MET O 3 TECHNICAL NOTE NO 15

The Incidence of Wind-driven Rain on Walls in the United Kingdom

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Met.O.3. Technical Note No.15.

The incidence of wind-driven rain on walls in the United Kingdom. By CATON,P.G.F.

London,Met.Off.,Met.O.3.Tech.Note No.15, 1982,31cm.Pp.37,7 pls.9 Refs.

An unofficial document - restriction on first page to be observed.

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THE INCIDENCE OF WIND-DRIVEN RAIN ON WALLS IN THE UNITED KINGDOM

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Introduction

The amount of rain incident on a wall of a building depends on the size spectrum of the raindrops, the speed and direction of the wind in the area (ie the wind undisturbed by the nearest buildings) and the peculiarities of the airflow around the building itself. Using a relation between the size spectrum of the raindrops and the rainfall rate on a horizontal surface (Laws and Parsons, 1943), Lacy (1965) has shown that the rate of impact of rain on a vertical wall is approximately proportional to the product of the rainfall rate and the component of wind speed normal to the wall; to a first approximation therefore, ignoring the deflection of raindrops around the building, the product of rainfall rate and wind speed may be taken as a measure of the amount of driving rain.

The first attempt to assess the geographical variation of wind-driven rain over the United Kingdom was made by Lacy and Shellard (1962). At that time there was inadequate information about wind during periods of rain, so the map constructed used products of annual average rainfall and annual average wind speed, and took no account of wind direction.

An up-dated version of the map is contained in the BRE Report: Driving rain index (Lacy 1976), which also includes an analysis of annual mean driving rain attributable to winds from various directions; this latter was based on summation of products of hourly rainfall and coincident wind speed for each of the chosen directions, using information from selected stations for the 10 year period 1957-66. Not surprisingly, the all-direction totals of driving rain derived from the hourly products do not coincide with the values based on the product of annual averages, although the general features of the geographical variation are the same. The ratios of the "hourly" to the "annual" indices at individual stations are mostly between 0.95 and 1.30, but at certain coastal stations lie between 1.35 and 1.50. Values of this ratio greater than unity clearly indicate that, during periods of rain, the wind speed tends to exceed the average value. Moreover, values of the ratio as high as 1.50 indicate that in certain areas, the Lacy (1976) index significantly underestimates the annual average total of driving rain. The first aim of the present investigation was therefore to prepare improved maps of annual average driving rain based on hourly products and taking account of wind direction so that the effect on walls with different orientations may be assessed.

As indicated above, the earlier work on driving rain tacitly assumed that to a first approximation the effects of buildings on the airflow around them could be ignored. The second objective of this work was to review the information now available about the amount of rain which actually impinges on walls under different wind speeds (ie to assess the collection efficiency of a wall). Adjustments were also made in the light of recent knowledge about the reduction of wind speed from the open country value caused within an urban area by the congregation of buildings.

There is a growing realisation that, when considering the penetration of rain through brickwork, the important factor is the amount of driving rain over a period of hours or days rather than the annual average total. The third aspect of this work was thus directed towards the development of a method of analysis that would yield information about spells of driving rain. The approach here was to determine the spell amounts likely to be exceeded on average once per year and once per three years.

Finally account has been taken of the properties of the brickwork itself. The current trend to fill the cavity between the outer and inner walls of buildings with an insulating material in order to reduce heat losses has stimulated interest in assessment of the amounts of driving rain incident on walls, because of the importance of ensuring that the risk of rain penetration does not rise to an unacceptable level. The foam-type insulating materials in common use are impervious to water but, should minute cracks develop in the foam, paths may be provided for moisture which has penetrated the outer wall to pass to the inner wall. Rain penetration of the outer wall normally occurs through cracks between brick and mortar but the probability of rain impinging on the cracks is considerably increased when the bricks are saturated and the excess water is running down the outer surface. The assessment of the frequency of saturation of the outer wall is therefore significant and involves consideration not only of the amount of rain being driven onto the wall, with an allowance for evaporation between periods of rain, but also of the properties of particular types of brick.

Maps of annual average driving rain

Assuming that there is no deflection of raindrops due to local modification of the airflow by buildings, the amount of driving rain that would be incident on walls facing 12 different directions (ie at intervals of 30 degrees) may be calculated from data observed at meteorological stations. Annual totals were obtained by summing the hourly products $RV\cos\theta$, where R is the hourly rainfall amount (measured on a horizontal surface), V is the simultaneous hourly mean wind speed, and θ is the angle between the hourly mean wind direction and the normal to the wall concerned. Average values were then derived from the annual totals during the 15 years 1959-73.

Hourly wind and rainfall data are available on magnetic tape for 20 stations, and the calculations of driving rain at these sites presented few problems. In order to ensure that the data were all fully comparable, a refinement was introduced whereby, using a method described in Climatological Memorandum No 79 (Caton 1976), measured wind speeds were standardized to a common measurement height and terrain roughness; in other words, the values of V used in the calculations of driving rain were those referring to a height of 10 m above open level country, ie terrain of a roughness characterised by a ratio of hourly maximum gust to hourly mean speed (gust ratio) of 1.60.

Hourly wind data are also available on magnetic tape for more than 30 additional stations; the corresponding hourly rainfall amounts have been written to tape only for a few recent years, but 3-hourly reports of present weather have been keyed for the years 1959-73 and these indicate ranges of intensity of precipitation. A method was therefore devised to make use of this information and thus permit calculations of driving rain for these additional stations. To provide a basis for the method, the data for the 20 stations with hourly reports were divided into groups according to season and wind direction, and the average hourly rain amount corresponding to each present weather code figure, season and wind direction was calculated. These average rain amounts were then assigned to the 3-hourly present weather reports and used to calculate total annual rainfall and also, when combined with hourly wind speeds, annual totals of driving rain; these latter were then multiplied by a calibration factor equal to the ratio of the true to the calculated annual rainfall, and the results showed very good agreement with the true driving rain totals. An important point that emerged from these calculations was that the variations across the country in hourly rainfall amounts corresponding to particular present weather code figures were slight and were no more than would be expected from topographical considerations. The procedure of calculating annual rainfall and annual driving rain was therefore repeated for those stations which report only at 3-hourly intervals, by attaching to each weather code figure three times the average hourly rain amount calculated for a nearby, topographically similar, hourly station. Clearly, a slight uncertainty is introduced by this procedure; but the method does take account of variations in precipitation frequency (because these are reflected by corresponding variations in the frequency of occurrence of particular weather code figures) and the uncertainty is minimized by the use of the calibration factor based on calculated and actual rainfall totals. Moreover, confidence in the method was increased by the fact that very similar results were obtained for a 3-hourly station by using rain amounts calculated for two different hourly stations. Thus estimates for St Mawgan (North Cornwall) were made using hourly rain amounts for Plymouth (South Devon) and Aberporth (West Wales); the results for each wall orientation were within about 20% and there was no difficulty in assigning appropriate values of driving rain.

Having calculated the annual average driving rain totals for each of 12 wall orientations at over 50 meteorological stations, there remained the problem of interpolating between these discrete data points. Clearly, the changes between data points are not linear, and it was decided that the best method of interpolation was to assume that the spatial distribution is proportional to the product of annual average rainfall (which is known in great detail from a network of about 7000 raingauges) and an appropriate wind speed. A similar assumption was made by Lacy when deriving his 1976 Index, and the procedure adopted differs only in the choice of wind parameter. Maps of wind speed exceeded for various percentages of time have been prepared, and the most appropriate of these is probably the 25 percentile map which indicates wind speeds approximately 1.4 times the annual average wind speed. Unfortunately, that particular map was not available at the time this analysis was undertaken, so the 10 percentile map (indicating winds approximately 1.8 times the annual average speed) was used. The point is however of no consequence because variations of rainfall account for most ot the variance in the driving rain product, and interpolation is necessary only over relatively small areas surrounding the data points; moreover, the patterns of the 50, 25 and 10 percentile maps are very similar, and when interpolating it is only the relative, and not the absolute, values which are used. It is therefore most unlikely that any significant errors have occurred during the interpolation process. The 10 percentile wind speed map showed values appropriate to altitudes between 0 and 70 m, and for locations at altitudes above 70 m the wind speed was increased as described in Climatological Memorandum No 79.

Variations in annual average driving rain between the data points arise because of (a) variations of rainfall and wind speed and (b) changes in the directional distribution of rain-bearing winds. To highlight the directional effects, driving rain values were standardized to a common level of annual rainfall and wind speed, and separate maps were prepared for each 30 degree wall orientation. These showed clearly both the gradual changes to be expected across the country and the superimposed effects at individual stations due to shelter by high ground; the sheltering effects were naturally different for different wall orientations. It was clear that the form of presentation adopted must take these effects into account; yet at the same time, the high cost of map reproduction necessitated a solution which enabled information for all wall orientations to be displayed on the same map.

From general topographical considerations, and in the light of the available meteorological stations, the United Kingdom was first divided into 27 Regions, with each of which is associated a key town or airport located close to a meteorological station. Driving rain amounts for the key town or airport are shown on the maps in the form of a large "compass", the wall orientation being identified by the outward normal. Regional boundaries are shown by broken double lines. Geographical variations within each Region are shown by a series of lines, between each of which appears a geographical correction factor that applies to the driving rain amount for <u>all</u> wall orientations.

In order to take account of the changes in the directional distribution of driving rain across a Region, it was necessary to divide many of the Regions into sub-Regions. The boundaries of these are shown by broken single lines. When delineating these (and also to an extent the Regional boundaries) the "standardized" maps referred to above were used as a guide. Since the factors controlling the directional variations are mainly topographical, the boundaries frequently lay along natural watersheds, thus conveniently avoiding large towns. However, a further important consideration was to minimize the discontinuities across a boundary and a number of sub-Regions were introduced on this account. Sub-Regional corrections are shown on the maps in the form of a small "compass" on which are marked appropriate figures for each wall orientation.

