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EVAPORATION AND TRANSPIRATION IN THE IRISH CLIMATE

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SUMMARY

The quantity "Potential Evapo-transpiration" (1,2) is defined as the amount of water used by vegetation under conditions of adequate water supply in the root zone of the soil. Prof. Thornthwaite, who introduced the use of potential evaporation into agricultural climatology, has evolved a formula expressing it as a function of air temperature, monthly mean temperatures and length of day. This formula is tested for Ireland by comparing actual measured run-off to run-off computed from an application of Thornthwaite's formula, and found inadequate. The causes of this are discussed, and suggestions made to render the formula applicable under Irish climatic conditions. Maps, based on monthly means of temperature and rainfall, showing the adequacy or otherwise of rainfall to meet the demands of evaporation and transpiration, are appended.

Introduction

The role of evaporation and transpiration in the hydrological cycle of the atmosphere is equal and opposed to that of precipitation. Despite this fact, the study of evaporation has been neglected in comparison to that of rainfall; for example, no less than 850 rain-gauges are operated by the Irish Meteorological Service but there was, in 1938, only one evaporation tank at a meteorological station in Great Britain or Ireland, namely that at Valentia (3). A small number of evaporation tanks are, however, maintained by other than meteorological interests but, on the whole, it may be stated that no overall picture of evaporation is available; the British Climatological Atlas for example, gives no information on this subject. The lack of observations of this important parameter arises from the difficulties inherent in measurement. In particular, observations from evaporation tanks are strongly influenced by the regime (laminar or turbulent) existing in the air flow over the water surface, that is to say, by wind velocity, height of tank edge above the ground, depth of water surface below rim of tank, and size of the tank itself. No international standardisation or comparison of evaporation tanks having been undertaken, the available figures may be unreliable.

Other attemps to measure evaporation, as for example by the use of Piche's evaporimeter, Livingstone's atmometer, etc., and by experiments involving the use of wind tunnels, are irrelevant since done under very artificial conditions.

Increasing interest in recent years in low-level atmospheric turbulence and in soil and moisture conservation has given a new impetus to the study of evaporation and transpiration. In the absence of comprehensive observational material the approach has been, perforce, indirect.

Three separate lines of attack are discernible:-

1. By studying the disposal of incoming radiation at the earth's surface to deduce the amount of energy consumed in evaporating water, hence the amount of water evaporated.

2. By a study of the kinematics of low-level turbulence.

3. By consideration of transpiration as a physical process under biological control.

The latter is the approach initiated by Prof. Thornthwaite and applied successfully by him in North America to the solution of many problems involving moisture conservation, and used in the formulation of a new climatic classification (4, 5, 1 et. al.).

Evaporation and transpiration (together called evapo-transpiration) depend on a number of meteorological factors; for example, soil temperature, air temperature, insolation, humidity, wind, degree of vertical mixing, etc. Attempts to express evapo-transpiration as a function of these parameters have failed, because a further factor, the amount of water available in the soil, is more important than any of them. In fact, the latter imposes an upper limit on transpiration, since the foliage of plants cannot transpire more water than is available to the roots.

In order to avoid the difficulties imposed by variability of soil moisture on the measurement and calculation of evapo-transpiration, Thornthwaite (loc. cit. and 6) proposed the use of "Potential Evapo-transpiration" which is defined as "the amount of water which will be lost from a surface completely covered with vegetation under conditions of adequate soil moisture." Soil moisture may be regarded as adequate if maintained at or close to field capacity. Thornthwaite has experimented with different empirical formulae to express potential evapo-transpiration as a function of meteorological parameters, and has finally arrived at a formula which uses temperature data and length of day alone as variables. Satisfactory results have been obtained from this formula despite the fact that no direct account is taken of other factors, as, for instance, wind, humidity, etc.: this is attributed to the fact that the variation of these factors is related to that of temperature.

However, an independent argument derived from biology leads also to the conclusion that transpiration is largely determined by temperature. It has been shown by Lehenbauer (7) and others that the rate of growth of plants is a function of temperature. The curve of rate of growth against temperature always shows a maximum, i.e., an optimum temperature for growth always exists. At temperatures above the optimum the rate of growth declines, eventually becoming zero: the popular assumption that growth is encouraged by increasing temperature arises from the coincidence that the temperature range experienced by plants in natural conditions lies below the optimum. In the case of maize, a plant which has been studied intensively, the optimum temperature is at 30°C, and the growth rate is zero at 40°C. The rate of growth can be expressed in the form

$$v(\text{rate of growth}) = a\,\frac{bce^{ct}}{(e^{ct} + b)^2}$$

a, b, c being constants, selected to give maximum growth at 30°C, where numerator and denominator are equal. The squared term in the denominator expresses the growth-inhibiting factor which becomes predominant at 30°C. The physical-biological explanation of this reduction in growth-rate above the optimum temperature is thought to be increasing difficulty for the plant structure in supplying the rapidly-increasing amounts of water needed for transpiration. The biological function of transpiration is the prevention of overheating and consequent damage by necrosis to the plant structure; increasing insolation demands the transpiration of increasing amounts of water. Eventually the demand for water will exceed the root system's ability to extract it from the soil and further increases of temperature lead to wilting. Thus, up to wilting temperature we can readily understand that transpiration will depend on temperature; the line of argument is supported by the experimental proof that photosynthesis and carbon dioxide assimilation and, therefore, growth and development respond to climatic changes in the same way as transpiration (8). A Rothamstead report (9) states "assimilation and transpiration can be treated as formally identical apart from a change in sign of the concentration gradient."

The formula devised by Thornthwaite is an empirical one based on the data for water consumption in irrigated plantations, run-off from catchments, and finally water consumption in evapo-transpirometers. The latter are tanks sunk in the ground, filled with soil in which vegetation is allowed to grow; arrangements are made to maintain an adequate water supply in the soil and to measure the quantities of water disposed of by the evaporation and transpiration processes. A simplified type of evapo-transpirometer is illustrated in Fig.1: an installation consisting of four such tanks has been in use in Valentia Observatory since mid-July, 1952.

<u>Use of Formula</u> Thornthwaite's formula (1) is -

$$e = 1.6\left(\frac{10t}{I}\right)^a$$

where e = Potential evapo-transpiration.

t = Temperature in °C.

I = sum of twelve monthly values of $(Tm/5)^{1.514}$, Tm being the monthly mean temperature.

a = function of I.

The values computed from this equation are appropriate to standard months of 30 days of 12 hours of daylight each. Reduction to actual months is effected by multiplication by a series of factors, which in Ireland are as follows:

Table I

Month	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Factor	.74	.78	1.02	1.15	1.33	1.36	1.37	1.25	1.06	.92	.76	.70

In practice it is necessary to do the computations by means of a nomogram, an example of which for Valentia is shown in Fig.2. As stated above, the readings obtained from the nomogram refer to standard months: readings appropriate to other periods are readily obtained by proportion.

It will be observed that different values of I, the so-called heat index, are represented by lines of different slope on the nomogram, all of which converge to a point corresponding to $t = 26.5^{\circ}C$ and $e = 13.5$ cms. The nomogram (Fig.2) shows lines corresponding to the heat index for Valentia Observatory in Kerry, and to a composite heat index for the Shannon Catchment; corresponding to the comparative homogeneity of climate throughout Ireland, the separation of the lines is but slight.

Application of Formula in Ireland

The most convenient method of testing the applicability of the formula is to use it to compute run-off from a watershed from which observations of actual run-off are available. This can be done for the Shannon Catchment above Killaloe where the flow has been recorded for many years: it is fortunate that rainfall readings are available for a large number of stations within the Catchment. The same is not true for temperature readings; Castleforbes, on the shores of Lough Ree, is the only station within the Catchment for which a long series of temperature observations exists. However, Markree Castle to the north and Birr Castle, just south-east of the Catchment, together with Castleforbes are adequate to supply an accurate picture of the temperature regime within this climatically very homogeneous area.

