad \tan i = \frac{\tan i_n}{\cos \varpi} = \frac{\tan i_e}{\sin \varpi}.$$

Separate catches for rains of different inclinations still become additive. For the equivalent vertical rainfalls r_1 and r_2 on any one gauge of the four, for catches C_1 and C_2, are

$$r_1 = R_1 + R_1 \tan a \tan i_1 = \frac{C_1}{a \cos a},$$

$$r_2 = R_2 + R_2 \tan a \tan i_2 = \frac{C_2}{a \cos a},$$

and

$$r_1 + r_2 = \frac{C_1 + C_2}{a \cos a}.$$

When the inclination of rain exceeds $\frac{\pi}{2} - \alpha$, C_2 becomes negative and is not recorded by its gauge, so that α should be made small. But the efficiency decreasing as $\sin \alpha$, α cannot be made very small. If the British rule, which applies to ordinary sites, that no obstruction must subtend a height of more than half its distance from the gauge, is observed, the maximum permissible slope of each of the gauge components will be 1 in 2, or $\alpha = 26° \ 30'$ for which $\sin \alpha = 0{\cdot}45$, and max. $i = 63° \ 30'$. For such a gauge

$i = 5°$	$C_1/C_2 = 1{\cdot}09$
10	1·19
15	1·31
20	1·41

It may be preferable to tabulate, instead of the direction and inclination of rainfall, its horizontal N.S. and E.W. components. The advantage is that the data become directly additive or separable. R_n and R_e are given at once by the gauge with vertical aperture. For the other gauge with four inclined elements we have

$$R = \frac{C_n + C_s}{A} = \frac{C_e + C_w}{A},$$

$$R_n = \frac{C_n - C_s}{B}, \qquad R_e = \frac{C_e - C_w}{B},$$

$$\tan \varpi = \frac{R_e}{R_n},$$

$$\tan i = \frac{R_n}{R \cos \varpi} = \frac{R_e}{R \sin \varpi},$$

in which $A = 2a \cos \alpha$ and $B = 2a \sin \alpha$, both constants for the gauge.

II. Construction and Use of Gauges.

Fig. 2 is a diagram of a suitable composite gauge of the first type. Four vertical apertures, which may be 10 sq. in. in area, set to face N., E., S., and W., are connected in pairs, by widening receivers, to a central square chamber. Inclined baffles in the back half of each receiver serve to collect the rain that has not been deposited in the front half. The velocity of the air passing over the baffles being reduced to a fraction of that of the wind, practically every particle of even misty rain can be caught by spacing the baffles closely enough. The apertures are made of elongated shape, and their ends pointed, in order to reduce turbulence when the air stream crosses a pair of them at a small incidence.

The vertical rainfall could be measured by a horizontal gauge incorporated into the middle of the composite one, but it will probably be more convenient to measure it separately in a standard gauge placed alongside.

Standard gauges should, as a rule, be shielded. A long series of measurements during nineteen months on Mt. Washington (6284 ft.) by S. Pagliuca (3)

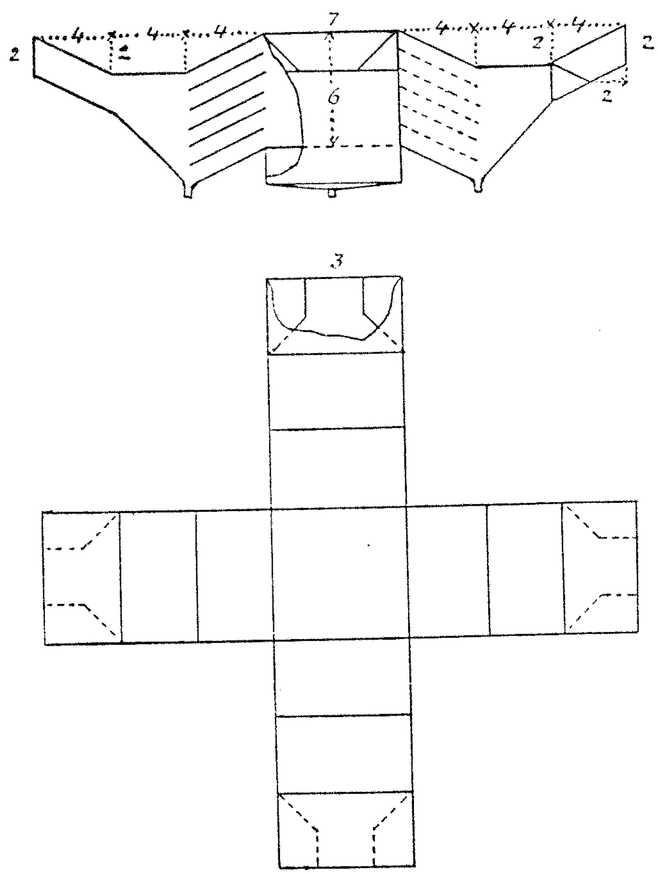

Fig. 2.

