COLLECTION OF WATER FROM CLOUD AT GIBRALTAR

By G. W. Hurst, B.Sc.*

CONTENTS

SUMMARY

RECTANGULAR FRAMES of metallic meshes were installed for a trial period on the upper Rock of Gibraltar as catchments for cloud droplets. Frequent measurements were made of water-catch caused by either cloud or rain. An estimate was made of the potential collection for a typical year primarily from cloud and secondarily from rain.

INTRODUCTION

The supply of adequate potable water at Gibraltar is an ever-increasing problem, due to the natural growth of population, and to improved amenities. Most of the water is obtained from catchments on the Rock slopes, and from wells at North Front. City Council catchments cover 38 acres, and provide a net yield of over 500,000 gal. per in. of rain. With an efficiency of collection of 60 per cent, this represents an annual yield of about 15 m.g., but there is wide variation in dry or wet years. Limited storage space sometimes causes loss in wet years if exceptionally heavy rainfall occurs during a short period. Wells provide about 25 m.g. yearly.

Other sources are distillation, and purchase from outside the Colony. Both are expensive, and output from the former is limited at present. Purchase is very dependent upon circumstances; for example, use has often been made in the past of new oil tankers on maiden voyages from the United Kingdom.

The Gibraltar summer is dry, with an average rainfall of less than 2 in. during the four months June to September. This, however, is the season of predominantly moist easterly winds, a feature of which is a low cloud plume over and to the west of the Rock, occurring

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NORTH FRONT AIRFIELD

MEDITERRANEAN SEA.

N

TOWN

Water
Catchment

Rock
Gun.

MIDDLE HILL
GAP

CATALAN
BAY

WATER

CATCHMENT

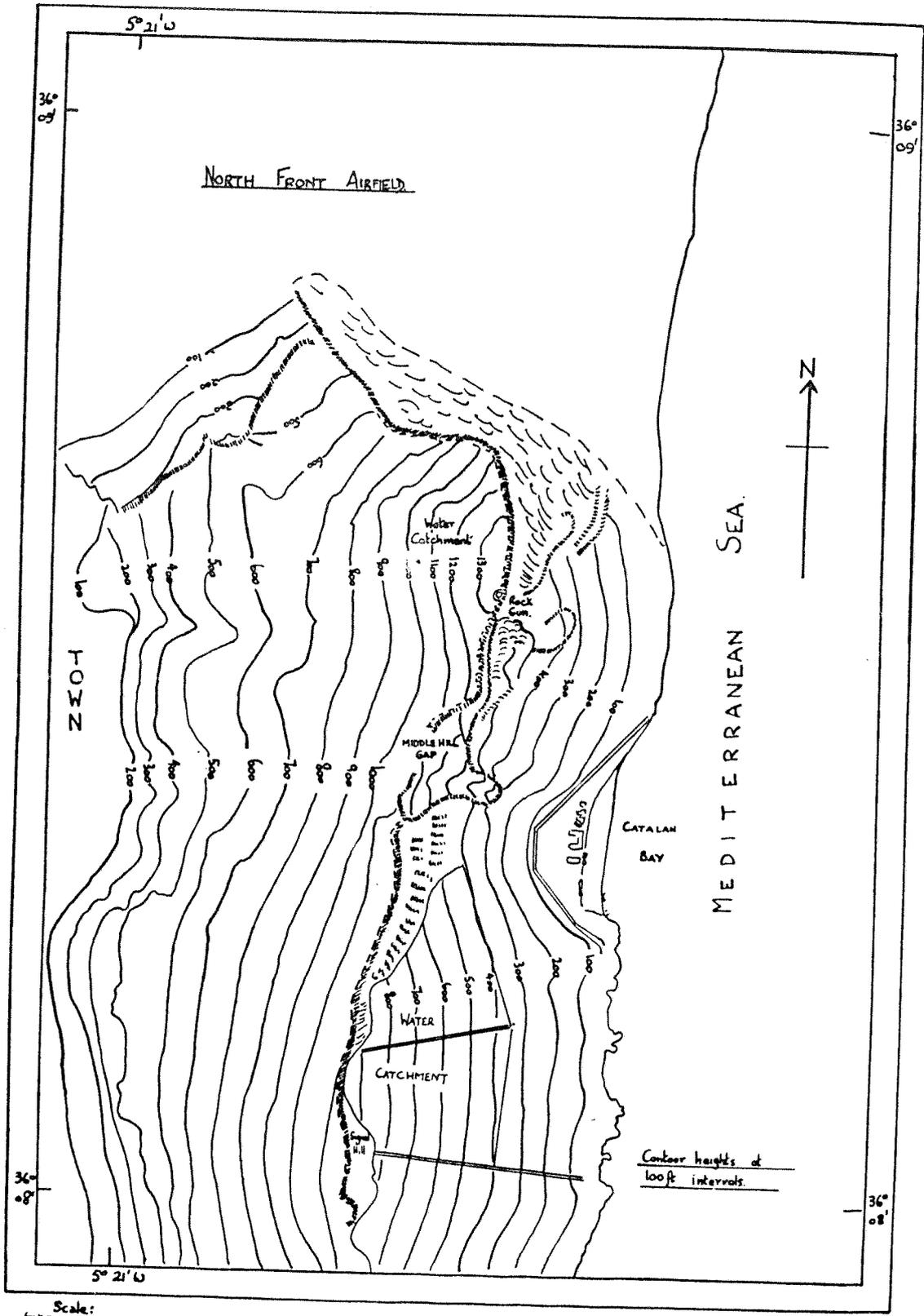Contour heights at
100 ft intervals.