Being the product of rainfall amount and wind speed, driving rain amounts are properly expressed in m^2/s. In these units, the annual average driving rain varies over the country from less than 1 m^2/s to more than 10 m^2/s. Differences of less than 1 m^2/s may be significant, and the unit is not very convenient for mapping purposes. Moreover, when applying correction factors, it is much simpler to add than to multiply. It was therefore decided to express all driving rain amounts and corrections on the maps in logarithmic units, so that corrections may be made by simple addition. The scale chosen put 6 units equal to 1 m^2/s and each additional 6 units corresponds to a multiplying factor of two; thus 6 units = 1.00 m^2/s, 7 units = 1.12 m^2/s, 8 units = 1.26 m^2/s, 9 units = 1.41 m^2/s, 12 units = 2.00 m^2/s, 15 units = 2.82 m^2/s, 18 units = 4.00 m^2/s, 20 units = 5.00 m^2/s, and 24 units 8.00 m^2/s.

As examples of the use of the maps, two points X and Y have been marked on map 1. Point X lies within the Exeter region where there are no sub-regions. A south-facing wall at Exeter would experience 17 units of driving rain, and the geographical correction for X is + 1. Since there is no sub-regional correction, the required figure for a south-facing wall at X is 18 units. Similarly, point Y lies in the Plymouth region. An east-facing wall at Plymouth would experience 12 units of driving rain, and the geographical correction for point Y is + 2; but point Y lies in a sub-region for which the east-facing index is 11 units. The required figure for an east-facing wall at Y is therefore 13 units.

As mentioned above, one of the considerations in delineating the boundaries was to minimize the discontinuities across them. The intention (not always achieved) was that for all wall orientations, the change in driving rain across a boundary should not exceed 2 units. Where the change across a boundary is 2 units, the error that arises near the boundary from strict interpretation of the map compared with the smooth transition that must physically exist is a maximum of 1 unit. This "error of presentation" may however be reduced by interpolation. Interpolation may similarly be used to determine driving rain values for wall orientations between those shown on the maps at 30 degree intervals; here also, the errors may be reduced to 1 unit or less. It may be noted that actual amounts of driving rain vary considerably from year to year (see Appendix 1); annual average values determined from 15 years of data have a standard error of around 0.6 unit.

The input of driving rain to brick walls

There have been a number of experimental studies of driving rain using special gauges set into the walls of buildings. Lacy (1965) has summarized the results prior to that date. Svendsen (1954) reported that over a three month period at Trondheim, Norway, a wall gauge 2 m above ground collected 60% of the amount in a free-standing driving rain gauge facing similar direction. Basart (1946) reported measurements in the Netherlands by Nell, 3.5 m above ground, suggesting that the collection efficiency of a wall decreased sharply for wind speeds below about 5 m/s (value at 3.5 m estimated from measurements 14.5 m above ground). A gauge on the 9th floor of a 10-storey block of flats situated on locally high ground in the suburbs of Glasgow recorded no driving rain when the component of wind speed normal to the wall measured 10 m above ground at the nearby Renfrew Airport was less than 1.5 m/s.

Lacy (1977) has reported measurements on houses on an exposed hill slope at Tredegar, South Wales, during the winter 1967-68. These comprise daily totals of driving rain in a wall gauge facing west approximately 1 m above garden level and in a gauge in the garden facing west 1.4 m above ground; measurements were also obtained from a wall gauge facing south 2 m above ground. The daily mean wind speed at the site was available from a cup contact anemometer, 2.8 m above ground. In Figure 1 the collection efficiency, defined as the ratio of the daily total of driving rain in the wall and garden gauges facing west, is plotted against the component of mean wind speed normal to the wall; [the mean wind direction during the period of rain was estimated by comparing the driving rain amounts on the west and south facing walls and also by inspection of meteorological charts].

For normal components of mean wind speed $\geq$ 5.0 m/s the plotted points form 2 groups, one with collection efficiency 0.50 and above, one with collection efficiency below 0.40; 6 of 7 occasions in the low collection efficiency group were associated with average rates of rainfall less than 1 mm/hr, whilst 10 of 11 occasions in the high collection efficiency group were associated with average rates of rainfall greater than 1 mm/hr. Rainfall at the higher rate may be expected to have a higher proportion of medium and large drops which are more likely than small drops to impinge upon the wall. The occasions in the high collection efficiency group account for 74% of the total driving rain measured by the garden gauge, and the mean collection efficiency of the wall gauge for these occasions was 0.59.

For normal components of wind speed $<$ 5.0 m/s there was again a broad separation of points according to average rate of rainfall. The mean value of collection efficiency of the wall gauge was 0.40 for occasions with average rate of rainfall $>$ 1 mm/hr and normal component of wind speed in the range 3.1-4.9 m/s; and as the normal component of wind speed decreased further, the collection efficiency become markedly less.

Based on these various studies, the collection efficiency of a vertical wall was formulated as follows:-

For $V\cos\theta \leq Y$ m/s, the collection efficiency = 0

For $Y < V\cos\theta < X$ m/s, the collection efficiency

$= K(V\cos\theta - Y)$

For $V\cos\theta \geq X$ m/s the collection efficiency = $K(X-Y)$

For most purposes X was set = 5 m/s, Y = 2 m/s, K = 0.20, implying a collection efficiency in moderate wind speeds equal to 0.60; this collection efficiency model is represented on Figure 1 by a full line. Alternative versions were X = 5 m/s, Y = 1 m/s, K = 0.15 to test the sensitivity of the results to a change of Y (where the uncertainty is probably greatest), and X = 5 m/s, Y = 2 m/s, K = 0.333 (collection efficiency in moderate wind speeds 1.00) to investigate driving rain amounts near the edges of walls.

The collection efficiency model can be applied using wind speeds observed 10 m above ground at a standard meteorological site. Alternatively, for an urban site, an allowance can be made for the reduction of the general wind speed by buildings. For example, it has been found (Buller, 1976) that at heights 1.5-7 m above ground in a suburban environment wind speeds are roughly one-half those measured at 10 m at a standard open site. When applying the model to an urban site, the normal component of wind speed ($V\cos\theta$) would be replaced by $pV\cos\theta$, when p is the ratio of the wind speed at the wall site to that at the meteorological site.

Evaluation of driving rain amounts in spells

The significant factor in many rain penetration problems is the amount of driving rain in a period of hours or days. When considering rain penetration through brickwork, the relevant period has no predetermined duration; it continues so long as the input of new driving rain exceeds the output by evaporation.

In order to assess the input of driving rain during a spell, a computer program was prepared which recorded the occasions when the running total over 96 hours of driving rain, formulated as described in the preceding sections, exceeded a specified threshold value for each wall orientation. For each such occasion a new accumulation was started for the wall orientation concerned and if the threshold was again reached within 96 hours the details were recorded; during a period of considerable driving rain the selected threshold was often reached every few hours or even every hour. Using a criterion for continuation of the spell (see below) the total spell amount and the duration (approximated by the interval between the first and last threshold occurrences) were derived; an addition was made to the amount equal to one-quarter of the threshold value to take account of the variable amount accumulated after the final threshold occurrence. The limit of 96 hours referred to above was sufficient to bridge the gap between succeeding storms in a weather sequence and tests showed that its precise value did not materially affect the spell amounts.

An adjustment was made for evaporation during the intervals between rain. Experimental data reported by Lacy (1977) indicate that evaporation is relatively rapid during the 12 hours following rain, but subsequently the rate slowly decreases. For dry intervals within a rain spell the evaporation adjustment was simply formulated as an average value equivalent to an input of 0.005 m^2/s per day of spell duration after one day; the one day exclusion was to avoid application of an evaporation adjustment during those periods of rain which were continuous for about a day and which were particularly significant in determining the spell amounts exceeded on average once per year or once per 3 years. The adjustment for evaporation was constant during changes both of collection efficiency and of the ratio of the wind speed at the wall site to that at the meteorological site.

The criterion for continuation of a spell was that each succeeding input should exceed 0.0002 m^2/s for each hour of the interval that had clapsed since the preceding input; where the interval was appreciable a pair or group of succeeding inputs could be added together before application of the criterion. The link between the criterion and the adjustment for evaporation ensures that the net spell amount provides a measure of the net driving rain during the period that the input exceeds the output through evaporation.

The analyses of spell amounts were made for a selection of the values of p (the ratio of the wind speed at the wall site to that at the meteorological site) 1.00, 0.70, 0.50, 0.40 and 0.30 for Plymouth, London (Heathrow), Leeming/Dishforth (near Northallerton, North Yorkshire) and Prestwick. The analyses yielded the numbers of spells with net spell amount exceeding various thresholds over the 15 year period 1959-73, and from these figures net spell amounts exceeded on average once per year and once per three years were obtained by graphical interpolation. These detailed analyses were supplemented by the results of earlier work for 14 stations in which the collection efficiency for driving rain was not varied with wind speed; this earlier work had nevertheless revealed a pattern of variation across the country to which the more precise analyses for Plymouth, Heathrow etc., conformed.

Since the analyses were insufficient to provide a direct basis for maps covering the United Kingdom, the results were related to the annual average driving rain. The ratio of the spell amount exceeded with given frequency to the annual average driving rain on the wall concerned was found to be a function of the wall orientation and for given orientation there was also a geographical variation between western and eastern districts of the United Kingdom. The variations reflect the frequency distribution of driving rain amounts in an average year; for walls facing north and east there are a moderate number of occurrences of driving rain including a few which are of large amount, whilst for walls facing south and west there are many occurrences but only a small proportion are of large amount.