showed that with wind velocities up to 30 mi./h. shielded gauges collected 4 per cent. more than unshielded ones. With wind velocities between 30 and 75 mi./h. the increase was 40 per cent., and, above 75 mi./h., 42 per cent. It seems that 30 mi./h. is a critical velocity above which turbulence of a different character sets in. Other observers have found larger increases in moderate winds, but it may be that they took average velocities made up partly of exceptional gusts accompanied by the heaviest showers.

A wooden shield in the shape of an inverted truncated pyramid of 30 × 30 in. base, and sides at 45°, was found by Pagliuca (3) to be a simple and efficient substitute for a Nipher shield.

A shielded gauge is nothing but a pit gauge raised above the surface of the ground, with the advantage that it is less affected by turbulence from the roughness of the ground, unless the pit gauge is surrounded by a smoothed space and provision made against splashing.

The second type of composite gauge that has been considered, the inclined composite, could consist of four funnels fixed on the faces, sloping 1 in 2, of the square pyramidal roof of a supporting box containing the receiving vessels. The further design will present no difficulty.

Another class of gauge, for use on mountain-slopes, are single inclined gauges set with their rim parallel to the surface of the ground; the catch of each divided by its area and by the cosine of its inclination gives the true equivalent rainfall over the slope.

III. Determination of Rainfall over a Catchment Area.

The practice of engineers is to estimate the volume of water falling as rain over a catchment area as being equal to the product of the area with the annual rainfall measured in standard horizontal gauges. (See, *e.g.*, Dict. Appl. Phys., vol. i (1932), p. 495.) To show that this rule can be very inaccurate, take (fig. 3) a section, in the direction of the rain, across a catchment area, from watershed A to watershed C. The arrows indicate the direction and force of the wind; the curved dotted lines the trajectories of raindrops.

Between A and B, at one height, the catch C_1 will be equal to the area of the strip $AB = l_1$ multiplied by the mean rainfall over the strip, as recorded by ordinary horizontal gauges, or $C_1 = l_1R_1$, independently of any varying inclination of the rain between A and B. From B to C the catch C_2 will be $l_2R_2(1 + \tan\alpha \tan i)$, and the true total catch $C_1 + C_2$, not $l_1R_1 + l_2R_2$ but $l_1R_1 + l_2R_2(1 + \tan\alpha \tan i)$.

The low velocity of fall of raindrops at high elevations, due to their smaller diameter, combines with the higher velocity of the wind to produce an average inclination of rain over BC always much higher than over AB, so that the difference between the true and the nominal catches may be considerable. To take a numerical example, supposing $l_1 = 3l_2$, $\alpha = 30°$, $i = 75°$, and $R_2 = 2R_1$, which seem possible figures at the mountain end of a catchment, we get relative values, for the total catch, of 100 and 186, that is a true value 86 per cent. in excess of the nominal.

The difference between the true and the nominal rainfall has been called by Horton ((1), p. 359) the "roof effect." This roof effect, resulting from boundary conditions, will be more marked in a small catchment than in a large one, and when comparing fluctuations of run-off with those of rainfall it may possibly be disregarded, as it is by engineers, without introducing serious error in the character of the relation. But it is otherwise when attempting a more complete study of the various gains and losses of water of a catchment, it becoming then essential to determine as accurately as possible the quantity of water received that has to be accounted for in the form of a balance-sheet of the rainfall.*

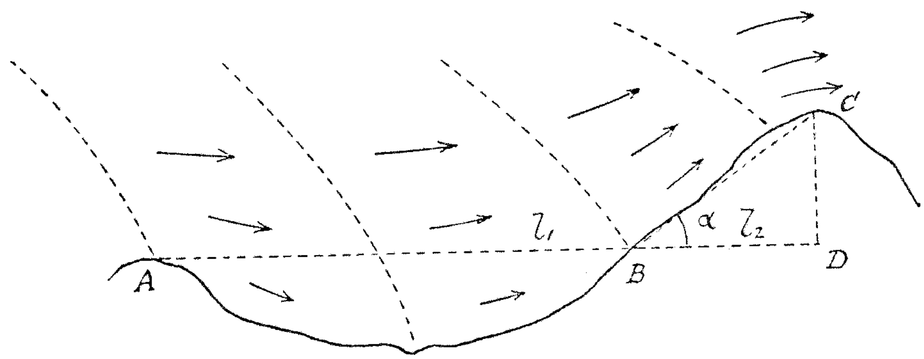

FIG. 3.