Scale:

Fig. 1

Middle Hill in relation to the rock ridge and slope

most frequently in the late night or early morning. This "levanter" cloud is often dense and persistent, and deposition of moisture on objects near the ridge is heavy.

Experience at Table Mountain (Nagel 1956)*, and in Tasmania (Twomey 1957), suggested that Gibraltar might be an ideal location in which to undertake a fairly thorough examination of the possibility of obtaining water supplies from this source. A pilot scheme for several months from mid-1957 was, therefore, undertaken.

SELECTION OF SITE

It proved unexpectedly difficult to find a suitable site. A position near the ridge of the Rock was desirable, in order to take full advantage of the greater density and higher frequency of cloud. Unfortunately, the eastern face is so steep in most places that wind motion at the ridge is nearer vertical than horizontal. The only place which seemed suitable was the Middle Hill gap. Its advantages were (a) good exposure to a horizontally blowing easterly wind, subject to a natural Venturi effect causing increased wind speed, and consequently higher cloud catch, and (b) the possibility of large-scale development of the project in the future. Moreover, an R.A.F. Signals Unit was stationed nearby, enabling readings to be made twice daily or more often as necessary.

Fig. 1 shows Middle Hill with the steep slope down to the sea to the east, and the gentler slope to the west. The main run of the ridge with the break in the sharp rocky edge at the Middle Hill gap is evident; Fig. 2, Plate 1, gives a more detailed plan, and indicates the position of the cloud catch installation.

EQUIPMENT

Only one type of metallic mesh was readily available—galvanized mosquito netting of $\frac{1}{16}$ in. mesh spacing and 33 gauge. This was made up into two frames nominally 6 ft. by 3 ft. (actual effective area 16 sq. ft.), one with a single thickness of mesh, and the other with double thickness, separated by about 2 in. The frames were mounted on legs to give an overall height above ground level of about 5 ft. 6 in. A rain-gauge was set below each to collect resulting cloud catch, with a third gauge between them to act as a check on the actual rainfall. Photographs of the installation are shown in Figs. 3 and 4, Plate 2.

Due to topographical control, cloud-forming winds could be expected to be almost invariably from between east and south-east, so consequently, use was made of flat frames set perpendicular to the direction east-south-east. It proved necessary to substitute 5 gal. drums for the collecting rain-gauges early in the experiment, as collecting rates at times were considerably heavier than had been expected; a measure reading in hundredths of a gallon was accordingly devised.

* References are given on p. 349.

OBSERVATIONS

Initially, readings of all gauges were taken twice daily, as close to 0600 and 1800 G.M.T. as the duties of the observers would allow. Observations included a wind speed reading by hand cup anemometer, and a general statement of conditions. To minimize loss from overflow, some additional readings were made during periods of cloud cover in July and August, and rain in autumn and winter. Notes were kept of the onset or lifting of cloud from Middle Hill, but as this often took place at night, the information is necessarily very incomplete.

The only other meteorological observations of any kind available from the upper Rock are those from the anemometer at Rock Gun with repeater dials in the North Front office, but the great length of cable has always caused considerable unserviceability.

THEORETICAL EXPECTATION OF CATCH

The Appendix, p. 350, presents an estimate of the catch which might occur during suitable conditions. The yield which might be expected for each frame in the height of summer with a 10 knot wind ranges up to 0·21 gal. per hr. for each 100 ft. cloud depth below the level of the collector. The yield increases with wind speed, though the increase is not linear. Air penetration and catches are appreciably greater with light winds with the single-meshed frame, but with stronger winds this is reduced by a marked tendency to "drop shake-off" in gusts—indeed with a really strong wind, amounts of water collected through the single mesh were trivial.

Summer yield periods gave considerably larger catches, and were also of more frequent occurrence than those of winter, due to the much greater frequency of suitable cloud, and to the higher temperatures, with consequent higher concentration of water droplets in a cloud for any particular degree of lifting.

ANALYSIS OF RESULTS

Table I (a) provides a statement of the actual water collected each month; the cloud-catch entries here relate to pure levanter cases, associated with negligible or no rainfall. The rain-catch columns include both rain and combined rain and cloud catches.

Table I (b) provides an estimate of the probable catch if there had been no loss of record due either to overflow or to damage to equipment. Cloud and rain are considered as separate elements. Comments on these data follow.