The computation of run-off from Potential Evapo-transpiration and rainfall proceeds on the assumption that transpiration is independent of soil moisture up to a limit; i.e., that vegetation will continue to grow and transpire despite falling soil moisture content while there is any moisture readily available to the roots. Until the soil in the root zone is dried out to this extent, the transpiration is equal to Potential Evapo-transpiration; thereafter, transpiration is limited to the amounts reaching the root zone as precipitation, as only insignificant amounts of moisture can reach the root zone by capillary action from below (10). According to Thornthwaite (1) the mean storage of moisture available to the roots of mature plants with fully developed root systems is about 10 cms. Working in Rothamstead and Cambridge, Schofield and Penman (11), (12) (13) have reached similar conclusions, namely, that transpiration proceeds uninhibited as the moisture deficit increases up to a limiting value of moisture deficit, which they find to be about 3 inches. Penman (12) suggests a dependence of soil moisture capacity on April and May rainfall, setting C (soil storage) $= 5.0 - 0.6\Sigma R$ inches, where ΣR = sum of April and May rainfall.

In making this test, the value used by Thornthwaite, 10 cms., has been used as an average moisture-holding capacity of the soil. In adducing this figure Thornthwaite presents tables (14) showing the percentage and amount of water obtained from successive layers of the soil for different plants and soils. The amounts of water removed from various depths depend on the root distribution which is dependent on the type of soil rather than the vegetation. In all but very heavy soils the roots ramify completely throughout the first foot of soil, so that all the available moisture can be obtained. At lower depths a varying quantity of the water available will be used because of less complete ramification of the roots. Thus, the greater root spread in a light soil uses more of the available water from the lower layers, compensating for the fact that less water is available in the upper layers: in heavy soils the water content of the upper layers is greater than in light soils and all this water will be used, but less water will be got from lower layers because of the less complete root spread.

Shannon Catchment

The "heat indices", I, for Birr, Markree and Castleforbes are 34.2, 31.2 and 31.2, respectively. Using these values of I together with the monthly temperature means 1920-50, the values of Potential Evapo-transpiration relevant to these localities were computed from the nomogram; they are shown in Table II below, where it will be observed there is but little variation in this quantity from one point to another: in fact, it could be said without serious error that potential evapo-transpiration shows no local variation across an area as homogeneous in temperature characteristics as the west of Ireland.

The rainfall over the basin is, however, far from homogeneous. To arrive at a reliable estimate of the monthly rainfall, isohyetal maps were prepared for each month using the means from 32 reporting points. The integration was done by planimeter. The water balance for the area thus derived is reproduced in Table II, which illustrates the method of drawing up a water balance used by Thornthwaite in his climatic classification (1). This classification depends on the concept of a moisture index which expresses the inadequacy of precipitation to meet water need. The water balance compares precipitation to water need (or potential evapo-transpiration) month by month, showing which seasons are deficient in moisture and which have a surplus, both being expressed qualitatively.

TABLE II

Computation of Mean Monthly Values of Run-off from Shannon Catchment Basin

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
1. Birr Temp. °C.	5.0	5.5	6.7	8.2	10.9	13.8	15.2	15.0	13.0	10.0	6.7	5.4	
2. Birr P.E. unadj. (cms.)	2.3	2.5	3.0	3.8	5.2	6.7	7.5	7.4	6.3	4.8	3.1	2.5	
3. Castleforbes Temp. °C.	4.4	4.8	6.1	7.8	10.5	13.2	14.6	14.3	12.2	9.3	6.1	4.8	
4. Castleforbes P.E. unadj. (cms.)	2.2	2.4	3.0	3.9	5.4	6.7	7.4	7.3	6.3	4.7	3.0	2.4	
5. Markree Temp. °C	4.7	5.0	6.1	7.8	10.6	13.0	14.4	14.2	12.4	9.0	6.3	5.0	
6. Markree P.E. unadj. (cms.)	2.3	2.5	3.0	3.8	5.3	6.4	7.1	7.0	6.1	4.4	3.1	2.5	
7. Average P.E. unadj. (cms.)	2.3	2.5	3.0	3.8	5.3	6.6	7.3	7.2	6.2	4.6	3.1	2.5	
8. P.E. adjusted (cms.)	1.7	2.0	3.1	4.4	7.0	9.0	10.0	9.0	6.6	4.2	2.4	1.8	61.2
9. Precipitation (cms.)	9.1	7.7	6.9	6.1	6.4	6.8	8.4	10.3	8.6	8.9	9.3	10.8	99.3
10. Storage change (cms.)	0	0	0	0	-0.6	-2.2	-1.6	1.3	2.0	1.1	0	0	
11. Storage (cms.)	10.0	10.0	10.0	10.0	9.4	7.2	5.6	6.9	8.9	10.0	10.0	10.0	
12. Actual Evapo-transpiration	= Potential Evapo-transpiration since moisture reserve not exhausted												
13. Surplus (cms.)	7.4	5.7	3.8	1.7	0	0	0	0	0	3.6	6.9	9.0	38.1
14. Surplus (in cusecs).	303	233	155	70	0	0	0	0	0	147	282	368	132 avg.
15. Surplus distributed (cusecs).	288	260	208	139	70	35	18	9	5	75	178	273	132 avg.
16. Run-off observed Killaloe - 1930-1944 avg. in cusecs.	362	261	192	128	69	60	63	76	116	176	260	305	171 avg.

Adjusted Potential Evapo-transpiration (line 8) is derived from the unadjusted P.E. of line 7 by the application of the factors in Table I. In months when precipitation exceeds water need (P.E.) the difference appears as surplus (line 13) available for building up soil storage to its assumed maximum value of 10 cms. or, if this is not required, for run-off. The amount available for run-off annually in the Shannon Catchment is thus computed to be 38.1 cms. per year, out of a total precipitation of 99.3 cms.: since soil storage is not exhausted during the Summer months actual evapo-transpiration proceeds at maximum rates throughout, i.e., equal to potential.

The amount available for run-off, if distributed evenly throughout the year, would give an average flow of 132 cubic metres per second (cusecs); this is 23% less than the average observed flow at Killaloe, 171 cusecs, over the period 1930-1944. (This figure is accepted by E.S.B. Hydrological Engineering Staff as the long-term mean. The average 1893-1941 of 191 cusecs. is considered, on technical grounds, to be 10% high). Thus, the straight-forward application of Thornthwaite's formula to the mean temperatures of the West of Ireland yields values for evapo-transpiration too high by no less than 30%.

In order to determine to what extent the difference actual — computed run-off depends on weather conditions and to discern if circumstances occur in which the formula may be applied directly, it was decided to make a detailed comparison year by year. A series of fifteen years was selected starting in 1933. It was assumed that the monthly rainfall could be adequately represented by the means of the readings from Killaloe, Portumna, Victoria Locks, Athlone and Lough Allen: the legitimacy of this assumption has been proven to very narrow limits. The water surplus was computed month by month as in the example shown above in Table II: the annual totals compared to the measured run-off are shown in Table III, which also indicate roughly the nature of the weather each year.

TABLE III

Average Annual Values of Run-off, Shannon Catchment Basin, 1933-1947

Year	E.S.B. average flow in Cusecs.	Computed average flow in Cusecs.	Diff. in Cusecs.	Diff. in %	Weather compared to Normals[x]
1933	111	67	-44	-40%	Dry, warm.
1934	148	128	-20	-14%	Avg., Avg.
1935	167	125	-41	-25%	" "
1936	178	138	-40	-22%	" "
1937	172	119	-53	-31%	Slightly dry; slightly warm.
1938	216	192	-24	-11%	Wet; cool.
1939	168	131	-37	-22%	Average; slightly warm.
1940	163	142	-21	-13%	Average; warm.
1941	137	100	-37	-27%	Dry; average
1942	169	127	-42	-25%	Average; average
1943	173	117	-56	-32%	Slightly wet; slightly warm.
1944	177	158	-19	-11%	Wet; slightly warm.
1945	159	104	-55	-34%	Average; warm
1946	208	195	-13	-6%	Wet; slightly cool.
1947	239	198	-41	-17%	Wet; warm.
Means:	172	136	-36	-23%	

[x] Cool or warm refer to April-September averages as the P.E. in these months vastly exceeds that in the remaining months.