Table 1 shows for the various regions and wall orientations the addition on a logarithmic scale to convert the values of annual average driving rain to spell amounts exceeded on average once per three years at the meteorological site [p = 1.0, c' (collection efficiency at moderate windspeed) = 0.6]. The spell amounts are on a scale such that a figure of 16 units corresponds to a spell amount of 0.1 m^2/s and each additional 6 units corresponds to a multiplying factor of two. In each region the additions are highest for walls facing 360, 030 and 060 degrees, and the range of values between orientations is greater in eastern districts of England and Scotland than in western districts.

The additions for spell amounts exceeded on average once per year (p = 1.0, c' = 0.6) are 5 units lower than those in Table 1 for walls facing 360, 030 and 060 degrees, and 4 units lower than those in Table 1 for walls facing 090 through 180 to 330 degrees.

The additions for spell amounts appropriate to the edges of walls (p = 1.0, c' = 1.0) are 5 units higher than the corresponding values for the main area of wall; (the inputs are increased in the ratio 1.0/0.6, equivalent to 4.4 units, and the additional 0.6 units or thereabouts arises because evaporation within the spell is a smaller proportion of the input and also because in isolated cases the spell duration is increased).

Table 2 shows the additions (negative) on a logarithmic scale to convert the spell amounts exceeded on average once per 3 years at the meteorological site (p = 1.0, c' = 0.6) to the corresponding spell amount at a suburban site with wind speeds one-half those at the meteorological site (p = 0.5, c' = 0.6). The spell amounts remain on the scale described above. In each region the subtractions are least for walls facing between 180 and 270 degrees and for these walls are lower in western than in eastern districts. The subtraction is essentially a function of the relevant wind strength; when the winds are strong, a reduction to one-half speed is more likely to keep the collection efficiency at value 0.6. The subtractions corresponding to a reduction of p are unchanged for a collection efficiency of 1.0 or for spell amounts exceeded on average once per year.

Maps of spell amount exceeded on average once per 3 years at a suburban site

The combination of the results in Tables 1 and 2 permits conversion of the maps of annual average driving rain to maps of spell amount exceeded on average once per 3 years at a suburban site having wind speeds one-half those at the meteorological site ($p = 0.5$, $c' = 0.6$). For the sub-regions surrounding the key towns in Tables 1 and 2 the conversion is exact. However, since there are changes across regional boundaries in Tables 1 and 2, additional to the changes in annual average driving rain, discontinuities of 3 and sometime 4 units appeared across some boundaries. The process described for annual average driving rain of standardizing values to a common level of annual rainfall and windspeed was therefore repeated, and sub-regional corrections were adjusted, where necessary, to ensure the smoothest possible transition between regional centres.

The addition to the map values to correspond to conditions at the edges of walls ($c' = 1.00$) is + 5 units. The addition to correspond to spell amounts exceeded once per year is – 5 units for walls facing 360, 030 and 060 degrees, and – 4 units for the remaining orientations. The change in map values resulting from use of the alternative collection efficiency function $X = 5$ m/s $Y = 1$ m/s, $K = 0.15$ is about + 0.5 unit.

The additions to the map values to correspond to alternative values of p are shown in Table 3. A value of $p = 0.9$ may be appropriate to a 2 storey building directly facing open country; $p = 0.7$ to the upper portion of a 3 storey building in a suburban environment; $p = 0.5$ to a 1 or 2 storey building in a suburban environment; and $p = 0.4$ or $p = 0.3$ to a low-rise building surrounded by higher buildings in a city centre.

A feature of the maps for eastern districts of England and Scotland is the magnitude of spells on walls facing north and northeast. For example, at Northallerton (North Yorkshire, Map No 2) the spell amounts on walls facing 360, 030 and 060 degrees significantly exceed those on walls facing south; this situation is the reverse of that for annual average driving rain (Map No 3). Over East Anglia (Map No 4) the spell amounts on walls facing 360, 030 and 060 degrees are about equal to those on walls facing south and southwest, and in London (Map No 5) the directional variation of spell amount shows a secondary maximum at 030 and 060 degrees. At Edinburgh the annual average driving rain (Map No 6) on walls facing 060 and 090 degrees is slightly below that on walls facing 210 and 240 degrees, but the spell amounts (Map No 7) are 3 units (40 per cent) higher at 060 degrees than at 210/240 degrees.

The moisture content in walls

The final factor to be considered when assessing the frequency of saturation of a brick wall is the moisture content of the wall at the commencement of a spell of driving rain. This initial moisture content reduces the capacity of the brickwork to absorb wind-driven rain.

A computer program was prepared to investigate the moisture content of walls and in particular the occurrences of saturation. The input of driving rain each hour was formulated as described earlier. The unit of input corresponding to 1 mm of rainfall on a horizontal surface, a wind speed of 1 m/sec normal to the wall and a collection efficiency equal to 1.00 (ie 0.001 m^2/s) represents an addition of approximately 0.2 kg/m^2 to the moisture content in the wall (Lacy, 1965).

When the moisture content reached a threshold corresponding to saturation of the wall (27 kg/m^2 ≡ 135 units of driving rain) the programme held the moisture content at this saturation level and printed out the amount of the excess driving rain while rain continued to reach the wall concerned.

To provide a representative sample of moisture states, the moisture content was printed out for 00 h on 1 November, 1 December, 1 January, 1 February and 1 March each winter. For walls facing south and west, severe spells of driving rain occur predominantly during the winter season, and to obtain a true picture of the capacity of brickwork to absorb such spells it is appropriate to consider samples of moisture content during the winter months. For walls facing north and east, spells of driving rain occur more uniformly through the year, and samples of moisture content during the winter months are representative of the whole year.

Between rainstorms, the moisture content of the wall decreased due to evaporation. The rate of evaporation from brickwork depends primarily on the resistance to the flow of water through the pores of the material rather than on the conditions of airflow and humidity at the surface. Experimental data are reported by Lacy (1977). Evaporation is relatively rapid during the 12 hours following rain, but subsequently the rate decreases gradually to a much lower level. During the first two days after rain the rates for Fletton and London Stock bricks are similar; however after 8 days the rate for Stocks is about twice that for Flettons. There appears to be a minimum moisture content, when evaporation effectively ceases; this minimum moisture content is lower for Stocks than for Flettons. The values of the evaporation function used in the computer model were as follows:-

Hours following rain	1-5	6-10	11-50	51-100	101-200	201-400	401-	Minimum moisture content
	Units per hour (1 unit ≡ 0.2 kg/m^2)							
Flettons	0.4	0.3	0.2	0.15	0.10	0.05	0.02	20 units
London Stocks	0.4	0.3	0.2	0.2	0.15	0.10	0.04	10 units

A difficulty experienced with the evaporation function was that, initially, each small amount of driving rain triggered a new start to the evaporation function, resulting in excessive drying. It is reasonable to expect that small amounts of wind-driven rain will evaporate quickly, but not that they should leave the brickwork drier than it would have been had there been no fresh input of driving rain. It was decided therefore to ignore inputs of driving rain below a minimum value. If the input, totalled over consecutive hours of new rain was less than Z units, the input was not accumulated and evaporation continued at the existing rate; when the input over consecutive hours exceeded Z units, the whole new input was accumulated and a new evaporation function was started. Experiments were conducted using 4 values of Z; of these the middle two, 2.5 and 4.5 units, gave similar and what seemed the most sensible results. Subsequently, following numerical study of the behaviour of the model following inputs of various sizes at various intervals, it was decided to standardize on Z = 3.5 units.

The program was run for values of p (the ratio of the wind speed at the wall site to that at the meteorological site) 1.00, 0.70, 0.50 and 0.40 for Plymouth, London (Heathrow), Birmingham Airport, Manchester Airport, Waddington (near Lincoln), Leeming/Dishforth (near Northallerton, North Yorkshire), Edinburgh and Prestwick. The collection efficiency function was usually X = 5 m/s, Y = 2 m/s, K = 0.20, (c' = 0.6) but X = 5 m/s, Y = 2 m/s, K = 0.333 (c' = 1.0) was also used to indicate moisture contents near the edges of walls; the evaporation function corresponding to Fletton bricks was normally used, but that corresponding to London Stock bricks was a variant. The period of analysis was July 1960 to March 1971; because the start date followed two months of predominantly dry weather the initial assumption of minimum moisture content in the walls was almost certainly valid.

The outcome of these studies can best be explained as follows. Fletton bricks at minimum moisture content can absorb an amount of driving rain equal to 0.115 m^2/s before reaching saturation; (saturation level 135 units minus minimum moisture content 20 units). The amount 0.115 m^2/s corresponds to 17 units on the logarithmic scale for spell amounts. Thus where the spell amount exceeded once per 3 years is 17 units, saturation will occur on average once per 3 years; where the spell amount exceeded once per 3 years is 21 units (22 units for walls facing 360, 030 and 060 degrees) the spell amount exceeded once per year is 17 units (see previous section) and saturation will occur on average once per year, provided that the bricks are always at minimum moisture content before commencement of the spell.

The average effect of the moisture content in the wall before the spell commences is to reduce the once per 3 year threshold by 1 unit to 16 units, and the once per year threshold by 2 units to 19 units (20 units for walls facing 360, 030 and 060 degrees). Thus where the spell amount exceeded once per 3 years is 16 units (0.100 m^2/s) saturation may be expected to occur on average once per 3 years; where the spell amount exceeded once per 3 years is 19 units (0.141 m^2/s) [20 units (0.156 m^2/s) for walls facing 360, 030 and 060 degrees] saturation may be expected to occur on average once per year. It will be seen that a quite small increase in the spell amount exceeded once per 3 years leads to a three fold increase in the expected frequency of saturation. The analyses showed that as the spell amount exceeded once per 3 years increased beyond 19/20 units the frequency of saturations increased very rapidly; this is because the average moisture content in the walls rises and smaller spell amounts, which occur much more frequently, are sufficient to cause saturation. [The reasons why walls facing 360, 030 and 060 degrees require a higher once per 3 year spell amount than remaining orientations to give saturations once per year are first that the north and northeast orientations show a higher ratio of spell amount exceeded once per 3 years to spell amount exceeded once per year; and second that for given level of spell amount exceeded once per 3 years, walls facing north and northeast show lower average moisture contents than the remaining orientations - the average moisture content depends on the frequency distribution of all driving rain amounts, and not particularly on a spell amount which is rarely exceeded].