The rainfall over a catchment can be ascertained by subdividing the area into a number of topographical elements on each of which a gauge is set up, parallel to the equivalent slope of the element, and its catch divided by the cosine of its inclination. Or the fall on any of the elements may be derived from the catch of horizontal gauges corrected, from the indications of a composite gauge, by means of the formula

$$r = R + R \tan \alpha \tan i \cos (\beta - \varpi).$$

The use of the second method should be restricted to the lower portion of a catchment, below a definite contour line, usually the greater portion, over which the wind would blow more uniformly than over the upper portion, but it may be extended to the whole of the catchment when there are no great differences in elevation. The composite gauge should be erected near the centre of the area on the most level ground available, preferably a rounded hilltop. The upper remaining extent may then be divided into sections comprising a middle ridge on which is located a gauge set parallel to the equivalent slope of the section. As the catch of the gauges will vary with altitude, two or three at different heights should

* The surface run-off, sub-surface run-off, evaporation, interception by plants and transpiration by plants, must in their sum equal the rainfall ± the loss or gain, during the period, of the stock of water stored in the catchment (in soil, rock, streams, lakes, marshes, dams, tanks).

be set up in one of the sections, all of them at one inclination, parallel to the equivalent slope of the whole of the section, from the indications of which the corrections needed to convert the catch of each gauge in the other sections into the average catch for its section may be estimated.

Inclined gauges for mountains on which the precipitation is high must necessarily be of small dimensions in order to keep down the quantity of water that has to be collected, particularly when the gauge cannot be visited and emptied daily.* Appropriately, they may consist of a cylindrical can of 10 sq. in. aperture with sides 6 in. high draining by means of a flexible tube into a 4-gallon drum placed lower down on the slope. The base of the gauge should be at ground level, and the surrounding surface cleared and smoothed.

The equivalent net slope of an area may be obtained by a method due **to Horton** (4). A graticule of N.S. and E.W. lines is laid upon a contoured map of the figure the slope of which is to be determined. The sum of the differences in elevation of the N.S. lines, at their intersections with the boundary, divided by the sum of the horizontal lengths of the lines, will give the N.S. component of the slope. The E.W. component is obtained similarly.

If (fig. 4) $\tan \alpha_n$ and $\tan \alpha_e$ are the N.S. and E.W. slope components, and OC is taken as 1,

$$h = \tan \alpha_n,$$
$$h/OA = \tan \alpha_e.$$

The line of dip BD of the plane BAC, and OD, are both perpendicular to the horizontal line AC. Whence

$$OD = \cos \beta = OA \sin \beta,$$
$$\tan \beta = \tan \alpha_e / \tan \alpha_n,$$
$$\tan \alpha = \frac{h}{OD} = \frac{\tan \alpha_n}{\cos \beta} = \frac{\tan \alpha_e}{\sin \beta}.$$

Horton (4) gets the equivalent formula

$$\tan \alpha = \sqrt{\tan^2 \alpha_n + \tan^2 \alpha_e}.$$

In the expression for the slope components the limiting values of $\Sigma(s\Delta d)$, when the graticule interval Δd becomes infinitely small, is the

* The importance of the size and accuracy of the collecting aperture of a gauge is sometimes unduly stressed having regard to the many greater sources of error in rainfall measurement, such as the variability of the fall over different points of even a small area. According to Ryves (5), "Trials with gauges of various diameters from 1 in. to 2 ft. have shown that if they are set perfectly level, and observed with great care, exactly the same rainfall has been recorded by all of them."

map area of the surface—that is, its **horizontal projection** P_z. Similarly $\Sigma(h_n \Delta d) = P_n$, and $\Sigma(h_e \Delta d) = P_e$, become the projections of the surface on the planes ZOE and ZON, so that $\tan \alpha_n = P_n/P_z$ and $\tan \alpha_e = P_e/P_z$. P_n and P_e are best obtained by plotting as ordinates the height differences of each N.S. and E.W. line, respectively, against abscissae s at Δd intervals and measuring the areas with a planimeter. If, through re-entrant angles of a boundary line, there are two partial height differences in one ordinate their sum is plotted.