The percentage differences of computed from actual surplus vary widely,. but in no case is the computed surplus greater than the actual. Possibly significant is the fact that the absolute amount of the differences shows a smaller co-efficient of variation, namely .375, than the percentage differences themselves, .432. This may indicate the quick or flash run-off in each year of a certain nearly constant amount of precipitation which escapes absorption into the soil, but this seems unlikely in view of the general absence of heavy precipitation in Ireland.

Thus, it is clear that the general and particular application of the method is not possible without modifications.

Shannon Airport Drainage Basin

A further test of a similar nature but on a smaller scale may be applied, namely, on the figures of climatic data and drainage from the confined drainage area of Shannon Airport. A map of the Airport area is shown in Fig. 3: an outer drainage channel runs along the northern and eastern boundaries of the Airport, carrying away all drainage from the higher ground around and discharging it into the river. The whole landing area is drained by 4" drains at a depth of two feet, spaced 50 ft. from one another, connected into 9" drains spaced at 550 feet, which themselves discharge into 24" drains 600 feet apart. The latter run WSW to ENE across the field and discharge into the inner Catchment drain, an open ditch, whose contents are pumped out at the pump house. Complete records of amounts pumped off and temperature and rainfall records at the Airport are available since 1939. There are no water sources (wells) inside the drainage area and no water infiltrates from the river, so that the water pumped off represents accurately the difference between rainfall and quantity used in evaporation and transpiration. The opportunity thus provided of testing the Thornthwaite method is better than the test over the Shannon Catchment itself as the area involved is homogeneous in plant cover and soil texture, and the area is so small and the drainage so efficient that the run-off is very quick. Therefore, the problem of estimating when the run-off from any particular rainfall will be detected at the outflow measuring point, almost intractable in the case of the very large (10,600 sq. km.) and very flat Shannon River Catchment, is here avoided, except in the case of rainfall on the last day of the month, when some of the run-off will be grouped into the next month's figures.

The figures for monthly run-off for the years 1939 and 1940, derived from water balances similar to that of Table II, are shown below in Table IV, compared to actual date of amounts pumped off.

TABLE IV.

Monthly Run-off from Shannon Airport Drainage Area, compared to observed quantities, in cms., over the whole area.

Year 1939.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year.
Computed Run-off.	7.9	4.4	3.2	0	0	0	0	0	0	0	10.2	5.3	31.0 cms
Observed Run-off.	10.5	4.8	5.5	0.7	0.4	0	0	0.6	0	0.3	13.4	8.9	45.1 cms
Year 1940: Computed Run-off.	3.4	8.2	2.3	6.2	0	0	0	0	0	0	5.1	9.8	35.0 cms
Observed Run-off.	3.7	9.8	3.3	5.8	0.1	0	0.3	0	0	0.9	7.8	8.2	39.9 cms

Thus, over the small area 780 acres of the Airport drainage, as over the large area of the Shannon River Catchment, the straightforward application of the formula yields run-off figures too low; the discrepancy over the two years quoted amounts to 22%.

The similarity of the discrepancies in these two tests under such dissimilar conditions of area, soil, etc., seems, at first sight, to indicate break-down of the formula in Irish climatic conditions. Closer examination of the figures, however, shows that the greater part of the difference between computed and actual run-off figures arises in the winter months - November, December, January and February. In these months Thornthwaite's formula yields appreciable amounts of evapo-transpiration, of the order 2 cms. per month at mean temperatures near 5°C. These quantities seem unduly large in any climate and especially in the Irish winter climate, for two reasons. Firstly, the measured evaporation from an open sheet of water (3, page 124) for the four months in question in an inland situation (London) averages over 35 years only .69 inches or 1.7 cms., in a coastal exposure (Southport) only .56 inches or 1.4 cms., and it is accepted that evapo-transpiration losses from vegetation never exceed evaporation from an open water surface (11, page 107, 9 page 29, etc.). In fact, Penman estimates that the ratio of transpiration from turf to evaporation from open water similarly exposed is for November-February, inclusive, only 0.6 (12, page 75). Secondly, it must be remembered that it is an essential feature of the theory that transpiration proceeds with growth (1, 8, 9 et. al.), and is thought of as a measure of growth activity. But air temperature, soil temperature and duration of sunshine are low in the winter months and growth is at a standstill, or very slow, so that transpiration must also be very low.

For both reasons, therefore, the amounts of water evaporated according to Thornthwaite's formula, appear much too big for conditions in Ireland or Great Britain. It was, therefore, decided to re-calculate the run-offs shown in Tables II and IV using the amount .3 cms. for evaporation and transpiration in each of the months November to February. The results are given in Tabes V and VI attached.

TABLE V

Observed Rainfall (A) and Run-off (B) in Shannon River Catchment, compared to Run-off computed under assumption of .3 cms. evapo-transpiration per month November-February (C)

Rainfall (A) in cms., Run-off (B and C) in cusecs.

YEAR		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	YEAR
1933	A	9.5	7.6	8.9	3.5	6.4	7.1	7.6	5.6	3.0	6.6	3.8	5.1	
	B	360	274	343	76	74	34	27	10	9	29	50	60	111
	C	350	325	271	135	67	34	17	9	4	2	1	1	101
1934	A	12.3	0.6	8.2	5.4	5.6	4.9	4.7	11.6	14.2	10.7	4.3	14.4	
	B	359	88	154	87	67	14	3	51	157	266	198	329	148
	C	247	124	152	111	56	28	14	7	20	143	154	360	118
1935	A	4.0	9.2	5.1	7.2	3.3	13.7	2.5	8.8	16.2	10.4	11.3	5.9	
	B	259	245	213	132	39	94	25	21	170	237	320	256	167
	C	256	310	190	152	76	54	27	14	32	147	298	263	151
1936	A	12.1	5.8	6.9	5.6	3.2	9.6	17.0	4.3	10.1	6.4	9.6	10.4	
	B	383	255	163	111	53	38	175	106	158	94	292	307	178
	C	372	298	222	150	75	38	115	58	29	15	197	305	156
1937	A	14.5	12.1	5.7	7.5	6.4	4.2	11.7	6.8	11.1	4.5	4.1	5.9	
	B	413	354	278	184	94	42	132	57	124	118	96	179	172
	C	442	462	315	202	101	50	25	13	7	4	61	145	152

TABLE V (Contd.)

Observed Rainfall (A) and Run-off (B) in Shannon River Catchment, compared to Run-off computed under assumption of .3 cms. evapo-transpiration per month November-February (C)

Rainfall (A) in cms., Run-off (B and C) in cusecs.

YEAR		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	YEAR
1938	A	14.0	4.3	4.7	0.4	8.9	9.8	15.1	10.4	6.9	19.5	14.2	9.3	
	B	508	230	167	51	40	95	174	205	79	420	387	423	216
	C	353	258	133	67	34	17	134	95	52	333	450	409	195
1939	A	12.1	8.2	7.0	3.8	3.1	5.8	10.1	5.2	4.6	5.7	22.3	7.3	
	B	454	242	282	81	41	9	36	43	24	41	373	387	168
	C	445	384	272	136	68	34	17	8	4	2	292	289	163
1940	A	7.4	10.1	9.2	8.9	4.9	3.3	9.3	1.8	7.1	13.5	10.2	10.8	
	B	176	397	277	183	92	22	34	5	26	126	299	343	163
	C	290	346	294	222	111	56	28	14	7	6	205	317	154
1941	A	6.5	9.5	7.0	4.2	5.7	2.1	5.7	2.6	2.9	8.5	15.0	6.7	
	B	203	355	194	149	51	15	15	36	16	97	287	242	137
	C	286	311	242	131	66	33	17	8	4	2	173	218	124
1942	A	12.8	3.4	6.8	6.0	10.5	0.6	10.1	14.4	11.5	7.9	2.6	10.7	
	B	323	220	221	197	80	37	31	126	189	213	116	277	169
	C	365	246	192	133	136	68	34	17	54	105	100	262	143

TABLE V (Contd.)

Observed Rainfall (A) and Run-off (B) in Shannon River Catchment, compared to Run-off computed under assumption of .3 cms. evapo-transpiration per month November-February (C)

Rainfall (A) in cms., Run-off (B and C) in cusecs.