Losses of record in July after installation on the 11th were considerable, overflow taking place five times. After the second occasion, the observers made more frequent readings to minimize loss. Estimates of these losses in Table I (b) have been made conservatively. Overflow loss was much less in August, and on the 29th large collectors were introduced. September was a particularly dry month, and although easterly winds were common enough, they were usually associated with a short sea track and little cloud.
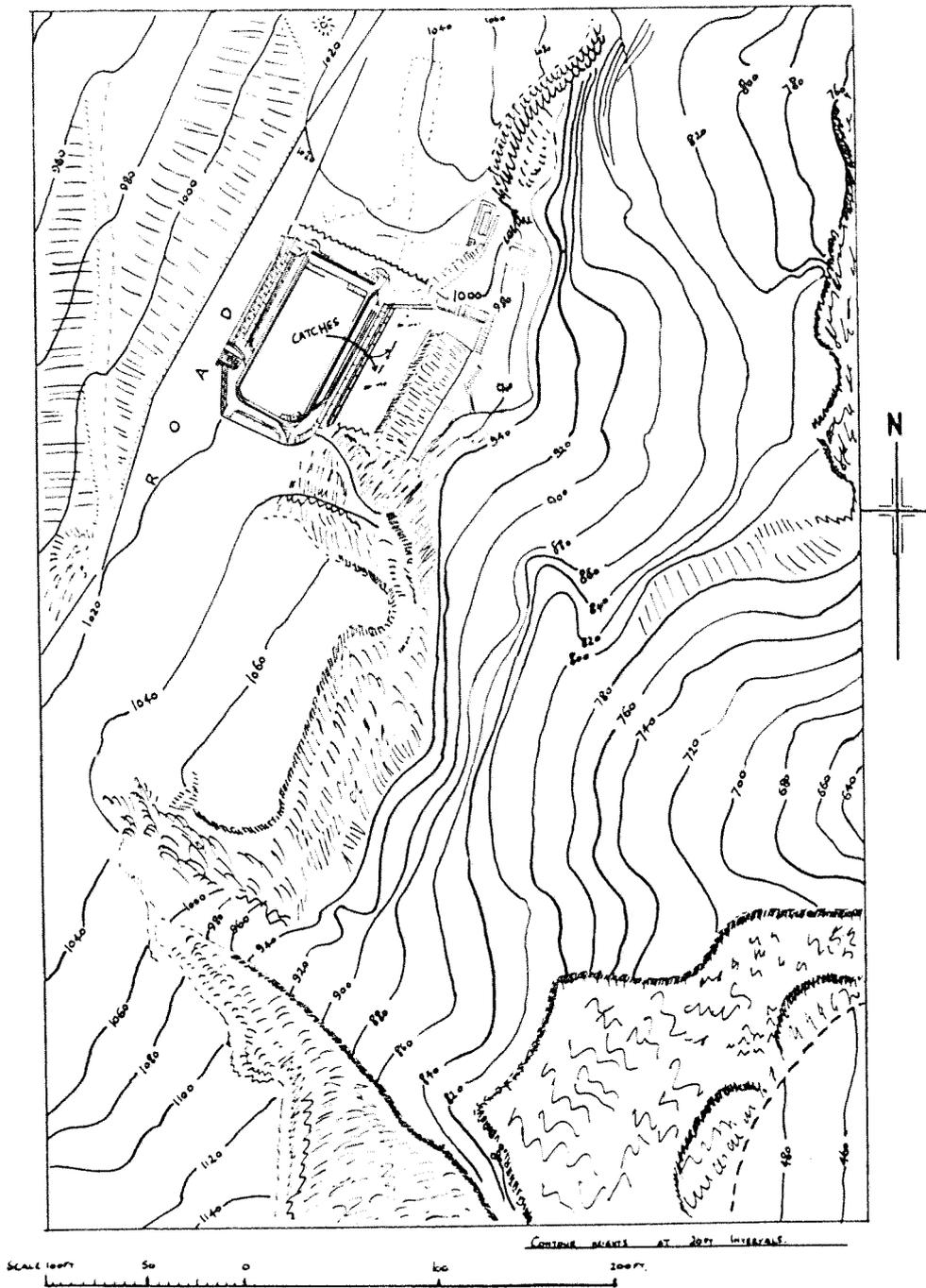
Fig. 2