The edges of walls, those portions of walls which project above surrounding buildings and whole walls in exposed locations have significantly higher spell amounts exceeded once per 3 years than are indicated in the maps. The frequency of saturation will be very much higher than for the main portion of walls in a sheltered suburban environment. However the results given above continue to apply - if the spell amount exceeded once per 3 years, read from the maps and increased by the amounts advised in the preceding section, is 16 units or less, saturation may be expected to occur not more frequently than once per 3 years on average.

As previously indicated, London Stock bricks dry faster and reach a lower minimum moisture content than Flettons. For London Stock bricks, therefore, each of the threshold values of spell amount exceeded once per 3 years in the two paragraphs immediately above may be increased by 1 unit; (a more precise estimate of this increase is $1\frac{1}{2}$ units, but the value has been rounded down as a safety precaution).

Practical application of the results

This section describes how the results of the preceding sections might be applied to determine the advisability of installing foam insulation between the outer and inner walls of buildings, constructed with unrendered facing bricks.

It is assumed for the sake of the argument that the criterion for advisability is that the main portion of the outer wall ($c' = 0.6$) should not become saturated more frequently than once per 3 years on average; this criterion implies that the edges of the outer walls ($c' = 1.0$) will be saturated about 3 times per year on average. (The criterion does not imply that rain will penetrate to the inner wall with the stated frequencies; only that the potential for rain penetration exists).

If the building is 1 or 2 storey, on reasonably level ground in a suburban environment inland, with uniform exposure of all four walls (ie a value of $p = 0.5$ is considered appropriate), the maps provide an immediate basis for the assessment. It is necessary to consider only the wall having the highest exposure to driving rain. If the map value for the most exposed wall determined by addition of the value for the 'key' town or airport, the sub-regional adjustment and the geographical adjustment, is 16 units or less, saturation of the outer wall may be expected to occur not more frequently than once per 3 years and, on the assumed criterion, foam insulation may safely be installed. In practice local authority officers will have read from the maps the values appropriate to their area for all wall orientations at interval 30 (or 10) degrees, and decisions will be automatic for 1 or 2 storey buildings in a "standard" environment (a high proportion of the building stock).

If the building is 1 or 2 storey in a suburban environment, located within 5 km of the sea or a large estuary, or situated on sloping ground, on a hillcrest or in a valley, it is necessary to add to the map value a topographic adjustment (Table 4) for those wall orientations to which such adjustment applies; the sector to be considered is 45 degrees each side of the normal to the wall concerned. The adjusted value for the most exposed wall is then compared with the threshold of 16 units as already described. The positive values of the topographical adjustment in Table 4 are empirical assessments based on the expected increase in mean wind speed compared with suburban sites on level ground inland; thus the proposed adjustment of + 3 units for sites in category b is adequate to cover an increase in the value of p from 0.5 to 0.6 (interpolation from Table 3).

If the building is not 1 or 2 storey, is not in a suburban environment, or if the exposure of the walls is not uniform, it is necessary to add to the map value first the topographic adjustment and second a terrain roughness adjustment (Table 5). If the exposure of the walls is not uniform it is necessary to assess each wall individually, considering the sector 45 degrees each side of the normal to the wall concerned. The proposed values of the terrain roughness adjustment in Table 5 are derived from Table 3 and correspond to assumed values of p which are also shown. The values may need to be revised in the light of any new BRE measurements of wind speed in urban areas. It is an awkward feature of Table 5 that the values corresponding to p = 0.9 and p = 1.0 depend significantly on geographical location and wall orientation. The best solution is to add, for each Region or Sub-Region, the terrain roughness adjustment and the "compass" values on the maps. Table 6 is an example of this approach, applicable to the London Region; the terrain roughness is identified by the value of p. To the values in Table 6 it is necessary to add only the topographic adjustment and the geographical correction. The final value for the most exposed wall is then compared with the threshold of 16 units as previously described.

As an example of the application of these ideas we may consider a two-storey house constructed of Fletton bricks on reasonably level ground at position Z on Map No 5. The walls of the property face 070, 160, 250 and 340 degrees. From 240° through 360° to 080° the house is protected by other properties within 50 m (terrain roughness category 3) but from 090° through 180° to 230° the outlook is open with only scattered trees at distances beyond 100 m (terrain roughness category 2). A quick glance at the map values for London (in which Region position Z lies) shows that the walls facing 160° and 250° are at greatest risk of saturation, and this is reinforced by noting that the house has an open aspect to east, south and southwest. Considering first the wall facing 160°, the spell amount (for the main portion of wall) exceeded once per 3 years for terrain roughness category 2 ($p = 0.9$) at position Z is 21 units (London value 18 units by interpolation in Table 6 between 150° and 180°, plus the geographical correction of + 3 units, Map No 5). The topographical adjustment is zero (Table 4, item e). The final value of 21 units exceeds the threshold value of 16 units corresponding to saturation once per 3 years, and in fact exceeds the threshold corresponding to saturation once per year (this is due to the open exposure). There is no need to analyse the situation further, since if the exposure of one wall exceeds the permitted criterion the use of foam insulation should not be encouraged. It is of interest, however, to look at the position of the wall facing 250 degrees since this is protected through some two-thirds of the sector 205 to 295 degrees. From Table 6, interpolating between 240° and 270°, the value for $p = 0.5$ is 8 units and for $p = 0.9$ is 17 units; giving two-thirds weight to $p = 0.5$ and one-third weight to $p = 0.9$, we arrive (with acceptable accuracy) at 11 units. To this value must be added the topographical adjustment zero and the geographical correction of + 3 units (Map No 5). The final value is less than the threshold of 16 units, and so we conclude that the main portion of this wall will not become saturated more frequently than once per 3 years, on average.

Concluding remarks

Amounts of driving rain are variable from year to year, and an analysis of this variability is given in Appendix 1. At all four stations the standard error of the average value tends to be higher for walls facing 360, 030 and 060 degrees than for remaining orientations; this stems from a greater year to year variability of driving rain on walls facing north and northeast, and in about one year in fifteen the annual total exceeded 160 per cent of the average value for the walls concerned. It was noted that a majority of years have annual totals below the average value and this emphasizes the folly of judging the long-term acceptability of cavity insulation solely by the absence of rain penetration in a short period of years.

The report has concentrated on frequencies with which brick walls become saturated with driving rain, but there are other applications of the available data which may briefly be mentioned.

In studies of rain penetration through windows, it may be appropriate to consider annual maximum driving rain amounts over periods of 1 hour and 12 hours, and to form by Gumbel analyses the amounts expected to be exceeded on average once per ten years. The results for Plymouth, London (Heathrow), Leeming/Dishforth (near Northallerton, North Yorkshire) and Prestwick are given in Appendix 2. The choice of once per ten years rather than once per three years is because estimates for the shorter return period from a set of annual maxima are unreliable, since in some years the second highest value may be significant. As a rough guide, ignoring this difficulty, the once per three year values are about 75% of the once per ten year values for walls facing 180, 210 and 240 degrees, and about 67% of the once per ten year values for the remaining orientations. The extreme amounts are higher at Plymouth and Prestwick than at Heathrow and

Leeming/Dishforth, although the differences are not as marked as the variations of annual average driving rain might suggest; it will also be noticed that, at each station, the extreme amounts are broadly similar for a range of wall orientations. The 1 hour and 12 hour amounts in Appendix 2 apply to the meteorological site and assume a collection efficiency of 1.0; in a suburban environment for which $p = 0.5$, $c' = 0.6$ the amounts will be approximately 0.30 times those in Appendix 2.

As an alternative to identifying the spell amounts exceeded once per year or once per three years, it is possible to show the frequencies of occurrence of specified spell amounts. Appendix 3 gives, for Plymouth, London (Heathrow), Leeming/Dishforth and Prestwick, and various values of p, the numbers of occurrences in the 15 year period 1959-73 of net spell amounts exceeding 0.05 and 0.10 m^2/s. Appendix 4 gives similar information for spell amounts without adjustment for evaporation during dry intervals within the spell; the criterion for continuation of the spell remains unchanged. The figures show the sharp drop in the number of spells exceeding a given threshold with reducing value of p and, for given p, between western and eastern districts of the United Kingdom. The tables in Appendix 4 have found application in assessing the frequency with which windows and walls receive a substantial wash by rain, removing a proportion of dirt and harmful pollutants.

Acknowledgement

The research described in this report was carried out at the request of, and funded by, the Building Research Establishment, Garston, Watford, Herts. United Kingdom. (The report and associated sets of maps were forwarded to BRE in 1977).