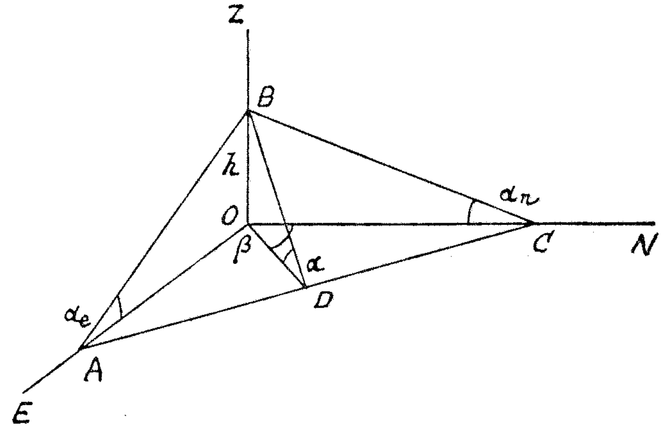

FIG. 4.

The interception by the topographical surface of the N.S. component of rainfall of any inclination will be the same as its interception by the horizontal projection P_z of the surface and the vertical projection P_n taken together. Similarly for the E.W. component and P_z with P_e. So that the topographical surface may be replaced by the surface of any plane figure of which the projection areas are also P_z, P_n, and P_e. If, in fig. 4, $AO \,.\, OC$ is made equal to P_z,

$$AO \,.\, OB = P_z \tan \alpha_n = P_n, \quad CO \,.\, OB = P_z \tan \alpha_e = P_e, \quad \text{and} \quad AC \,.\, BD = P$$

is therefore a surface of which the projections are P_z, P_n, and P_e. P may be called the equivalent area of the topographical surface and ABC the equivalent plane of its boundary. P, on this plane, is given by

$$P^2 = P_z^2 + P_n^2 + P_e^2.$$

IV. Interpretation of Catches.

The inclination of rain is the resultant of the velocity of the wind and the rate of fall of the raindrops, which may be anything from 0 in a dry fog, 1 m./s. or less for snow or mist, 3 m./s. for fine rain, to 8 m./s. for the largest

drops (Brooke and Pagliuca (6), quoting Pers).* **On mountains, at cloud levels in which misty rains prevail, the inclination may become almost horizontal, or even upwards, and extraordinary differences in equivalent rainfall result.**

The neglect of this influence of the inclination of rain has been a fruitful source of error in the interpretation of some recorded catches. Thus, under the name of "condensation" of rain by vegetation, there has been attributed to vegetation some capacity of collecting more rain than would otherwise fall on the surface it covers or shields. **J. F. V. Phillips (8) set** up **two 5-in. gauges, one as control, the other surmounted by a frame of wire-netting, 1 ft. high, filled with leafy branchlets.** In one year the catch of the control was 50·02 in. and that of the "condensation" gauge 94·56 in. **He attributed the increase to "condensation," particularly that of mists, which "precipitate large amounts of moisture upon cool surfaces, such as vegetation in its various forms, and on outcrops of rock along the mountain faces."** 1931

J. Phillips' figures do not afford the smallest indication that the increase in the "condensation" gauge was due to anything but the inclination of the rain.

Let d (fig. 5) be the diameter of the gauge, h the height of the intercepting cylinder of foliage, and i the inclination of the rain from the vertical.

* When they are very low, the settling velocities of raindrops may be computed from Stokes' formula put in the form

$$V = 2gr^2(\rho_p - \rho_f)/9\mu,$$

which gives the following values:—

d mm.	V m./s.	$\frac{Vl}{\nu}$
0·02	0·013	0·01
0·04	0·050	0·15
0·06	0·113	0·5
0·08	0·20	1·2

When the Reynolds number, Vl/ν, becomes large the formula ceases to be applicable. From Pers' data, referred to above, may be derived

$d = 0·3$ mm.	$V = 1·1$ m./s.	$Vl/\nu = 24$
1·0 ,,	5·3 ,,	385

The diameter of the drops in ordinary rain is about 1·5 mm., for which $V = 7$ m./s. approx.

The size of drops may be computed by the methods of Meteorological Optics from the optical effects they produce on light. According to Whipple (7) the size of the droplets producing the corona, which frequently appears when the moon is seen behind a thin cloud, averages about 0·02 mm. diameter, the range being from 0·01 to 0·06 mm. The drops in the falling rain which produce rainbows are usually larger, from 1·0 to 0·3 mm. in diameter, but the presence of supernumerary bows indicates the predominance of drops with diameter 0·25 to 0·05 mm.