Middle Hill Gap, showing location of catches

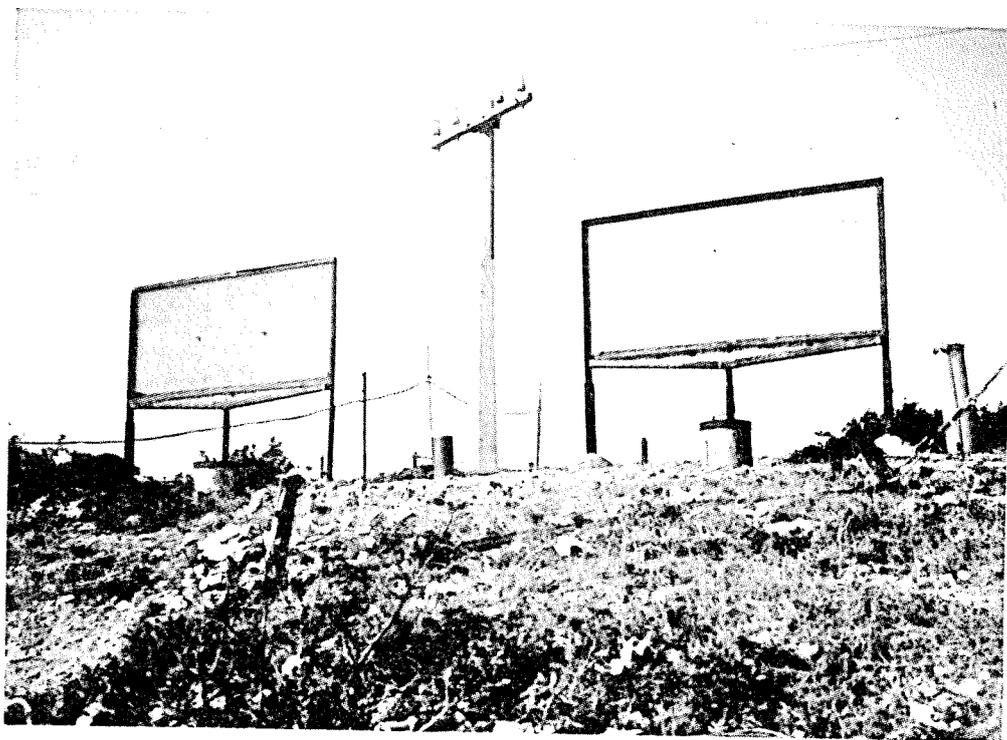*Plate 2*   COLLECTION OF WATER FROM CLOUD

Fig. 3

The two catches in position, with check gauge between; view from the east
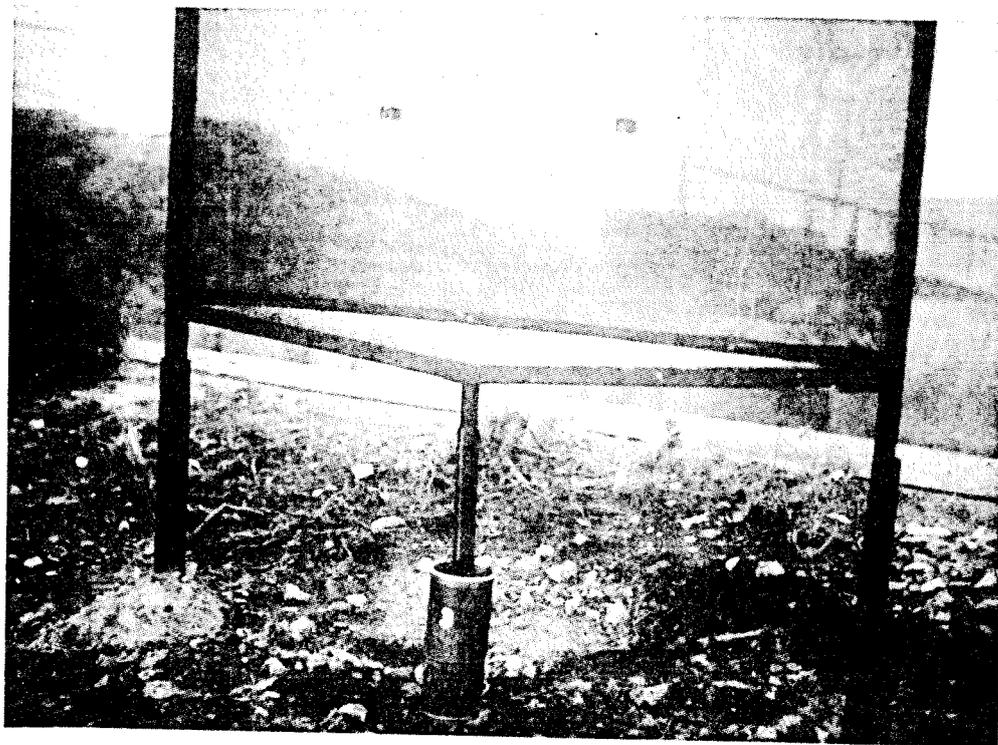

Fig. 4

Closer view of double mesh gauge in thin levanter conditions, slow
collection taking place