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Figure 1. Collection Efficiency of West-facing Wall At Tredegar, Winter 1967-68

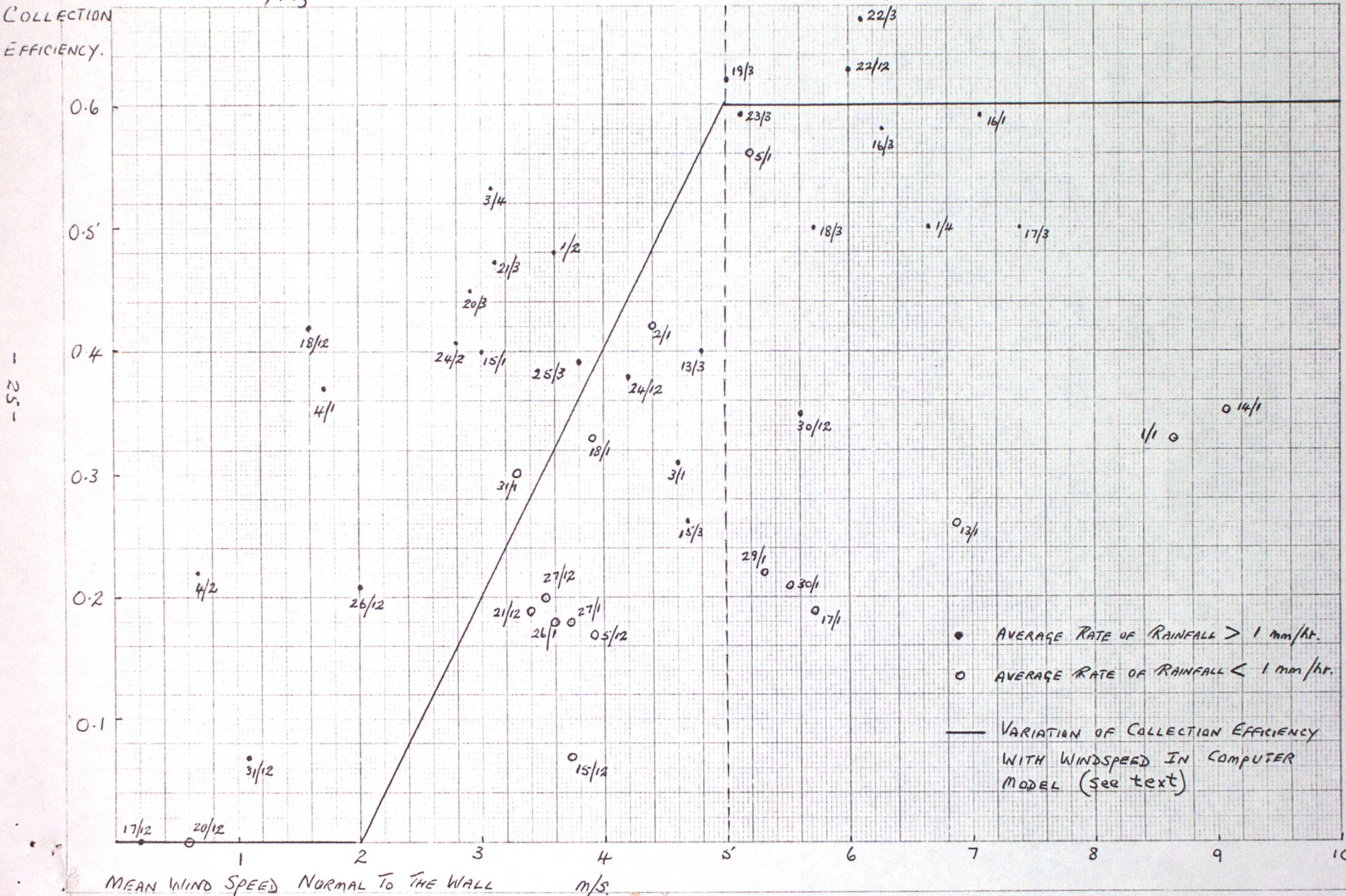


Table 1

Addition to convert annual average driving rain to spell amount exceeded once per 3 years at meteorological site $\rho = 1.0$ $c' = 0.6$

	030	060	090	120	150	180	210	240	270	300	330	360
Plymouth	13	13	12	11	11	11	11	11	11	11	12	13
Exeter	13	13	11	10	10	11	11	11	11	11	12	13
Salisbury	13	13	11	10	10	10	10	10	10	10	11	13
Heathrow	13	13	11	9	9	9	9	9	9	9	11	13
London	14	14	12	10	9	9	9	9	9	9	11	13
Portsmouth	13	13	11	10	10	10	10	10	10	10	11	13
Gatwick	13	13	11	9	10	10	10	10	9	9	11	13
Chelmsford	14	14	12	11	9	9	9	9	9	9	11	13
Peterborough	14	14	13	11	9	9	9	9	9	10	12	14
Oxford	13	13	11	9	9	9	9	10	10	10	11	13
Birmingham ap	14	14	12	10	9	9	9	9	10	10	11	13
Worcester	14	14	12	10	9	9	10	10	10	10	11	13
Milford Haven	13	13	12	10	10	11	11	11	10	10	11	13
Aberystwyth	13	13	11	9	9	10	10	10	10	10	11	13
Manchester ap	13	13	11	10	9	9	9	9	9	10	11	13
Lincoln	15	15	13	11	10	9	9	9	9	10	13	15
Northallerton	15	15	13	11	10	9	9	9	9	10	13	15
Carlisle	14	14	12	10	9	10	10	10	10	10	11	13
Prestwick	14	14	12	10	9	10	10	10	10	10	11	13
Edinburgh	14	15	13	11	9	9	10	10	10	10	12	14
Inverness	14	13	11	9	9	9	10	10	10	10	11	13
Oban	13	13	11	9	9	10	11	11	11	11	12	13
Hebrides	13	13	11	10	10	10	11	11	11	11	12	13
Unst/Shetland	13	13	11	10	10	10	10	10	10	10	11	13
Aldergrove	13	13	11	10	10	10	10	10	10	10	11	13
Isle of Man	13	13	11	10	10	10	10	10	10	10	11	13

Table 2

Addition to convert spell amount at meteorological site $\rho = 1.0$ $c' = 0.6$ to spell amount at suburban site $\rho = 0.5$ $c' = 0.6$

	030	060	090	120	150	180	210	240	270	300	330	360
Plymouth	-13	-13	-12	-11	-10	-9	-9	-9	-9	-10	-12	-13
Exeter	-13	-13	-12	-11	-10	-10	-10	-10	-10	-11	-12	-13
Salisbury	-13	-13	-12	-12	-11	-10	-10	-10	-10	-11	-12	-13
Heathrow	-12	-12	-12	-12	-11	-10	-10	-10	-11	-12	-13	-13
London	-12	-12	-12	-12	-11	-10	-10	-10	-11	-12	-13	-13
Portsmouth	-13	-13	-12	-12	-11	-10	-10	-10	-11	-12	-13	-13
Gatwick	-12	-12	-12	-12	-11	-10	-10	-10	-11	-12	-13	-13
Chelmsford	-12	-12	-11	-12	-11	-10	-10	-10	-11	-12	-12	-12
Peterborough	-11	-11	-11	-12	-11	-10	-10	-10	-11	-12	-12	-12
Oxford	-12	-12	-12	-12	-11	-10	-10	-10	-11	-12	-13	-13
Birmingham ap	-12	-12	-12	-12	-11	-10	-10	-10	-11	-12	-12	-13
Worcester	-13	-13	-12	-12	-11	-10	-10	-10	-11	-12	-12	-13
Milford Haven	-13	-13	-12	-11	-10	-9	-9	-9	-9	-10	-12	-13
Aberystwyth	-13	-13	-12	-11	-10	-9	-9	-9	-9	-10	-12	-13
Manchester ap	-13	-13	-12	-12	-11	-10	-10	-10	-10	-11	-12	-13
Lincoln	-11	-11	-11	-12	-11	-10	-10	-10	-10	-11	-12	-12
Northallerton	-11	-11	-11	-12	-11	-10	-10	-10	-10	-11	-12	-12
Carlisle	-13	-13	-12	-12	-11	-10	-9	-9	-9	-10	-12	-13
Prestwick	-13	-12	-12	-12	-11	-10	-9	-9	-9	-10	-12	-13
Edinburgh	-11	-11	-11	-11	-11	-10	-10	-10	-10	-11	-12	-12
Inverness	-11	-11	-12	-12	-11	-10	-10	-10	-10	-11	-12	-12
Oban	-12	-12	-12	-11	-10	-9	-9	-9	-9	-10	-11	-12
Hebrides	-11	-11	-11	-10	-9	-9	-9	-9	-9	-10	-11	-11
Orkney/Shetland	-11	-11	-11	-10	-9	-9	-9	-9	-9	-9	-10	-11
Aldergrove	-12	-12	-11	-11	-10	-9	-9	-9	-9	-10	-11	-12
Isle of Man	-12	-12	-11	-11	-10	-9	-9	-9	-9	-10	-11	-12

Table 3

Addition to spell amount for $\rho = 0.5$ $c' = 0.6$ (Maps 17-32) to give spell amounts for alternative values of ρ

	Value in Table 2				
	-9	-10	-11	-12	-13
1.0	+9	+10	+11	+12	+13
0.9	+8	+9	+10	+11	+12
0.7	+5	+5	+6	+6	+7
0.5	0	0	0	0	0
0.4	-4	-4	-5	-5	-5
0.3	-10	-11	-12	-12	-13

Table 4

Values of the topographic adjustment.

The sector to be considered is 45 degrees each side of the normal to the wall.

a. Sites where both b and c/d apply:- the sum of the appropriate adjustments

b. Sites known to be abnormally windy, such as (i) on the crest of a hill, (ii) on an exposed hill slope, (iii) in a valley shaped to produce a channeling of the wind into the sector concerned — +3 units

c. Sites with sea or a large estuary within 1 km in the sector concerned — +2 units

d. Sites with sea or a large estuary 1-5 km distant in the sector concerned — +1 unit

e. Sites away from the coast where the surroundings are generally level — zero

f. Sites which are more sheltered than normal such as in valleys shaped to produce a channeling of the wind out of the sector concerned — −1 unit

Table 5

Values of the terrain roughness adjustment

	Terrain description (after CP3, Ch 5)+	1 storey 5 m high	2 storeys 7.5 m high	3 storeys 10 m high
1.	Walls facing the sea or open level country with no windbreaks within 1 km	+8 to +12 p = 0.9	+9 to +13 p = 0.95	+9 to +13 p = 1.0
2.	Walls facing open country with scattered windbreaks (buildings or trees) 50 m to 1 km distant.	+7 to +11 p = 0.85	+8 to +12 p = 0.9	+9 to +13 p = 0.95
2a.	Walls separated from open country by a row of closely-spaced buildings or trees, less than 50 m distant.	+6 p = 0.7	+7 p = 0.75	+8 to +12 p = 0.9
3.	Walls in the midst of a generally built-up or wooded area with open space to the wall less than 50 m; this category covers the typical suburban situation; the general level of the rooftops and obstructions is assumed to be about 10 m.	0 p = 0.5	0 p = 0.5	+6 p = 0.7
4.	Walls in the centre of large towns and cities, which are heavily protected by trees or buildings. The general height of the obstructions is assumed to be 25 m or more.	-5 p = 0.4	-5 p = 0.4	-2 p = 0.45

+ The sector to be considered is 45 degrees each side of the normal to the wall.