YEAR		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	YEAR
1943	A	14.6	5.1	2.8	4.0	8.9	9.0	6.2	13.7	7.0	10.4	9.2	7.4	
	B	431	355	85	63	100	107	25	87	163	197	213	270	173
	C	424	210	155	78	39	19	9	14	19	130	247	269	143
1944	A	12.2	4.4	1.1	5.2	5.8	6.4	10.9	9.1	12.1	13.2	15.8	12.5	
	B	305	226	47	60	26	35	54	42	196	267	391	478	177
	C	387	273	137	68	34	17	9	4	17	199	417	458	168
1945	A	7.5	10.1	4.8	4.0	9.5	10.5	9.6	6.5	9.5	11.0	3.0	11.9	
	B	233	415	132	108	69	93	150	48	100	146	139	293	159
	C	376	388	200	100	52	55	28	14	7	102	106	290	143
1946	A	12.2	11.6	3.3	3.4	5.6	8.9	11.1	13.8	15.7	5.7	12.0	13.9	
	B	393	497	131	54	27	53	94	125	369	204	236	440	208
	C	389	426	215	108	54	27	14	115	244	140	309	433	206
1947	A	10.5	5.4	12.9	9.9	11.1	10.7	8.9	3.7	10.1	10.8	15.5	9.4	
	B	435	151	457	301	177	151	152	83	72	160	442	282	239
	C	424	323	385	303	232	148	74	37	19	28	325	348	221

TABLE VI

Rainfall and Run-off from Shannon Airport Drainage Area, assuming Evapo-transpiration 0.3 cms. per month November to February, in cms.

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
1939: **Rainfall cms.**	9.4	7.1	6.4	3.2	3.5	5.1	9.3	6.6	3.1	4.0	23.7	6.5	
Run-off observed cms.	10.5	4.8	5.5	.7	.4	0	0	.6	0	.3	13.4	8.9	45.1
Run-off computed cms.	9.1	6.8	3.2	0	0	0	0	0	0	0	13.2	6.2	38.5
1940: **Rainfall cms.**	4.4	10.6	6.0	11.5	2.5	2.9	9.3	0.4	6.6	11.9	10.3	11.4	
Run-off observed cms.	3.7	9.8	3.3	5.8	.1	0	.3	0	0	.9	7.8	8.2	39.9
Run-off computed cms.	4.1	10.3	2.3	6.2	0	0	0	0	0	0	7.5	11.1	41.5

The average deficiency under the assumption stated is 9% over the Shannon River Catchment, and 6% over the Airport Catchment, an agreement which may be considered close enough to be of practical value. Thus, the application of the Thornthwaite formula and procedure, modified by the assumption of only .3 cms. evaporation and transpiration losses per winter month, will yield values for run-off which agree closely with the observed values: it must, however, be noted that the greatest disagreement between computed and observed values invariably occurs at the end of the summer dry spell, when observed run-off increases more quickly than the computed values. Though this effect has been a small influence on the annual averages, it is of importance for reliable estimation of time of onset of winter flow conditions for those interested in hydrology or drainage. Doubtless, the discrepancy could be eliminated by making suitable assumptions concerning the soil moisture storage capacity; but this must await the further study of the soil in Ireland.

Experimental Installation of Evapo-transpirometers in Valentia Observatory:

An installation designed to measure evapo-transpiration, consisting of four cylindrical tanks similar to the one shown in Fig.1 has been in operation at Valentia since July, 1952. The mode of operation is to sprinkle on the surface of each tank an amount of water sufficient to ensure some run-off each day; thus, adequate soil moisture throughout the soil in each drum is ensured, so that the figures deduced for water use correspond to the definition of potential evapo-transpiration. Obviously, the potential evapo-transpiration is the difference rainfall plus applied water minus measured run-off. The rainfall is measured in a rain-gauge close at hand, and the whole observational area is well-exposed to prevailing weather conditions. Since the percolation of watet through the soil is inevitably subject to some delay, it may occur that a rainfall occurring towards the end of a day and, therefore, recorded with the applied water for that day, will not appear as run-off until the next day, or even later. Thus, the daily figures for water use may be subject to great fluctuations and it will be necessary to sum them over periods of at least a week to ten days. The longer the period over which the figures are totalled, the less important the influence of accidental fluctuations. For this reason, the figures for measured evapo-transpiration over calendar months are compared below in Table VII with those expected from Thornthwaite's formula.

TABLE VII

	Aug. '52	Sept. '52	Oct. '52	Nov. '52	Dec. '52
P.E. measured (cms.)	9.1	5.8	3.5	.8	.3
P.E. computed (cms.)	9.1	5.7	3.4	2.3	2.4

	Jan. '53	Feb. '53	Mar. '53	Apr. '53	May '53
P.E. measured	1.1	0.6	3.7	5.3	3.9
P.E. computed	2.4	2.5	3.5	4.2	7.0

While the figures thus far available are too scanty to form the basis of a new formula, they do verify to a remarkable degree the applicability of the modified Thornthwaite procedure already deduced from examination of the run-off figures for the Shannon River and Shannon Airport Catchment Basins. It will be noted that the P.E. measured in November 1952 was .8 cms.; this may appear high in comparison with the .3 cms. assumed in the calculation of run-off: but it must be borne in mind that Valentia is in the warmest region of Ireland, whereas the figure .3 cms. is to be applied as an average figure over the inland areas of the catchments described where winter temperatures are considerably lower than at Valentia.

Accepting the agreement between measured and computed P.E. at Valentia August to October, 1952 and March, 1953 onwards as proof of the applicability of Thornthwaite's formula during the growing season, and thus avoiding the difficulties raised by the lack of agreement during the winter, we can proceed to draw monthly maps showing the adequacy or inadequacy of rainfall to meet the demands made by evaporation and transpiration. The accompanying two series of maps (Figures 4-11 and 12-16), show (1) the difference rainfall minus evapotranspiration for each of the months March to October, and (2) the accumulated soil moisture deficits at the end of the months June to October. The material on which the maps are based comprises the British Rainfall atlas monthly means 1881-1915 and the monthly mean temperatures for the same period. The computation of monthly Potential Evapotranspiration follows the method indicated above. Since the gradient of temperature over Ireland is but slight, the computed Potential Evapotranspiration varies but slightly from point to point, so that the maps reflect largely the variations of rainfall.

It is essential to bear in mind that the maps present an average picture. Large divergences from this average may occur in individual years.

The first series, (Figures 4 to 11) shows how and where the measured rainfall exceeds the losses by evaporation and transpiration. Where positive values are mapped there is water available in excess of the needs of the plant cover: negative values indicate that rainfall falls short of the amount of water required by the plant cover which must then draw on the reserve of moisture in the root zone of the soil.

Throughout the country rainfall is more than adequate in the months of March and April, great excesses occuring, as is to be expected, in all the mountainous areas of Donegal, Connemara, Kerry and Wicklow. In May, however, as temperature rises and increasing growth occasions increasing transpiration, a slight deficiency occurs all over the country except in the mountainous areas. The deficiency again occurs in June, when only small areas in Donegal, Connemara, Kerry and Wicklow experience an excess. July presents a similar picture but the increase of rainfall in August combined with slight fall in temperature and shortening days causes a surplus of water everywhere except in Louth and Dublin and South Tipperary and Limerick. In September a slight deficiency occurs over most of the Central Plain, but in October large surpluses occur everywhere.

The second series of maps (Figures 12 to 16) shows the net soil moisture withdrawals accumulated at the end of June, July, August, September and October. It will be seen that the withdrawals from soil moisture amount to 8 - 9 cms. by the end of September in Co.Louth, Dublin and part of Tipperary. The surpluses of October reduce this deficit of soil moisture very considerably and from November to April a surplus of water is available everywhere.

The withdrawals of moisture to meet the demands of evaporation and transpiration will be detrimental to the development of plants in areas where the root zone of soil is incapable of holding sufficient moisture to meet these withdrawals. Thornthwaite believes the average soil moisture reserve in the United States is about 10 cms. Other workers in England have postulated a figure of about 8 cms.