Then

$$\left(\frac{\pi d^2}{4} + dh \tan i\right) \Big/ \frac{\pi d^2}{4} = \frac{C}{R},$$

where C is the catch of the "condensation" gauge and R that of the control, whence

$$\tan i = \frac{\pi}{4} \cdot \frac{d}{h}\left(\frac{C}{R} - 1\right).$$

In the example given,

$$\tan i = 0{\cdot}327\left(\frac{94{\cdot}56}{50{\cdot}02} - 1\right) = 0{\cdot}286,$$

making $i = 16°$.

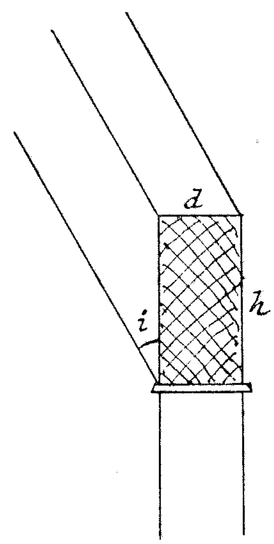

Fig. 5.

The surprising thing is not that the "condensation" gauge should have collected more than the control, but that it should have collected so little more, because, in the region experimented in, rain drives normally from the west at an angle which, to the eye, appears to be greater than 16°. One reason may have been that the cylinder of foliage was too open to intercept all the rain; another that the air streaming around it deflected some of the drops. Further loss may have been due to splashing and to the blowing away of part of the moisture before it could trickle down to the gauge. And there may have been some real "interception" of rain as understood by scientific experimenters.*

* "Interception of precipitation" is defined "as the process by which precipitation is caught and held by foliage, twigs and branches of trees, shrubs and other vegetation, and evaporated without reaching the ground" (11). It envisages a *loss* of rain to the

(1903)

Marloth (9), some years previously, had conducted similar experiments on the top of Table Mountain (3500 ft.). He also used, over his collecting gauge, a frame of wire-netting, with the difference that, instead of foliage, he had inserted a number of restionaceous stems, which made a screen more permeable to the wind and draining more readily into the gauge, thus to a great extent avoiding the sources of error which affected J. Phillips' experiments, but introducing others that will be mentioned presently. **Stewart** (10), **criticising** Marloth's paper, was at some pains to measure accurately the superstructure of Marloth's gauge, but, not having considered quantitatively the effect of the inclination of the rain, could only conclude that "**the problem is as far from being solved as before the experiments were undertaken.**"

The surface of the superstructure, consisting of rods, a ring, wire-netting, and restionaceous stems, was found to be 113·8 sq. in.,* equal to an intercepting surface of $113{\cdot}8/\pi = 36{\cdot}2$ sq. in. The receiving surface of the collecting gauge was contracted by the construction to 18·2 sq. in. against 19·6 sq. in. for the control (5-in.) gauge.

We have then C' and C being the catches in the reed and the control gauges, R the rainfall in the latter, and i the inclination of the rain to the vertical:

$$C' = 18{\cdot}25R + 36{\cdot}2 \tan i,$$
$$C = 19{\cdot}6R,$$
$$\frac{C'}{C} = 0{\cdot}932 + 1{\cdot}846 \tan i; \qquad \tan i = 0{\cdot}542\frac{C'}{C} - 0{\cdot}505.$$

Regarding the sources of error in Marloth's experiments:

(1) The particles of rain in the south-east cloud are very fine. **Marloth himself says (14, p. 99), "Such a cloud is really an intimate mixture of an ordinary cloud with a very finely distributed rain in its initial stages."** Textbooks of meteorology teach that clouds are really nothing else but fog or mist (except upper clouds composed of spiculae of ice). This is borne out by the experience of campers on mountains, and, in the present case, by the "Table-cloth" in which the particles of water driven over the edge of Table Mountain are so minute that they dissolve immediately the descending air stream they are carried in becomes slightly warmed up by adiabatic compression at a lower level.

(2) The small rate of fall of such particles, relatively to the high velocity of the south-east wind, causes the rain to drive at a very low inclination

soil, not a gain, as imagined by J. Phillips in letters entitled "Rainfall Interception by Plants" (12 and 13) which refer to his experiments noticed above, but entirely ignore real interception.