Table 6

Combination of "compass" values and terrain roughness adjustment for the London Region

Wall orientation (degrees)

	030	060	090	120	150	180	210	240	270	300	330	360
p = 1.0) p = 0.95)	17	17	16	16	18	20	20	19	16	13	14	16
p = 0.9	16	16	15	15	17	19	19	18	15	12	13	15
p = 0.85	15	15	14	14	16	18	18	17	14	11	12	14
p = 0.75	12	12	11	11	14	16	16	15	12	8	9	11
p = 0.7	11	11	10	10	13	15	15	14	11	7	8	10
p = 0.5	5	5	4	4	7	10	10	9	5	1	1	3
p = 0.45	3	3	2	2	5	8	8	7	3	-1	-1	1
p = 0.4	0	0	-1	-1	2	6	6	5	0	-4	-4	-2

APPENDIX 1

VARIABILITY OF ANNUAL DRIVING RAIN

1. PLYMOUTH (MOUNT BATTEN), 1959-73

wall orientation (degrees)	030	060	090	120	150	180	210	240	270	300	330	360
	Per cent of annual average driving rain											
20% of annual values lie above	129	131	122	114	120	123	124	125	124	128	113	115
20% of annual values lie below	73	71	73	77	80	77	76	75	76	78	80	72
Standard error of average value	8.1	9.1	7.7	7.7	5.8	6.6	6.8	7.0	6.7	6.8	7.5	8.0
	Annual average driving rain m^2/sec (10 m above terrain of gust ratio 1.60)											
	0.78	1.18	1.92	3.03	4.25	5.07	5.09	4.33	3.09	1.82	0.98	0.70

2. LONDON (HEATHROW), 1959-73

wall orientation (degrees)	030	060	090	120	150	180	210	240	270	300	330	360
	Per cent of annual average driving rain											
20% of annual values lie above	128	134	129	123	117	114	117	119	117	123	125	121
20% of annual values lie below	70	71	74	82	85	83	82	82	83	76	72	66
Standard error of average value	9.3	9.3	7.6	6.0	5.7	5.8	5.6	5.6	5.8	6.5	7.7	8.4
	Annual average driving rain m^2/sec (10m above terrain of gust ratio 1.60)											
	0.70	0.71	0.76	0.99	1.36	1.67	1.76	1.51	1.07	0.74	0.63	0.64

APPENDIX 1 Cont'd

3. LEEMING/DISHFORTH (near Northallerton, North Yorkshire), 1959-73

wall orientation (degrees)

	030	060	090	120	150	180	210	240	270	300	330	360
	Per cent of annual average driving rain											
20% of annual values lie above	125	127	119	122	125	123	120	119	124	121	114	122
20% of annual values lie below	68	80	80	79	79	80	80	78	77	79	82	75
Standard error of average value	8.3	7.1	6.3	6.8	6.1	5.8	5.4	5.7	6.6	5.7	5.3	6.9
	Annual average driving rain m^2/sec (10m above terrain of gust ratio 1.60)											
	0.92	0.84	0.92	1.21	1.44	1.48	1.30	0.97	0.79	0.85	0.93	0.96

4. PRESTWICK, 1959-73

wall orientation (degrees)

	030	060	090	120	150	180	210	240	270	300	330	360
	Per cent of annual average driving rain											
20% of annual values lie above	129	127	120	117	122	121	118	115	116	118	129	131
20% of annual values lie below	71	73	75	72	70	74	82	84	84	81	73	66
Standard error of average value	9.0	7.6	8.2	6.9	7.0	6.3	4.7	4.2	4.4	5.8	8.2	10.2
	Annual average driving rain m^2/sec (10m above terrain of gust ratio 1.60)											
	0.64	0.83	1.06	1.49	2.11	2.88	3.45	3.40	2.68	1.75	0.95	0.60

Note: The 20 percentile values are estimates derived by meaning the values for years 2, 3, 4, 5 and 11, 12, 13, 14 in the ranking order. At all four stations the standard error of the average value is higher for walls facing 360°, 030° and 060°.

APPENDIX 2

EXTREME VALUES OF DRIVING RAIN AMOUNT OVER PERIODS OF 1 HOUR AND 12 HOURS

The values expected to be exceeded once per 10 years on average are expressed as percentages of the annual average driving rain. Absolute amounts are also given, obtained by applying the percentages to the values of annual average driving rain for the standardised sites (10m above terrain for which the gust ratio = 1.60)

The percentages may also be applied to the map values of annual average driving rain (maps 1-16) in the regions based on the stations for which results are shown; between these stations the percentages may be estimated by interpolation.

Amounts apply to the meteorological sites and assume a collection efficiency of 1.0.

A driving rain amount of .10m^2/sec corresponds approximately to 20 litres of water per square metre of vertical surface.

1. PLYMOUTH (MOUNT BATTEN), derived from data 1959-73

wall orientation (degrees)

	030	060	090	120	150	180	210	240	270	300	330	360
	Once per 10 year amount as Percentage of annual average driving rain											
1 hour value	9.7	8.1	6.3	5.0	3.7	2.9	2.9	3.1	3.5	4.1	8.8	13.3
12 hour total	30.8	27.0	20.8	13.7	9.0	8.4	8.4	8.6	10.5	11.0	21.0	32.9
	Once per 10 year amount m^2/sec											
1 hour value	.08	.10	.12	.15	.16	.15	.15	.13	.11	.08	.09	.10
12 hour total	.24	.32	.40	.41	.38	.43	.43	.37	.32	.20	.21	.23

2. LONDON (HEATHROW), 1959-73

wall orientation (degrees)

	030	060	090	120	150	180	210	240	270	300	330	360
	Once per 10 year amount as Percentage of annual average driving rain											
1 hour value	10.8	11.7	10.4	6.1	4.0	4.1	4.2	5.3	9.1	11.1	11.7	14.2
12 hour total	31.4	28.3	25.2	15.6	12.1	12.8	13.5	15.7	19.3	21.6	32.5	29.8
	Once per 10 year amount m^2/sec											
1 hour value	.08	.08	.08	.06	.05	.07	.07	.08	.10	.08	.07	.09
12 hour total	.22	.20	.19	.15	.16	.21	.24	.24	.21	.16	.20	.19

APPENDIX 2 Cont'd

3. LEEMING/DISHFORTH (near Northallerton, North Yorkshire), 1959-73

	030	060	090	120	150	180	210	240	270	300	330	360
	Once per 10 year amount as Percentage of annual average driving rain											
1 hour value	16.3	19.7	15.5	8.8	5.5	4.2	4.6	5.4	6.8	7.1	9.2	11.8
12 hour total	24.4	26.8	25.0	16.8	14.4	11.6	12.0	13.6	16.1	13.6	17.3	21.5
	Once per 10 year amount m^2/sec											
1 hour value	.15	.17	.14	.11	.08	.06	.05	.05	.05	.06	.09	.11
12 hour total	.22	.23	.23	.20	.21	.17	.16	.13	.13	.12	.16	.21

4. PRESTWICK, 1959-73

	030	060	090	120	150	180	210	240	270	300	330	360
	Once per 10 year amount as Percentage of annual average driving rain											
1 hour value	13.3	9.9	6.0	3.6	3.0	2.3	1.9	2.0	3.0	4.9	8.8	13.7
12 hour total	53.7	36.2	20.0	10.9	9.9	8.1	7.1	8.1	11.4	14.8	33.0	52.3
	Once per 10 year amount m^2/sec											
1 hour value	.09	.08	.06	.05	.06	.07	.07	.07	.08	.09	.08	.08
12 hour total	.34	.30	.21	.16	.21	.23	.25	.28	.31	.26	.31	.31

APPENDIX 3

FREQUENCY OF SPELLS EXCEEDING THRESHOLD VALUES (AMOUNTS ADJUSTED FOR EVAPORATION DURING SPELL)

A driving rain amount of .05 m^2/s corresponds approximately to 10 litres of water per square metre of vertical surface.