If it be assumed that the root zone of the soil in Ireland can hold on the average 10 cms. of water available to plants for their transpiration needs, then it is apparent from the second series of maps that, in a "normal" year, no place in Ireland suffers from water shortage sufficiently intense to affect growth adversely. In years drier than normal, however, water shortage may reduce crop yields over the whole area of the Central Plain.

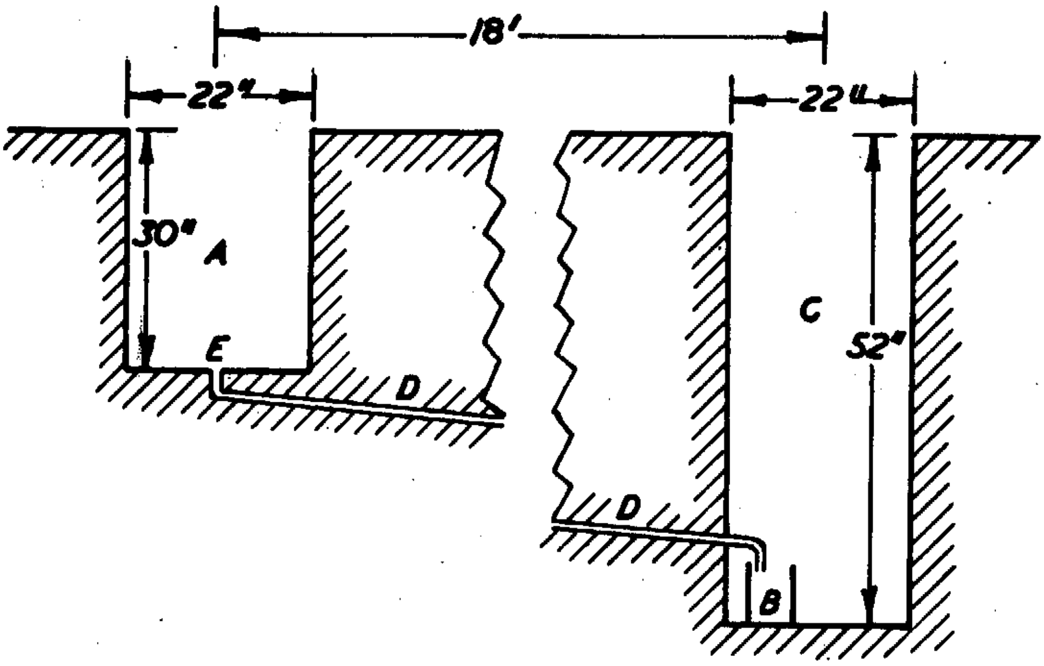
A possible application of the maps would be the determination of areas climatically suitable for different types of crops. For instance, it might seem unwise to attempt the cultivation of cereals in areas where rainfall exceeds evapo-transpiration in July and August, as the ripening and drying might be severely handicapped in such areas. Crops needing abundant soil moisture might best be concentrated in areas where the soil moisture deficit is low.

Conclusions:

Experience to date, namely, the computation of run-off over a very large basin, the Shannon River above Killaloe, and a small one, the Shannon Airport Drainage Area, and the direct measurement of potential evapo-transpiration at Valentia, suggests that the Thornthwaite formula for potential evapo-transpiration as a function of temperature works well in the Irish climate except in the winter months, when it yields figures of water use through evaporation and transpiration which are much too high. Consideration of the magnitude of evaporation alone, known from observations at Valentia and locations in Great Britain, together with estimates of growth rates during the winter season, confirm this conclusion.

Calculation of run-off under the arbitrary assumption that evaporation and transpiration together amount to, say, .3 cms. per month November to February has given results good enough to encourage the use of the procedure for estimating soil moisture deficits, volume of drainage water and time of running of drainage works as well as predicting river run-off.

Experimental work now in progress will, it is hoped, provide a solid basis for a modification of the Thornthwaite formula which will fit it more closely to the climatic conditions existing here.



A. Drum: contains 3" gravel on bottom, filled up with soil

B. Small can to catch drainage water

C. Central pit containing drainage can; walls lined to prevent collapse

D. One inch copper pipe

E. Outlet covered by strong copper screen for drainage from tank.

FIG.1

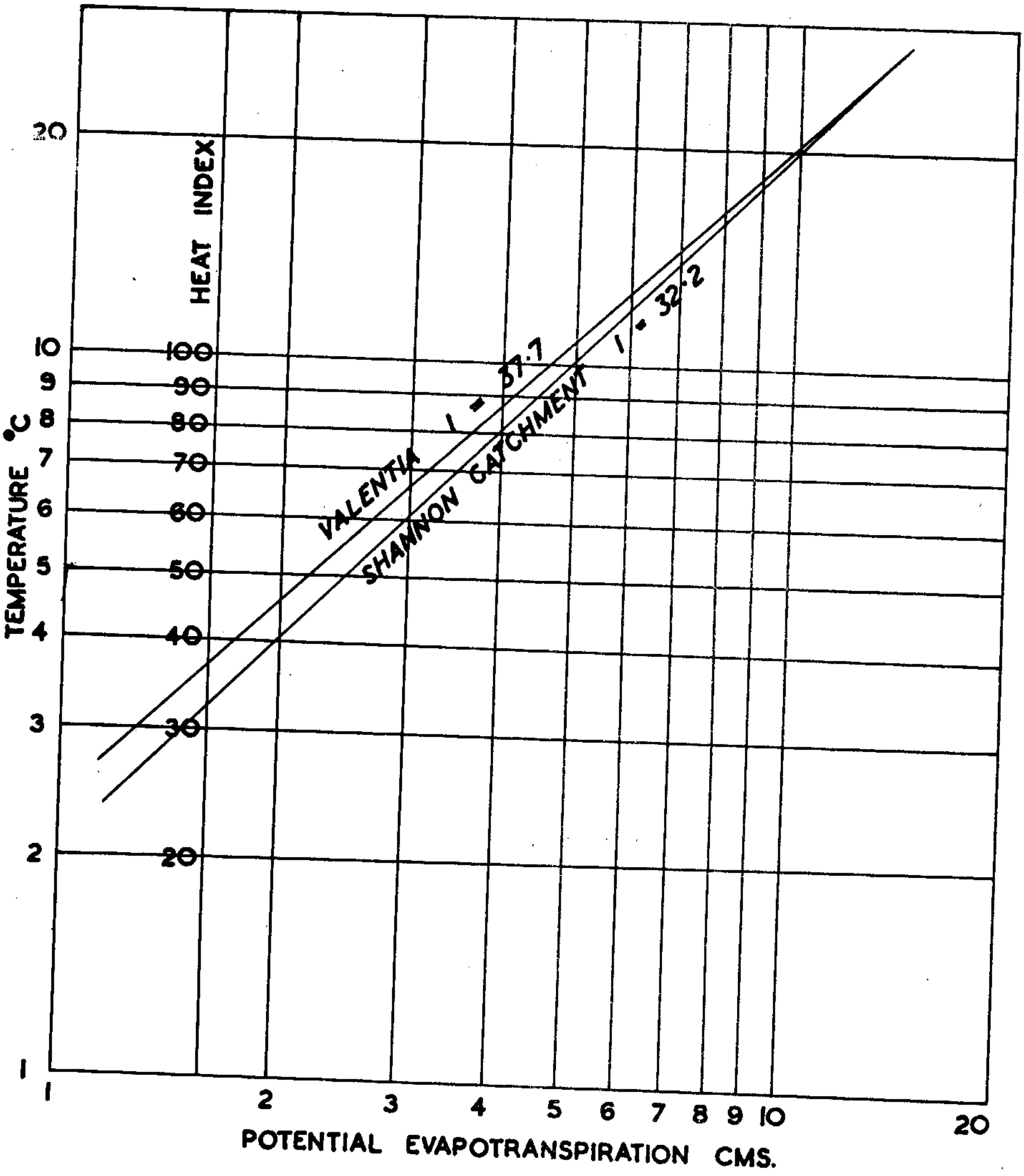
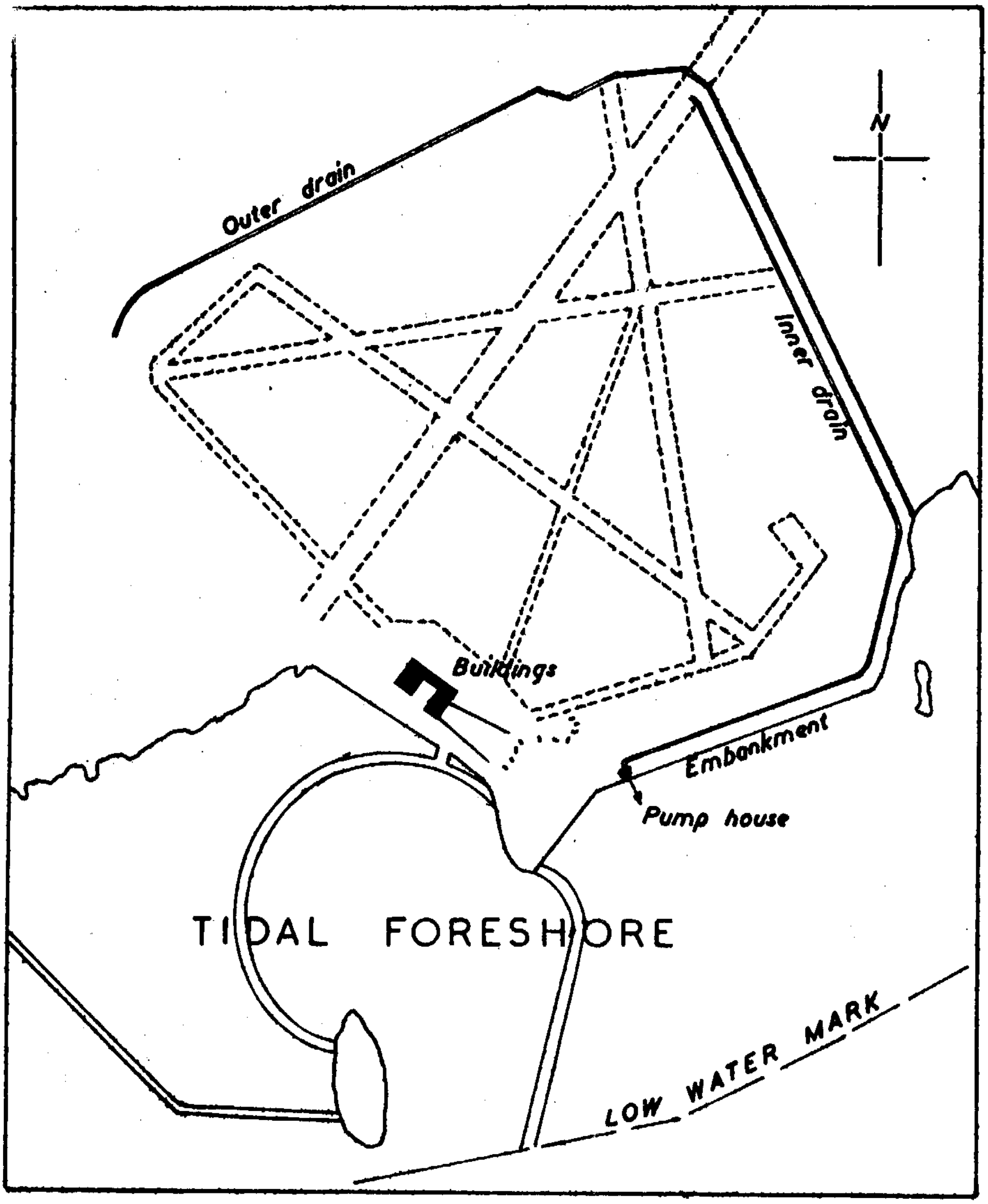