TABLE I

(a) CLOUD AND RAIN COLLECTIONS AT MIDDLE HILL, 11TH JULY 1957 TO 28TH FEBRUARY 1958

Month	Catch from cloud (unassociated with rain)				Catch from rain (in some cases with cloud)			
	Catch		Rain during catch		Catch		Total rain	
	Single, gal.	Double, gal.	M. Hill, mm.	N. Front, mm.	Single, gal.	Double, gal.	M. Hill, mm.	N. Front, mm.
July	>12·56	>14·90	—	—	—	—	—	—
Aug.	>20·92	>19·86	0·3	—	—	—	0·3	—
Sept.	3·41	5·12	Tr	—	2·51	3·65	30·8	37·8
Oct.	15·30	14·84	0·5	1·6	5·54	3·93	46·7	42·9
Nov.	2·94	4·46	Tr	0·1	24·51	>30·62	170·2	176·1
Dec.	—	—	—	—	6·50	9·12	150·2	158·4
Jan.	1·45	1·45	1·8	—	28·36	>31·83	61·3	50·6
Feb.	1·67	1·41	Tr	0·1	2·26	2·99	12·8	8·9

(b) ESTIMATED CATCHES 1ST JULY 1957 TO 28TH FEBRUARY 1958 ALLOWING FOR MISSING RECORDS, ETC.

Month	Catch due to cloud		Catch due to rain	
	Single, gal.	Double, gal.	Single, gal.	Double, gal.
July	26·0	30·0	—	—
Aug.	26·0	25·0	—	—
Sept.	3·4	5·1	2·5	3·7
Oct.	15·3	14·8	5·5	3·9
Nov.	6·5	9·5	23·7	30·8
Dec.	0·5	1·0	18·1	24·5
Jan.	22·5	27·6	7·3	8·7
Feb.	2·3	2·2	1·6	2·2

The highest rate of collection in the summer months was 0·87 gal. in one hour with the double mesh, and 1·54 gal. in two hours with the single in mid-August; this occurred late at night with a cloud base of 400 ft. (i.e. cloud base 600 ft. below the frames) with a wind of about 15 knots. It is very probable that higher rates would have been measured during the period had overflow not occurred.

The screens were blown down in an easterly gale on 23rd November. The wind speed at Middle Hill was not known, but anemometer gusts up to 43 knots at North Front, and 76 knots at Rock Gun were observed. The screens were re-erected on 28th, during which time 20 mm. had been collected in the check gauge at Middle Hill.

A more serious loss of record occurred on 11th December when the screens, which had not been strengthened, blew down again, and could not be replaced until 20th.

January proved the most interesting month during the experiment, with prolonged moderate rain (27th to 29th) accompanied by very low, dense levanter cloud. There was a little loss of record due to overflow early in this period, and for the remainder, three-hourly measurements were made. The maximum rate of collection was
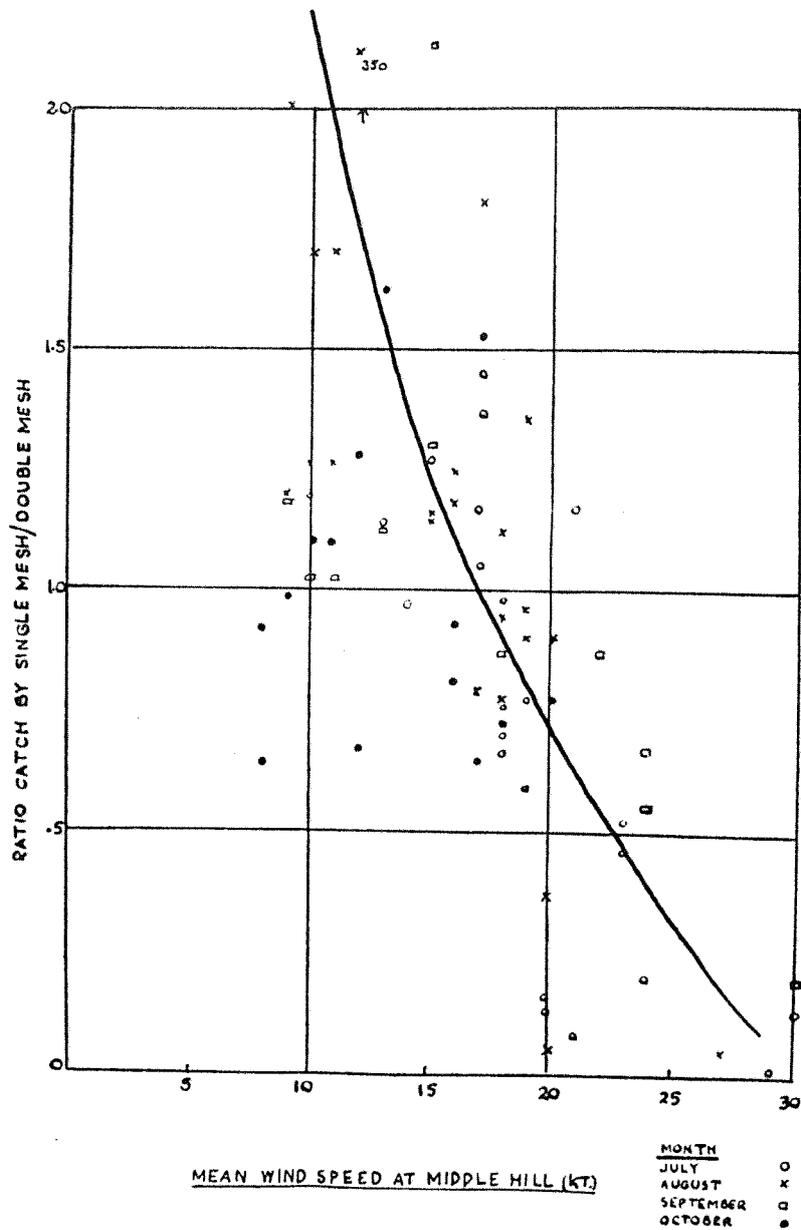
Fig. 5
Relative efficiency of catch with different wind speeds