1. PLYMOUTH (MOUNT BATTEN) 1959-73

	Threshold .05 m^2/s				Threshold .10 m^2/s			
Wall orientation (degrees)	090	180	270	360	090	180	270	360
	number of occurrences in 15 year Period 1959-73							
p = 1.0 c' = 0.6	>90*	>90*	>90*	13	36	>90*	53	3
p = 0.5 c' = 0.6	10	82	31	1	3	30	9	0
p = 0.3 c' = 0.6	0	9	2	0	0	1	0	0

2. LONDON (HEATHROW) 1959-73

	Threshold .05 m^2/s				Threshold .10 m^2/s			
Wall orientation (degrees)	090	180	270	360	090	180	270	360
	number of occurrences in 15 year Period 1959-73							
p = 1.0 c' = 0.6	15	46	21	17	5	17	4	7
p = 0.7 c' = 0.6	5	19	8	6	0	4	0	1
p = 0.5 c' = 0.6	0	6	1	2	0	0	0	0
p = 0.4 c' = 0.6	0	1	0	0	0	0	0	0
p = 0.3 c' = 0.6	0	0	0	0	0	0	0	0

3. LEEMING/DISHFORTH (near Northallerton, North Yorkshire) 1959-73

	Threshold .05 m^2/s				Threshold .10 m^2/s			
Wall orientation (degrees)	090	180	270	360	090	180	270	360
	number of occurrences in 15 year Period 1959-73							
p = 1.0 c' = 0.6	11	34	10	23	3	4	1	10
p = 0.5 c' = 0.6	1	1	0	3	0	0	0	0

APPENDIX 3 Cont'd

4. PRESTWICK 1959-73

Wall orientation (degrees)	Threshold .05 m^2/s				Threshold .10 m^2/s			
	090	180	270	360	090	180	270	360
	number of occurrences in 15 year Period 1959-73							
p = 1.0 c' = 0.6	26	>90*	>90*	8	4	27	39	4
p = 0.5 c' = 0.6	2	10	20	1	0	1	3	0

*When the number of occurrences exceeds 90 (ie an average of 6 per year) the exact number was not determined.

APPENDIX 4

FREQUENCY OF SPELLS EXCEEDING THRESHOLD VALUES (WITHOUT ADJUSTMENT FOR EVAPORATION)

A driving rain amount of .05 m^2/s corresponds approximately to 10 litres of water per square metre of vertical surface.

1. PLYMOUTH (MOUNT BATTEN) 1959-73

	Threshold .05 m^2/s				Threshold .10 m^2/s			
Wall orientation (degrees)	090	180	270	360	090	180	270	360
	Number of occurrences in 15 year Period 1959-73							
p = 1.0 c' = 0.6	> 90*	> 90*	> 90*	15	41	90*	56	3
p = 0.5 c' = 0.6	10	85	32	1	4	32	13	0
p = 0.3 c' = 0.6	0	15	2	0	0	2	0	0

2. LONDON (HEATHROW) 1959-73

	Threshold .05 m^2/s				Threshold .10 m^2/s			
Wall orientation (degrees)	090	180	270	360	090	180	270	360
	Number of occurrences in 15 year Period 1959-73							
p = 1.0 c' = 0.6	17	55	22	18	5	20	5	7
p = 0.7 c' = 0.6	5	23	9	6	0	6	0	1
p = 0.5 c' = 0.6	0	8	1	2	0	1	0	0
p = 0.4 c' = 0.6	0	1	0	0	0	0	0	0
p = 0.3 c' = 0.6	0	0	0	0	0	0	0	0

3. LEEMING/DISHFORTH (near NORTHALLERTON, NORTH YORKSHIRE) 1959-73

	Threshold .05 m^2/s				Threshold .10 m^2/s			
Wall orientation (degrees)	090	180	270	360	090	180	270	360
	Number of occurrences in 15 year Period 1959-73							
p = 1.0 c' = 0.6	12	36	10	23	3	9	1	13
p = 0.5 c' = 0.6	1	1	0	4	0	0	0	0

APPENDIX 4 Cont'd

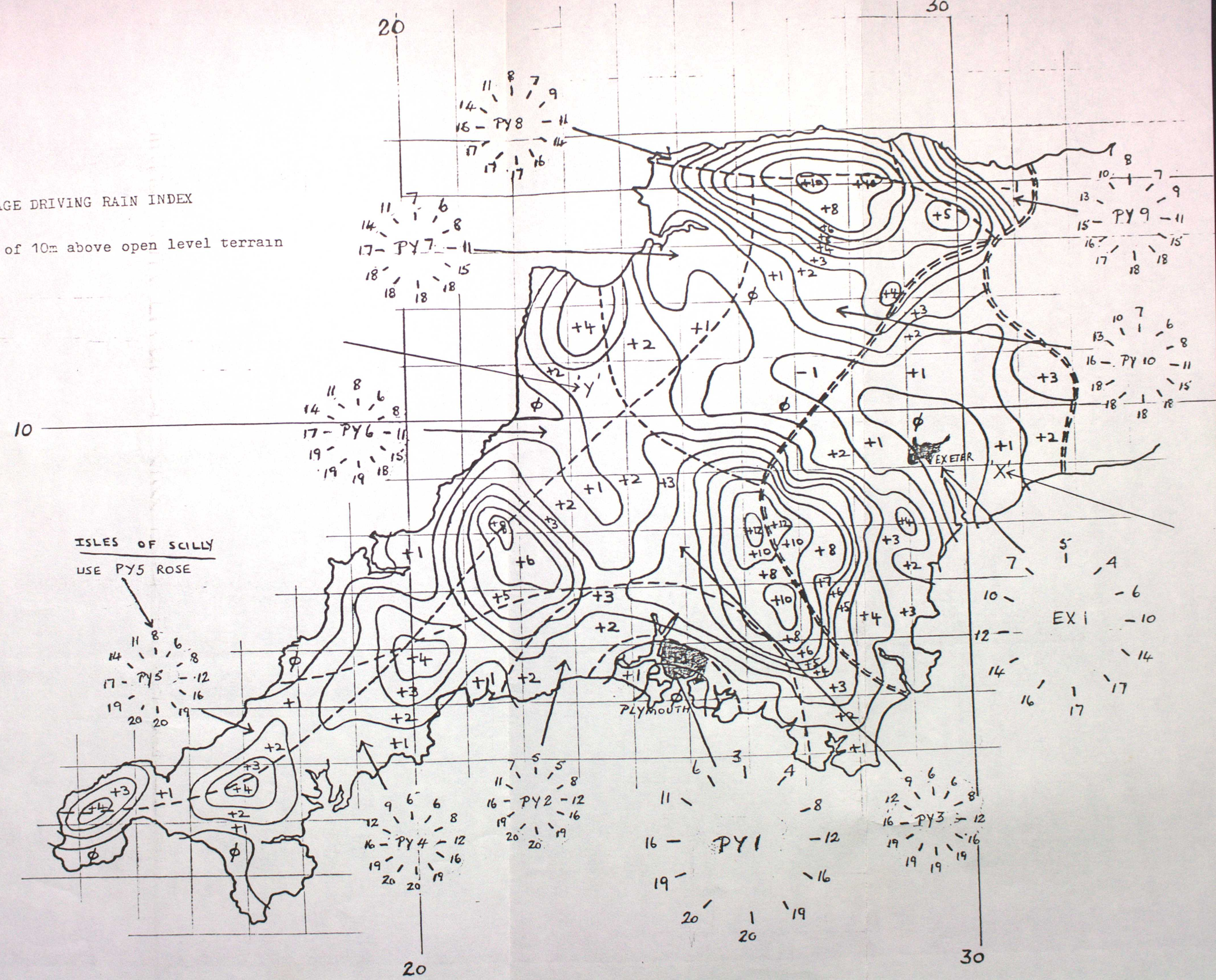
4. PRESTWICK 1959-73

Wall orientation (degrees)	Threshold .05 m^2/s				Threshold .10 m^2/s			
	090	180	270	360	090	180	270	360
	Number of occurrences in 15 year Period 1959-73							
p = 1.0 c' = 0.6	26	>90*	>90*	8	4	37	40	4
p = 0.5 c' = 0.6	2	11	22	1	0	1	4	0

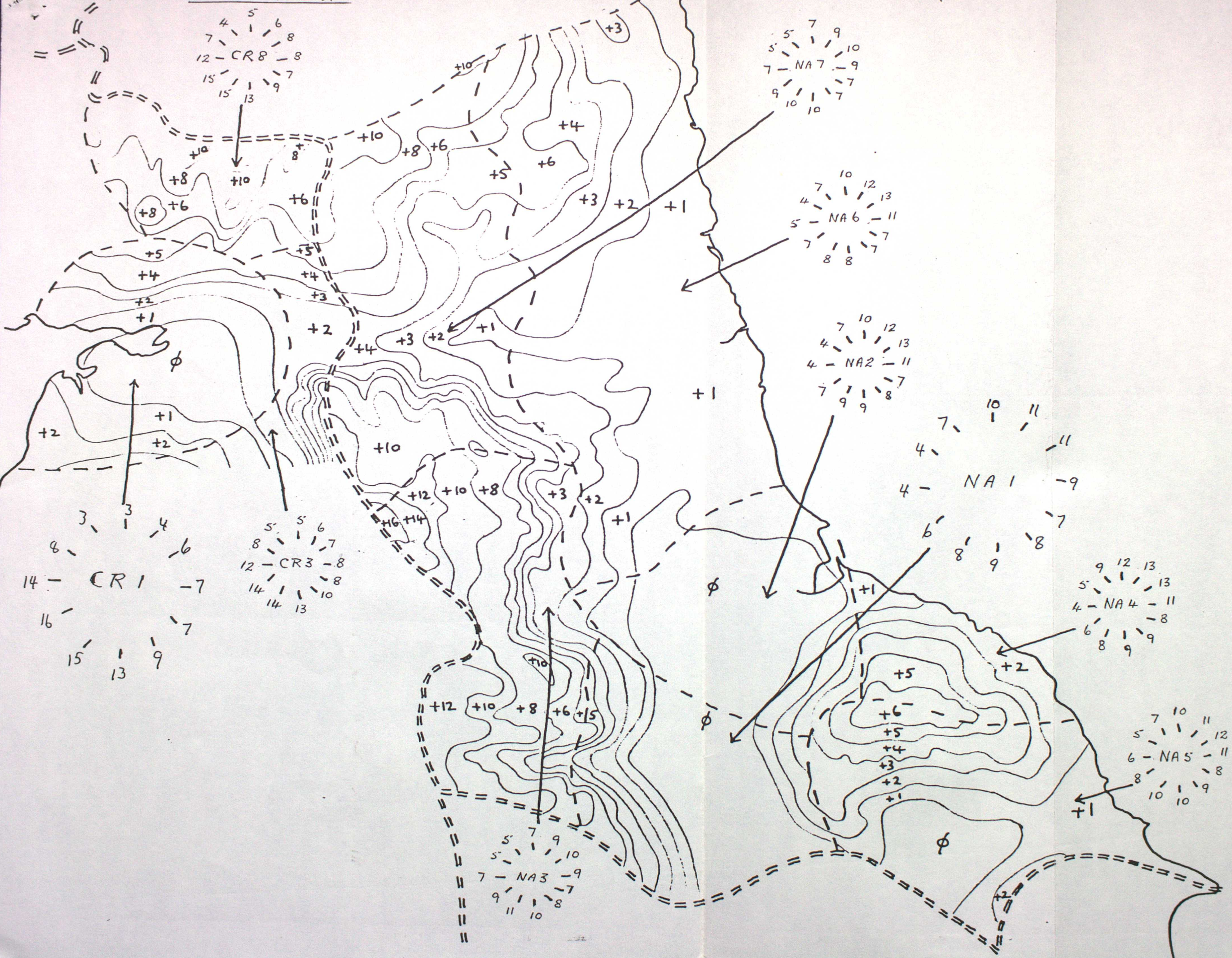
*When the number of occurrences exceeds 90 (ie an average of 6 per year) the exact number was not determined.