HEAT INDEX
TEMPERATURE °C
20
10
9
8
7
6
5
4
3
2
1
100
90
80
70
60
50
40
30
20
VALENTIA I = 37·7
SHANNON CATCHMENT I = 32·2
1
2
3
4
5
6
7
8
9
10
20
POTENTIAL EVAPOTRANSPIRATION CMS.

FIG. 2

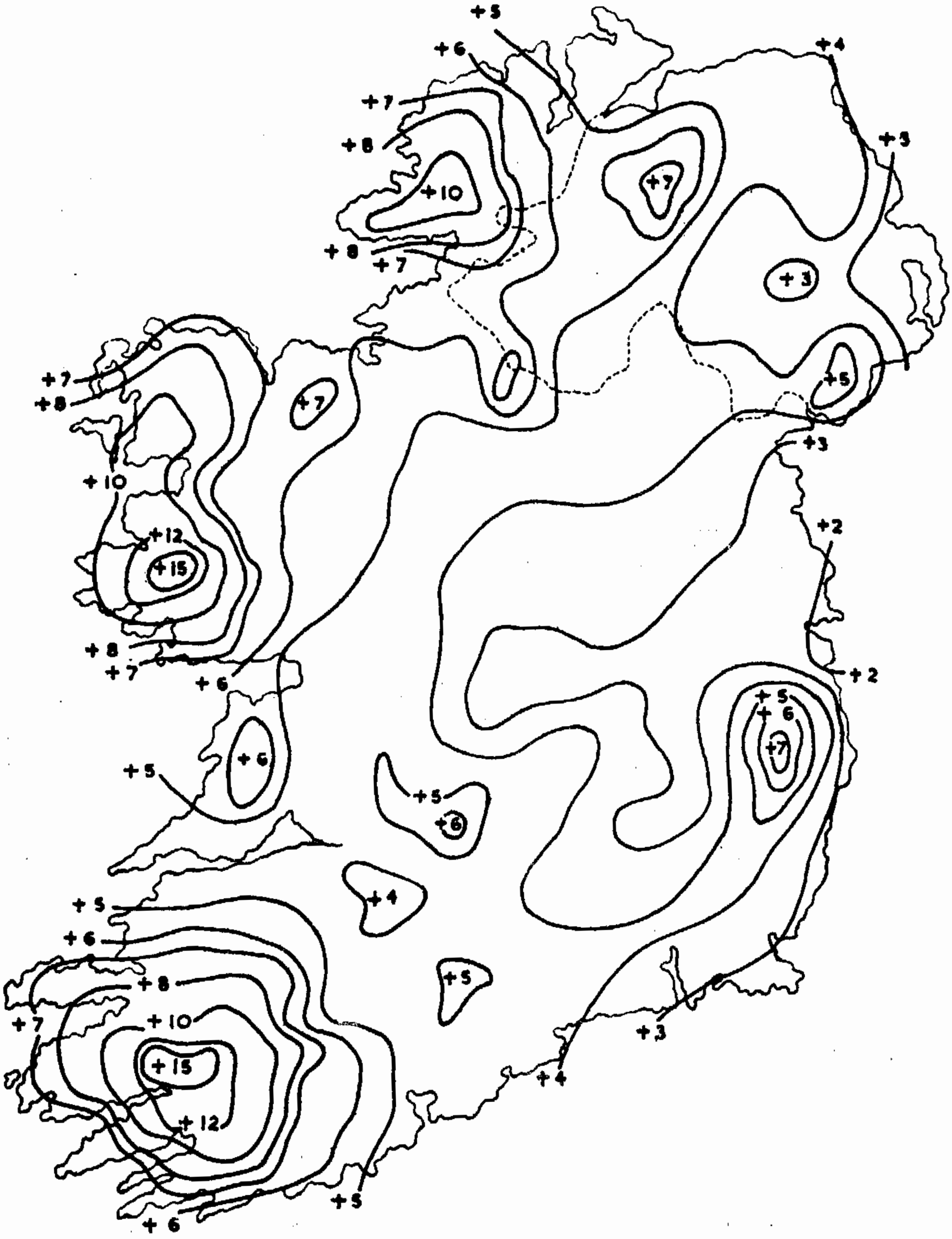


SHANNON AIRPORT

FIG. 3

RAINFALL – EVAPOTRANSPIRATION (CMS)
(MEANS 1881 – 1915)