* **"The result is well under the actual area," for reasons given by Stewart (10, p. 415).**

to the horizontal. This being so, a glance at the photograph of the gauges on Table Mountain, reproduced in Marloth's first paper (9, p. 408), shows that when rain drives at this low angle, the control gauge and the reed gauge must both have been obstructed by higher bushes to the windward. This is further proved by recorded catches (Marloth (9), p. 406) of 15·22 and 14·64 in., and (Marloth (14), p. 102) of 9·55 and 0·15 in., in the reed gauge on days when the control collected nothing. Also by the fact that the open gauge at Maclear's beacon, close by, collected during one period (Marloth (9), p. 406) 6·99 in. against 4·97 in. in the control, and in another period (Marloth (14), p. 102) 9·55 in. against 1·44 in.

The data have now become too vague to yield any satisfactory determination of the inclination of the rain. All that can be done is to show that the catches are consistent with possible values of the rate of fall of the raindrops and of the velocity of the wind.

(3) During 56 days of the season of S.E. clouds, from December 21, 1902, to February 15, 1903, the control gauge collected 4·97 in., and the gauge with reeds 79·84, of which 29·86 in. were without any corresponding catch in the control, and, therefore, were due to rains from which both the control and the collecting base of the reed gauge were completely screened by bushes. The gauge at Maclear's beacon on the same mountain-top collected during the same period 6·99 in. of rain, and there is no reason to suppose that a properly exposed gauge near the reed gauge would have collected less. However, to depart least from the recorded figures and because the catch in the reed gauge was lost through a portion of the container having become full and overflowed on three occasions, a mean value of 5·98 in. is taken as a possible value of the catch of the control had it been properly exposed, an excess of 1·01 over the recorded catch, which must also be applied to the collecting base of the reed gauge, giving finally, as possible figures, 5·98 and 80·85 respectively. Then

$$\tan i = 0{\cdot}542\,\frac{80{\cdot}85}{5{\cdot}98} - 0{\cdot}505 = 6{\cdot}81,$$

$$i = 81^\circ\ 40'.$$

If the mean velocity of the S.E. wind was 20 mi./h. = 8·95 m./s., the rate of fall of the mist particles would be 8·95/6·81 = 1·3 m./s.

(4) In a second series of experiments, "near Maclear's beacon," for the month of January 1940, the control gauge showed only 1·44 in. of rain and the reed gauge 48·42, of which 9·70 were without any corresponding catch in the control. During the same period the catch at Maclear's beacon was 9·55 in. Taking as before the mean of 1·44 and 9·55 or 5·50 as the possible unobstructed catch of the control, and adding the 4·06

excess to the reed gauge, we get as possible values, with a large measure of uncertainty, 5·50 and 52·48 in. respectively. Then

$$\tan i = 0{\cdot}542 \frac{52{\cdot}48}{5{\cdot}50} - 0{\cdot}505 = 4{\cdot}60,$$

$$i = 77^\circ\ 40'.$$

For a wind velocity of 20 mi./h. the rate of fall of the mist particles would be 8·95/4·60 = 1·9 m./s.

(5) Two more series of observations were made, this time at the Woodhead Reservoir (alt. 2496 ft.), where at 1000 ft. lower elevation the raindrops would normally be larger.

One series, for the month of January 1904, gave 1·83 in. for the control, and for the reed gauge 13·73, of which 4·77 corresponded to only 0·02 in. in the first, leaving 13·73 − 4·77 = 8·96 in. caught in the reed gauge when 1·83 − 0·02 = 1·81 in. were collected in the control. Assuming, in the absence of any other indications, that the ratio of 1·81 to 8·96 would hold for unobstructed catches of the control and reed gauge, making these 2·23 and 13·73, and adding the excess 2·23 − 1·81 = 0·42 to the catch of the reed gauge, making it 14·15, we have

$$\tan i = 0{\cdot}542 \frac{14{\cdot}15}{2{\cdot}23} - 0{\cdot}505 = 2{\cdot}93,$$

$$i = 71^\circ\ 10'.$$

For a wind velocity of 20 mi./h. the rate of fall of the raindrops would be 8·95/2·93 = 3 m./s., corresponding to fine rain, according to Pers' table previously cited.

(6) In the second series, for the month of January 1905, the catch in the control was 1·45 and in the reed gauge 15·86, of which 4·90 corresponded to only 0·04 in. in the first. Using again the ratio of the remainders for the total, and proceeding as in the last case, we get possible catches of 2·08 and 16·53 respectively, and

$$\tan i = 0{\cdot}542 \frac{16{\cdot}53}{2{\cdot}08} - 0{\cdot}505 = 3{\cdot}80,$$

$$i = 75^\circ\ 20'.$$

For a wind velocity of 20 mi./h. the rate of fall of the drops would be 8·95/3·80 = 2·4 m./s., still corresponding to fine rain.