4·26 gal. in three hours, of which only about 0·8 gal. would corre-spond to rain catch, bearing in mind a surface wind of 13 to 15 knots, and a collection of only 6·1 mm. in the check gauge. Clearly this was no normal January, but it is typical of the kind of phenomenon experienced in many years. In November 1955, for example, almost 20 in. of rain fell in six days in levanter conditions with extensive low cloud, which would almost certainly represent a considerably greater yield.

RELATIONSHIP BETWEEN WIND STRENGTH AND CLOUD YIELD FOR THE TWO FRAMES

Fig. 5 shows a plot of the ratio of the yield from the single to that in the double meshed frame against the estimated wind speed at Middle Hill during the period of catch. The summer months July to October were taken for this purpose, with occasions of overflow or light collection disregarded. Acceptable conditions were defined as those either with a minimum catch of 0·10 gal. in each gauge over a particular period, or with at least 0·20 gal. in one, though less than 0·10 gal. in the other.

It is seen that both frames are about equally efficient with wind speeds of about 17 knots, though the spread of points is considerable. The single-meshed frame is obviously the better with wind speeds of 12 knots and below, whereas there is a far richer yield of water with the double-meshed frame with a wind speed of over 20 knots; indeed, the single-mesh catch was negligible with winds stronger than 25 knots. These differences are due to better penetration through the single mesh in light winds, and to "drop shake-off" in strong winds.

The wide spread of readings is probably due to variation in gustiness and turbulence, and to the difficulty of making satisfactory estimates of the mean wind speed at Middle Hill on all occasions. Comparative use had to be made of North Front and Rock Gun data in many cases.

RELATIONSHIP BETWEEN WIND AND RAIN YIELD

Frame catch with rain was of secondary importance, so little attempt was made to establish a close relationship. Approximately, it was found that 1 mm. of rain yielded about 0·12 gal. of water with either mesh, with variations in the range 0·06 to 0·16 gal. Catches appreciably higher than 0·16 gal. were almost always the result of cloud contribution. In comparison, a solid horizontal catchment, of area 16 sq. ft., would intercept 0·33 gal., of which 0·27 gal. could be collected (allowing for the 80 per cent efficiency of collection experienced with metallic sheets).

A tendency existed towards heavier yields with stronger winds, though this was not as marked as expected. Catch was usually rather higher with the double than with the single mesh. The period of the experiment was rather dry, with 475 mm. of rain at North Front, compared with the long-term average of 604 mm. The Middle Hill rainfall was 472 mm.

EXPECTATION OF CATCH BASED ON RESULTS OVER PERIOD OF TRIAL

Variation was too great for a satisfactory estimate to be made of the average expectation of cloud catch for individual months, though a fair estimate can be made of probable rain yield, using average rainfall data. Table II gives the monthly collections over the period of the experiment, and four-monthly estimated totals over the year, based on

actual amounts for cloud, and on actual and average monthly rain totals for North Front.

TABLE II

(a) MONTHLY CATCH EXPECTATION FROM LEVANTER CLOUD AND RAIN

Month	From cloud			From rain			Average rain, North Front, mm.
	Single, gal.	Double, gal.	Higher, gal.	Single, gal.	Double, gal.	Higher, gal.	
July	26·0	30·0	32·0	—	—	—	0·2
Aug. ..	26·0	25·0	28·0	0·1	0·1	0·2	1·5
Sept... ..	3·4	3·1	5·6	1·9	2·7	3·0	28
Oct.	15·3	14·8	17·4	9·3	6·5	10·0	72
Nov. ..	6·5	9·5	9·6	21·0	27·3	27·8	156
Dec.	0·5	1·0	1·0	14·2	19·2	19·6	124
Jan.	22·5	27·6	31·6	16·2	19·3	20·0	112
Feb.	2·3	2·2	2·5	13·6	18·7	18·7	110

(b) FOUR-MONTHLY CATCH EXPECTATION FROM LEVANTER CLOUD IN RAIN

Month	From cloud			From rain			Average rain, North Front, mm.
	Single, gal.	Double gal.	Higher, gal.	Single, gal.	Double, gal.	Higher, gal.	
July to Oct.	71	75	83	11	9	13	102
Nov. to Feb.	32	40	45	65	84	86	502
Mar. to June	60	65	75	27	34	36	219
Year ..	163	180	203	103	127	135	823

The columns headed "Higher" represent the catch which would have accrued if the higher value of single- or double-mesh yield had been taken on all occasions. The third four-monthly period, spring and early summer, has been taken as complementary to late summer and autumn, with slightly lower cloud yields, as the main levanter period is usually high summer.