MARCH

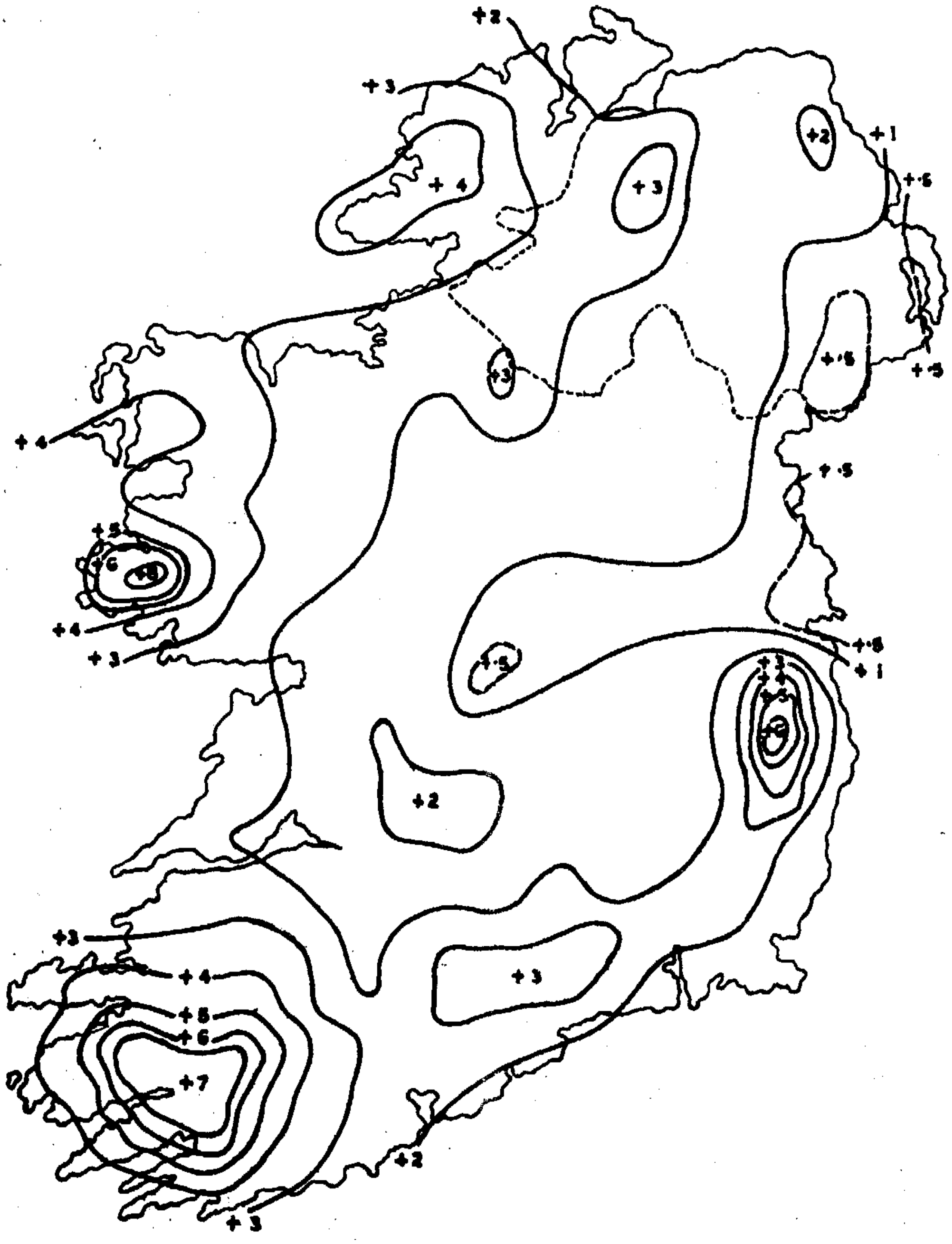


+ = *Excess water to be drained off*
− = *Withdrawals from soil moisture reserves*

FIG. 4.

RAINFALL – EVAPOTRANSPIRATION (CMS)
(MEANS 1881 – 1915)

APRIL

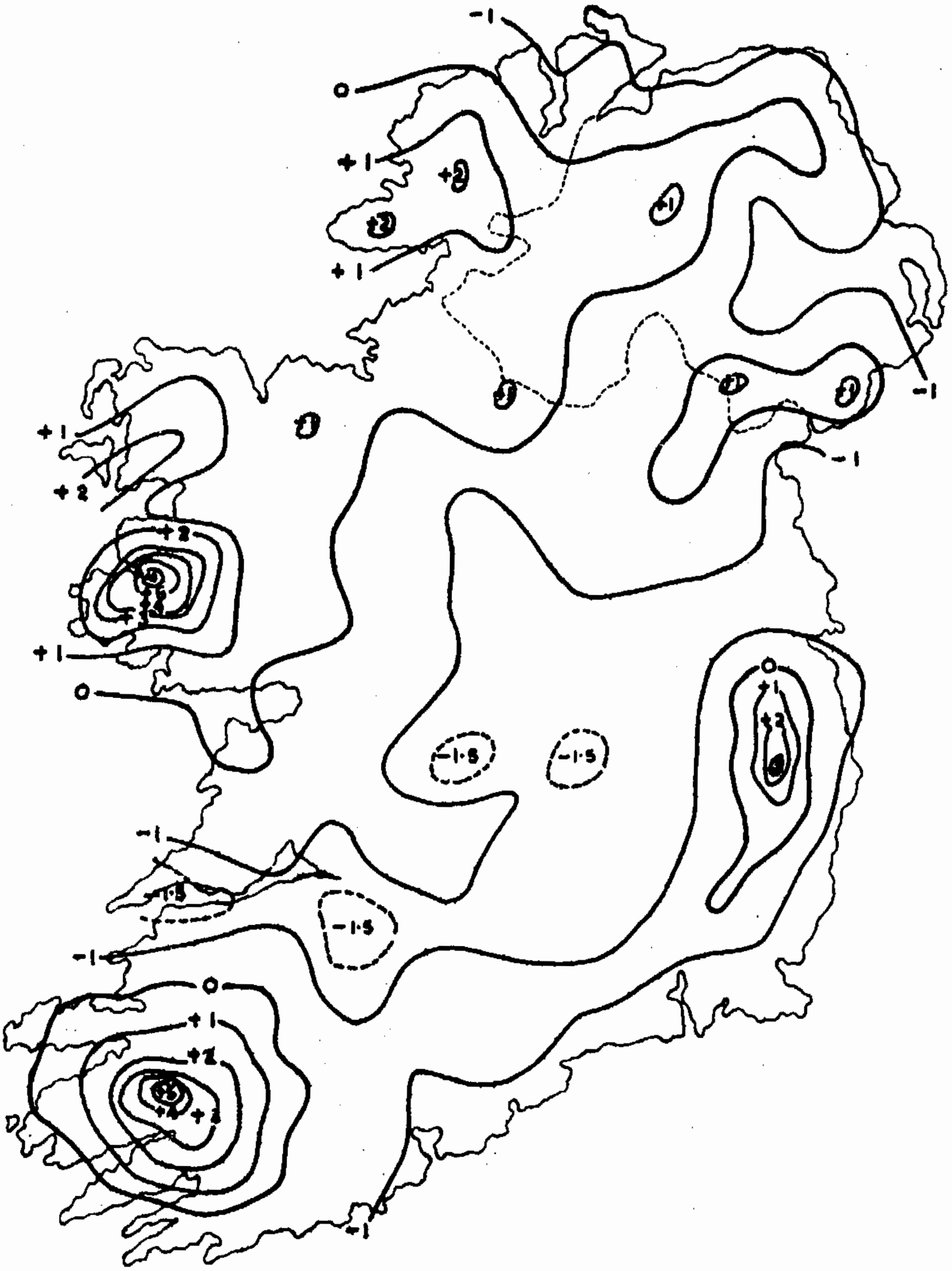


+ = *Excess water to be drained off*
– = *Withdrawals from soil moisture reserves*

FIG. 5.