The results of all four series of observations made by Marloth are therefore compatible with possible wind velocities in a "south-easter" and normal rates of fall of mist particles or raindrops, and give no support to his contention that vegetation condenses moisture, in addition to the rainfall it mechanically receives. The catches given in Marloth's papers have been corrected, not because they would have led to different conclusions, but only because they were manifestly too small. Indeed, since the rate of fall of water particles may vary from 0 in a fog to 8 m./s. in heavy rain, and wind velocity is also variable, any ratio between the catches of a control and a "reed" gauge would be compatible with some rate of fall of the water particles and some velocity of the wind, within limits.

Marloth's observations, having been fundamentally vitiated by the incorrect exposure of his gauges to the rains of low inclination prevalent on Table Mountain, cannot be made to yield, even approximately, a true measure of the equivalent inclination of the rain for any of the periods considered. **The numerical results they yield have been given merely to make clear, by examples, that enormous differences in the catches of control and "reed" gauges must result from rains of high inclination.**

It might seem unnecessary to recall at this time of day this ancient controversy were it not that some South African botanists and others, notably J. Phillips (12, 13), Dyer (15), Levyns (16), and Wicht (17), still assume that Marloth "demonstrated" the reality of his conclusions.

Summary.

1. The factors which govern the catch of rain over a given area are shown to be the vertical rainfall, the inclination of the rain, its direction, and the slope and aspect of the ground. The mathematical relations between these five factors are deduced.

2. Methods of measuring the inclination and direction of rain are discussed and suitable gauges proposed.

3. Application is made to the determination of the true equivalent rainfall over a catchment area.

4. The neglect of the influence of the inclination of rain on the equivalent rainfall is shown to have been a fruitful source of error in the interpretation of some recorded catches.

Witte Els Bosch,
April 1941.

Addendum.

Since the above paper went to press, Dr. C. L. Wicht, Forest Research Officer at Jonkershoek, Stellenbosch, has had a multiple rain gauge constructed, substantially to the design proposed in the present paper, and with this, and another gauge with vertical apertures that is being made, intends to carry out an experimental investigation of the subject, in connection with the studies of the hydrology of the Jonkershoek drainage basin on which he has been engaged for some years. His results, which necessarily cannot be immediate, will be awaited with interest.

Dr. Wicht's inclined gauge, of which fig. 6 is a photograph, is constructed with apertures at 45°, instead of 1 in 2, giving greater sensitiveness, while the addition of a vertical gauge makes it, in most cases, still possible to determine i_n and i_e when these, either or both, have exceeded + or $-45°$ some of the time. The supposition is that, on any gauge facing the

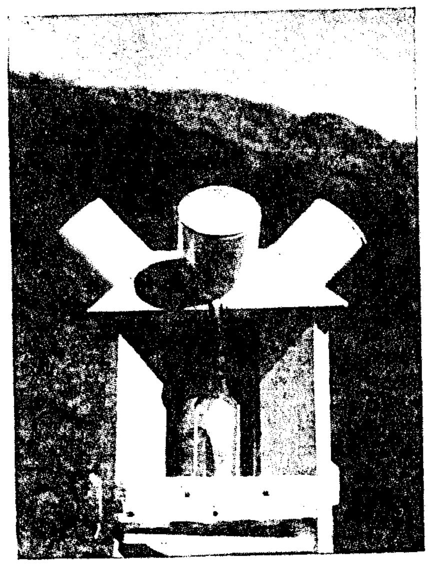

FIG. 6.

weather, the inclination component i has not varied beyond the limits of $+90$ and $-45°$, which may be valid from day to day, but not for extended periods.

Substitute, for the catches C, the equivalent vertical rainfall $r = C/a \cos \alpha$, this being for 5-in. gauges at 45°, and C in cubic inches, $r = 0{\cdot}072\ C$. Then $\tan i_n$ may be derived from either $\frac{r_n - R}{R}$ if r_n is greater than r_s, or from $\frac{R - r_s}{R}$ if r_s is the greater, and similarly for $\tan i_e$.

Trial observations of the gauge were made at Jonkershoek from August 14 to September 23, 1941. On September 1, 17, and 22 the bottles overflowed. On August 15 and 20 the measures were inconsistent.