In a typical year it is seen that a catch of 16 sq. ft. will produce a yield from rain of well over 100 gal., and from cloud 200 gal.—probably much more, as estimates of loss have been very conservative. More than half the annual catch would occur in the five months May to September, the dry part of the year. The catch in a typical year due to rain on a horizontal catch equal in area to the meshes would be 220 gal. (allowing for 80 per cent efficiency of collection), so with a total yield from cloud and rain very well in excess of this, a meshed frame at Middle Hill is clearly a considerably more efficient collector than a horizontal catchment of the same area.

There should be no question of large-scale catches adversely affecting other supplies. Contribution from a frame anywhere in Gibraltar from the levanter cloud would be completely free, as the cloud in most cases dissipates a mile or two to the west with no precipitation therefrom.

Contribution from rain would be unaffected by an installation at Middle Hill, as there are no water catchments to the east or west of

this point; extensions on the ridge in other areas might make trivial differences in air flow over the ridge, but it is not thought that either this, or the actual water collected by cloud frames could have any noticeable effect on normal catchment yields. There would be no effect on well supplies, which fill by drainage from the Spanish Hills north of Gibraltar.

SUMMARY AND RECOMMENDATIONS

Collection from cloud of at least 7 gal. per sq. ft. of mesh could be expected in a typical summer, with an annual total of 12 gal., and an additional 8 gal. due to rain contribution. A 10,000 sq. ft. catch at Middle Hill would seem quite feasible, representing a yield of 70,000 gal. in summer from cloud, rather less over the rest of the year, and a further 80,000 gal. due to rain. Amounts would probably be appreciably in excess of this, as with a really large collector, the tendency of the wind to flow round, rather than through the meshes, would be much less.

Wind-tunnel research should be made into the best wire dimensions for catch, and the general layout of the most efficient type of collector; it might well emerge that the best solution would be a well-separated double mesh, or possibly a single mesh with a sloped surface behind to collect shake-off. In the light of such experiments, yields could almost certainly be brought far higher than the above estimates, and at least 200,000 gal. should be attainable from a 10,000 sq. ft. frame in summer, particularly as the catch would be standing at a higher level than the pilot scheme, and so more effectively in the cloud layer. This summer catch would correspond to a fall of about 0·5 in. of rain on the catchments in an otherwise often completely rainless period.

If the experiment could be tried at Middle Hill and it proved successful, adoption at other locations on the upper Rock might be made, using catches just to the east of the ridge, and offset slightly from the vertical so as to obtain a more nearly perpendicular air flow through the meshes.

ACKNOWLEDGMENTS

REFERENCES

Nagel, J.P. 1956 *Quart. Journ. Royal Met. Soc.*, vol. 82, p. 452, "Fog precipitation on Table Mountain".
Twomey, S. 1957 *Weather*, vol. 12, p. 120, "Precipitation by Direct Interception of Cloud-water".

APPENDIX
EXPECTATION OF YIELDS FROM MESHED CLOUD CATCHES

The volume of water passing through the framework per unit time in cloud conditions is clearly given by:

Volume of water $= V_c A G$ where the symbols have the significance stated.
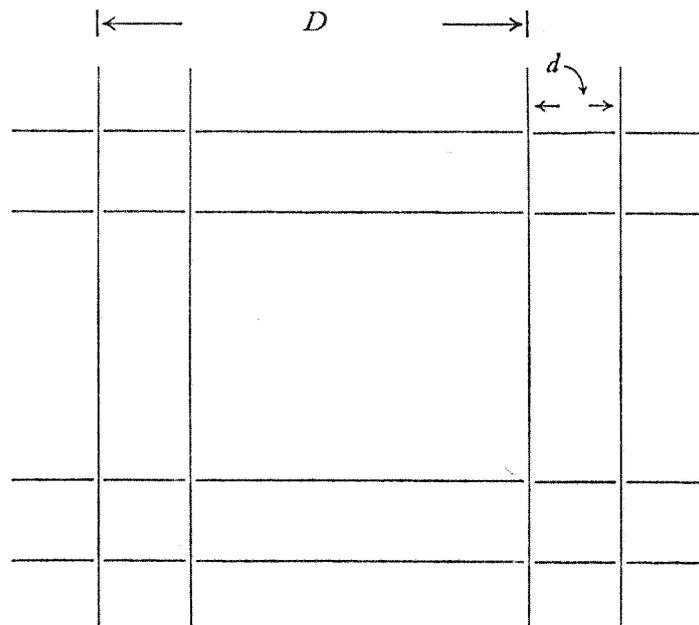
V = Free wind speed at catch level
V_c = Wind speed through catch
A = Area of catch
a = Area of mesh surface within frame
G = Concentration of water droplets
D = Mesh spacing
d = Diameter of wire
d' = Average diameter of water droplets
E = Efficiency of catch; i.e., ratio of water caught to that passing through.