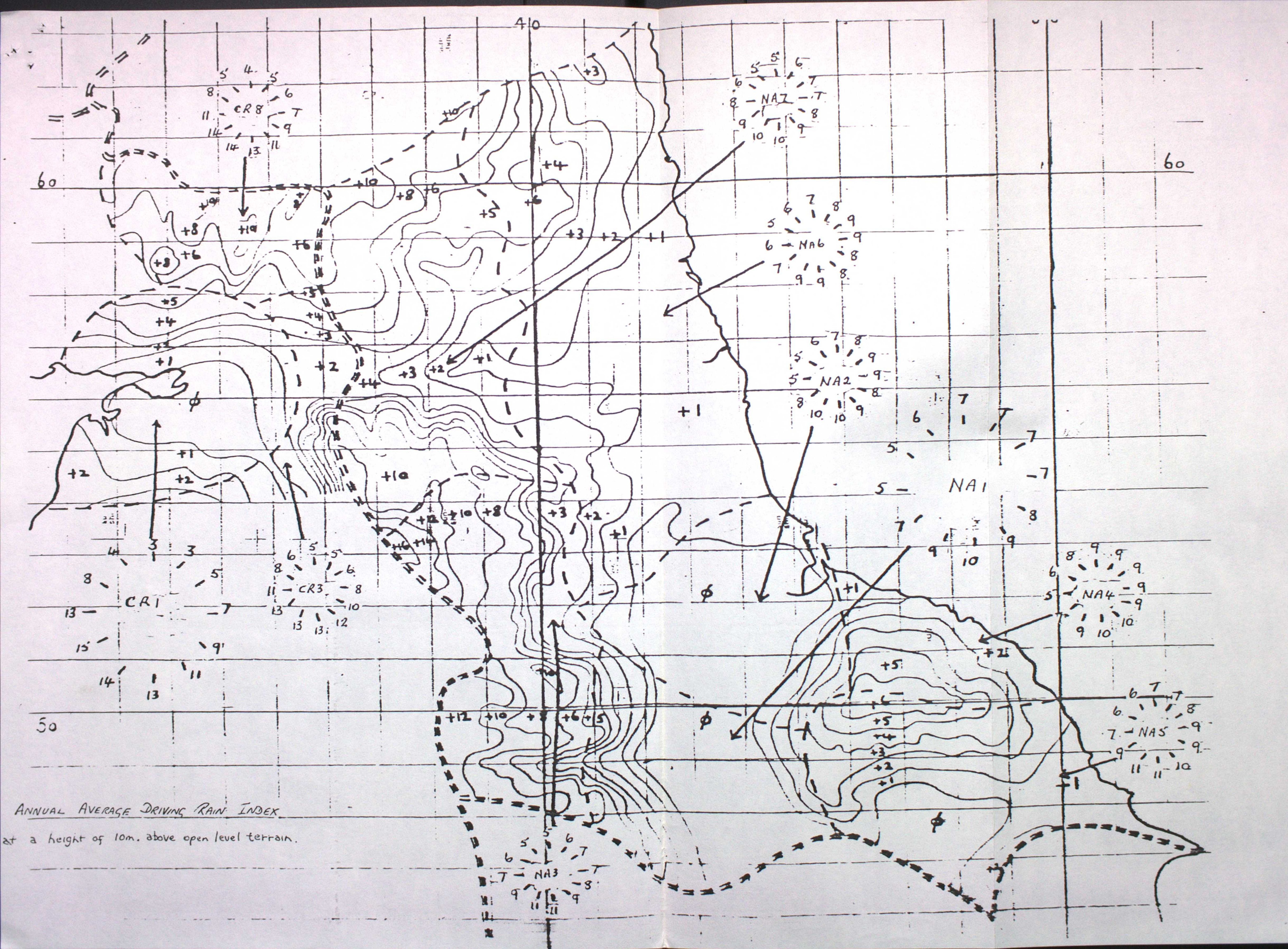
ANNUAL AVERAGE DRIVING RAIN INDEX

at a height of 10m above open level terrain



SPELL AMOUNT EXCEEDED ONCE PER 3 YEARS
AT SUBURBAN SITE.



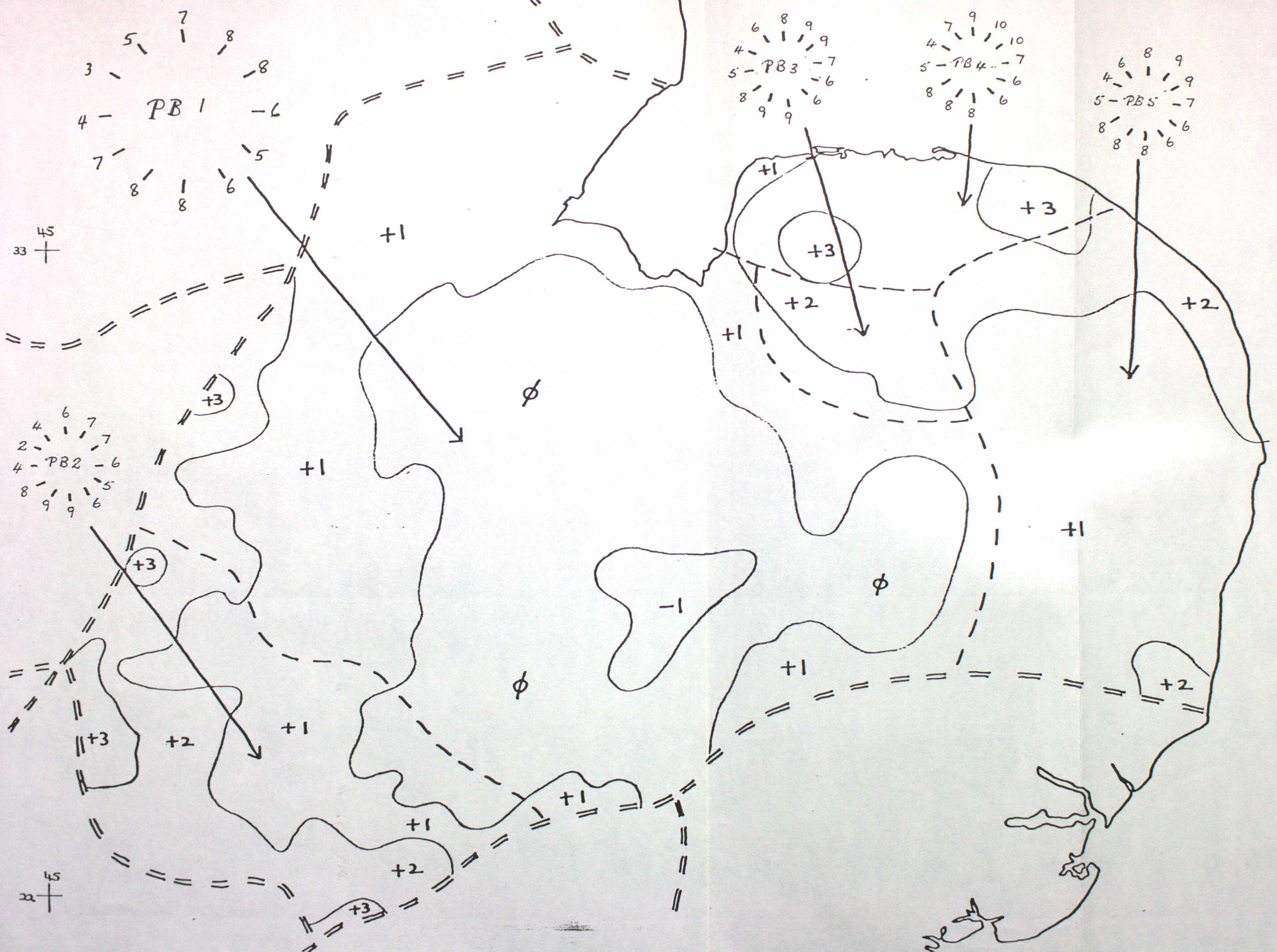


Annual Average Driving Rain Index

at a height of 10m. above open level terrain.

SPELL AMOUNT EXCEEDED ONCE PER 3 YEARS

AT SUBURBAN SITE $P = 0{\cdot}5$ $c' = 0{\cdot}6$



SPELL AMOUNT EXCEEDED ONCE PER 3 YEARS

AT SUBURBAN SITE $P = 0.5$ $c' = 0.6$

ANNUAL AVERAGE DRIVING RAIN INDEX

at a height of 10m. above open level terrain.

SPELL AMOUNT EXCEEDED ONCE PER 3 YEARS AT SUBURBAN SITE