The following table gives particulars and results for the other days on which rain fell:—

1941.	R inches.	r_n.	r_s.	r_e.	r_w.	tan i_n.	tan i_e.	tan $\bar{\omega}$.	$\bar{\omega}$.	i.
Aug. 14	·59	1·28	·11	·16	1·27	1·17	−1·15	− ·98	315° 30′	58° 30′
16	·01	·07	·01	·01	·05		insufficiently determinate			
18	·24	·07	·56	·46	·12	1·33	·92	·69	145 20	58 10
26	·04	·08	·02	·02	·11	1·00	−1·75	−1·75	299 40	63 40
29	·29	1·03	·03	·05	·98	2·54	−2·38	− ·94	316 50	74 0
30	1·02	2·08	·24	·18	3·00	1·02	−1·94	−1·90	297 50	65 30
31	·22	·72	·03	·10	·53	2·27	−1·41	− ·62	328 10	69 30
Sept. 2	1·00	2·74	·12	·51	1·80	1·74	− ·80	− ·46	335 20	62 30
3	·64	·97	·36	·69	·66	·52	·08	·15	8 40	28 0
13	·21	·37	·15	·10	·60	·76	−1·86	−2·45	292 10	63 30
14	·57	1·13	·15	·14	1·17	·69	− ·75	−1·09	312 30	45 30
15	1·20	2·12	·51	·78	1·69	·77	− ·41	− ·53	332 0	41 0
16	·50	·76	·28	·30	·77	·52	− ·54	−1·04	313 50	36 50
18	·39	·59	·24	·20	1·27	·51	−2·26	−4·43	282 40	66 40
19	·19	·19	·21	·17	·29	− ·11	− ·53	−4·82	281 40	28 20
23	·45	·85	·72	·82	·31	·89	·82	·92	42 40	50 30

The method may be extended to cover continuous periods during which daily observations have been made. When the inclination of any of the rain components exceed $+45°$ the theoretical negative catches in the lee gauge of the pair are not recorded, so that, if $r_1 > r_2$, it may no longer be permissible to use the observed r_2, for which must be substituted a computed $r_2 = 2R - r_1$ in order to satisfy the necessary condition $\tan i = \frac{r_1 - R}{R} = \frac{R - r_2}{R}$. Conversely, if $r_2 > r_1$, r_2 observed and $r_1 = 2R - r_2$ computed must be used.

For example, taking the longest uninterrupted period in the above table, that from September 2 to September 16, the totals, after substitution of computed for observed figures where necessary, are $R = 4{\cdot}12$, $r_n = 8{\cdot}09$, $r_s = 0{\cdot}15$, $r_e = 1{\cdot}62$, and $r_w = 6{\cdot}62$. From these, $\tan i_n = 0{\cdot}964$, $\tan i_e = -0{\cdot}606$, $\tan \varpi = -0{\cdot}629$, $\varpi = 327° \; 50'$, and $i = 48° \; 40'$, R being the rainfall and ϖ and i the equivalent azimuth and inclination of the rain for the period.

Jonkershoek is a narrow valley running up, in a S.E. direction, between ranges of mountains from 4000 to 5000 feet high. The altitude of the station is not given, but it would be about 1000 feet.

The observations detailed above indicate that, at Jonkershoek:

1. The inclination of rain is frequently very great and comparable with the still greater values that were estimated for Table Mountain at a higher altitude.

2. The catches recorded could all be accounted for, on each day, by

rain components, persisting from one general direction at inclinations ranging from nearly horizontal, with gusts and fine or misty rain, to nearly vertical during lulls, so that negative inclinations produced by veering of the wind, if they did occur, are not likely to have exceeded $-45°$ on the one day.

3. A multiple gauge with apertures at 1 in 2 slope would be no better than one at 45° because, on account of the high inclination of some of the rain, it would still give catches C, or their corresponding rainfalls r, neither directly additive.

4. The multiple gauge with vertical apertures being free from this limitation is to be preferred, but the gauge at 45°, if the validity of the assumption made for the reductions can be confirmed, would remain useful for checking at times the working of the other.

5. It is possible that the rainfall recorded in the vertical gauge forming part of a multiple combination is systematically too low, by perhaps 5 or 10 per cent., and that a separate shielded gauge would yield more accurate results. Turbulence may be expected to be greater over the vertical gauge than over the gauges with vertical or inclined apertures because, on level ground, any wind will strike the aperture of a vertical gauge at a very small angle, while, in the other gauges, this can only happen when the wind actually blows from near one of the cardinal points.

WITTE ELS BOSCH,
November 1941.

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