Single Mesh.—The loss of speed of the air through the catch will be approximately proportional to the area of metal within the catch frames, so

$$1 - \frac{V_c}{V} = \frac{a}{A}$$

or

$$V_c = V\left(1 - \frac{a}{A}\right)$$

and volume of water $= \left(1 - \frac{a}{A}\right) V A G$

Now $1 - \dfrac{a}{A}$ = unobstructed area

$$= \left(1 - \frac{d}{D}\right)^2$$

So volume of water $= \left(1 - \dfrac{d}{D}\right)^2 VAG.$

Of this flow, only part will hit the mesh and be collected. Consider a water droplet of diameter d'. Effectively, the wires of the mesh are increased to $(d + 2d')$, as a drop within distance d' from a wire will be caught, so,

Unobstructed area $= 1 - E = \left(1 - \dfrac{d + 2d'}{D}\right)^2$

and $\qquad E = 1 - \left(1 - \dfrac{d + 2d'}{D}\right)^2$

and volume of water caught

$$\left(1 - \frac{d}{D}\right)^2 \left\{ 1 - \left(1 - \frac{d + 2d'}{D}\right)^2 \right\} VAG \quad .. \qquad .. \quad (1)$$

Double Mesh.—If the two collecting surfaces of the mesh are close to each other, the speed of air through the catch is now given by

$$V_c = V\left(1 - \frac{a}{A}\right)^2 = \left(1 - \frac{d}{D}\right)^4.$$

and total flow of water $= \left(1 - \dfrac{d}{D}\right)^4 VAG$

Unobstructed area $= 1 - E = \left(1 - \dfrac{d + 2d'}{D}\right)^4$

and volume of water caught

$$= \left(1 - \frac{d}{D}\right)^4 \left\{ 1 - \left(1 - \frac{d + 2d'}{D}\right)^4 VAG \right\} (2)$$

Of the quantities in these relations, d and D are fixed for particular meshes; d' is small and not critical, and V can be estimated fairly accurately. G has been assessed approximately by considering the forced ascent of moist air, assuming the saturated adiabatic lapse rate to apply above the condensation level. Liquid water so liberated per 100 ft. of lift at Middle Hill should normally vary between 0·14 g. per cu.m. (equivalent to $8·2 \times 10^{-7}$ gal. per cu. ft.) at a mean temperature of 70° F. to just over 0·10 g. per cu. m. at 55° F.

Assuming a temperature of 70° F., a lift of 100 ft., a free wind speed of 10 knots and a drop size of 0·0004 in., with the experimental catches in use ($A = 16$ sq. ft., $D = 0·0625$ in., and $d = 0·011$ in.), the hourly flow of water through the single-meshed frame would be 0·55

gal., of which 0·19 gal. would be caught; corresponding amounts through the double-meshed frame would be 0·38 and 0·21 gal. The potential yield could amount to 2 gal. per hr. with a stronger wind and a cloud base below 500 ft. The maximum actual rate of collection during the experiment was 1·25 gal. in the double mesh in January (excluding the rain element); with a cloud base of 300–400 ft., a wind speed of 15–20 knots, and a temperature of 55–60° F., the potential catch was 1·8 gal., and the efficiency of collection 70 per cent. The highest summer rate recorded was 0·87 gal. with an efficiency of just over 60 per cent.

Optimum dimensions for meshes.—For the single-meshed frame, putting $x = d/D$, and ignoring d', equation (1) becomes

$$\text{Volume} = (1-x)^2\{1-(1-x)^2\} \quad \cdots \quad \cdots \quad \cdots \quad \cdots \quad (3)$$

and the optimum ratio for x is given by $\dfrac{d}{dx}(\text{Vol}) = 0$

whence $x = 0.29$ as the physical conditions of the screen require $1 > x > 0$. That is, the ratio of the diameter of the meshes constituting the frame to their spacing should be 0·29, and had the Middle Hill experiment been conducted with wire of unchanged mesh spacing, but of a diameter 0·018 in., collection would have been approximately 10 per cent higher.

For the double-meshed frame, equation (2) becomes

$$\text{Volume} = (1-x)^4\{1-(1-x)^4\} \quad \cdots \quad (4)$$

for which the only value of x to satisfy $1 > x > 0$ proves to be 0·16. The mosquito netting used, with a ratio just under 0·18 is close to this value, and so was very suitable for the purpose.

It is clear from equations (1) and (2) that the efficiency of a mesh increases as it becomes finer. Wind-tunnel experience would be essential to determine the finest mesh which would be strong enough to withstand the high gusty winds experienced on the top of the Rock. There is no advantage in using a close double-meshed type of catch, provided the drop shake-off problem can be solved.

THE PAPER
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