RAINFALL – EVAPOTRANSPIRATION (CMS)
(MEANS 1881 – 1915)

MAY

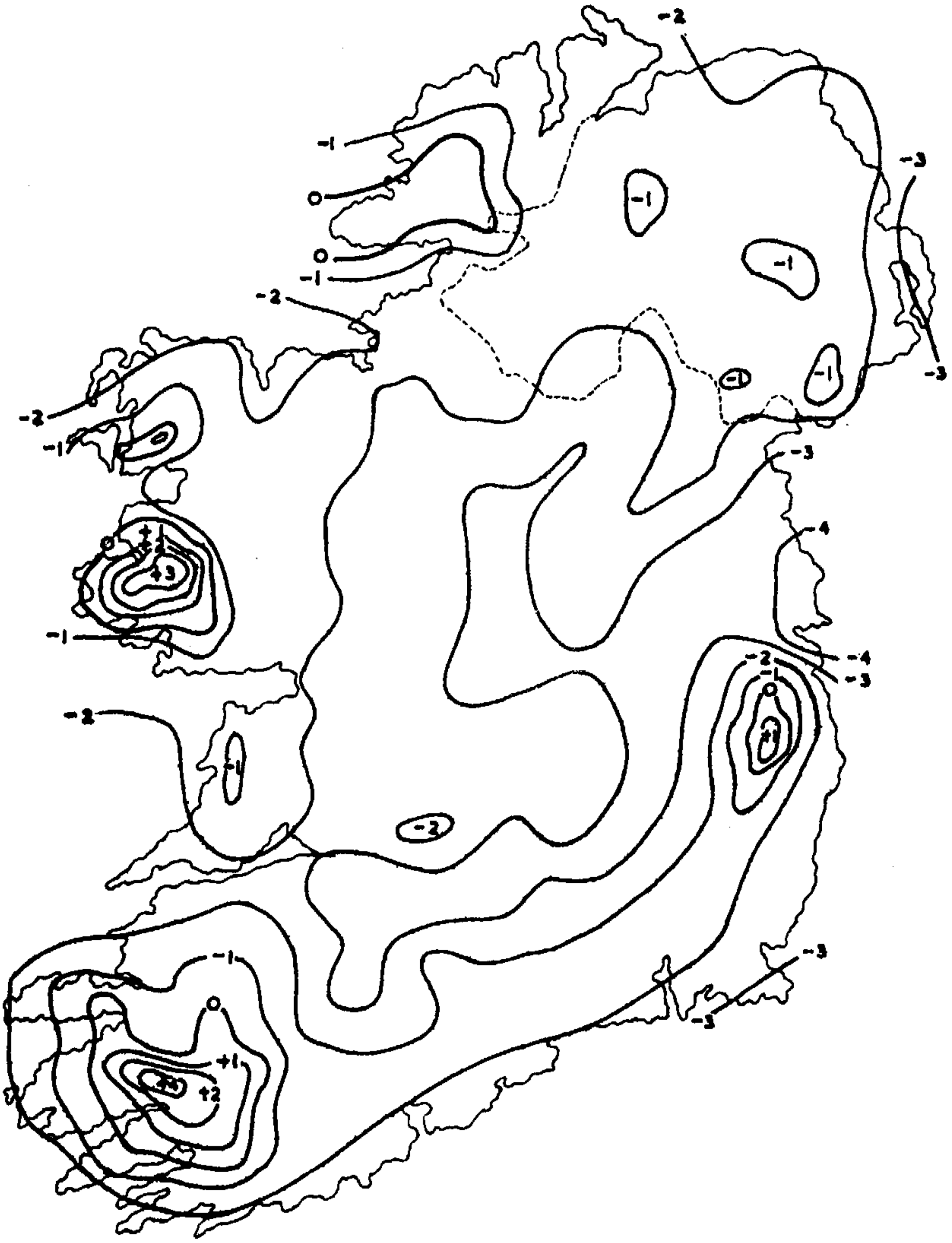


\+ — *Excess water to be drained off*
– — *Withdrawals from soil moisture reserves*

FIG. 6.

RAINFALL – EVAPOTRANSPIRATION (CMS)
(MEANS 1881 – 1915)

JUNE

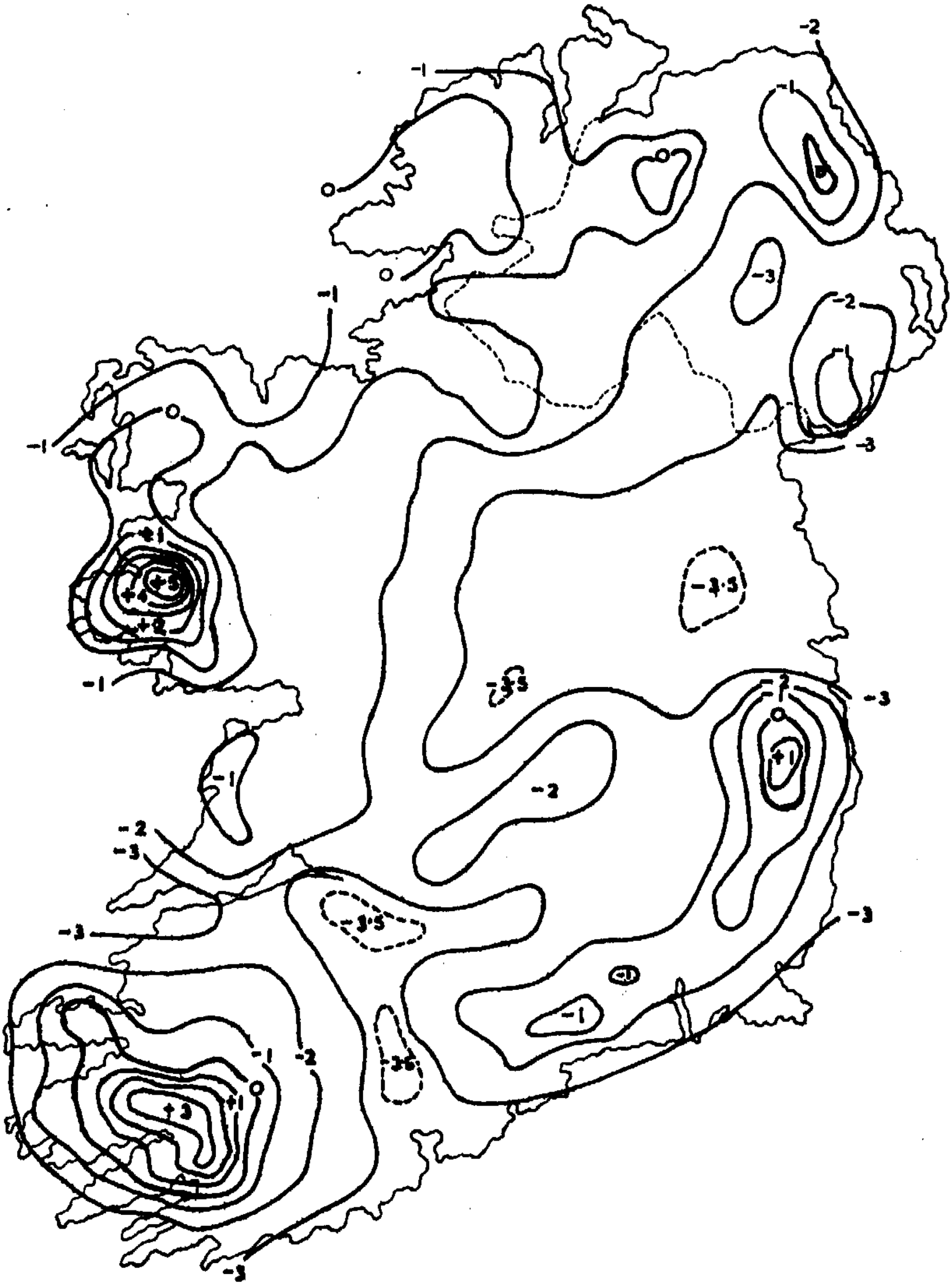


+ = *Excess water to be drained off*
– = *Withdrawals from soil moisture reserves*

FIG. 7.

RAINFALL — EVAPOTRANSPIRATION (CMS)
(MEANS 1881 — 1915)

JULY

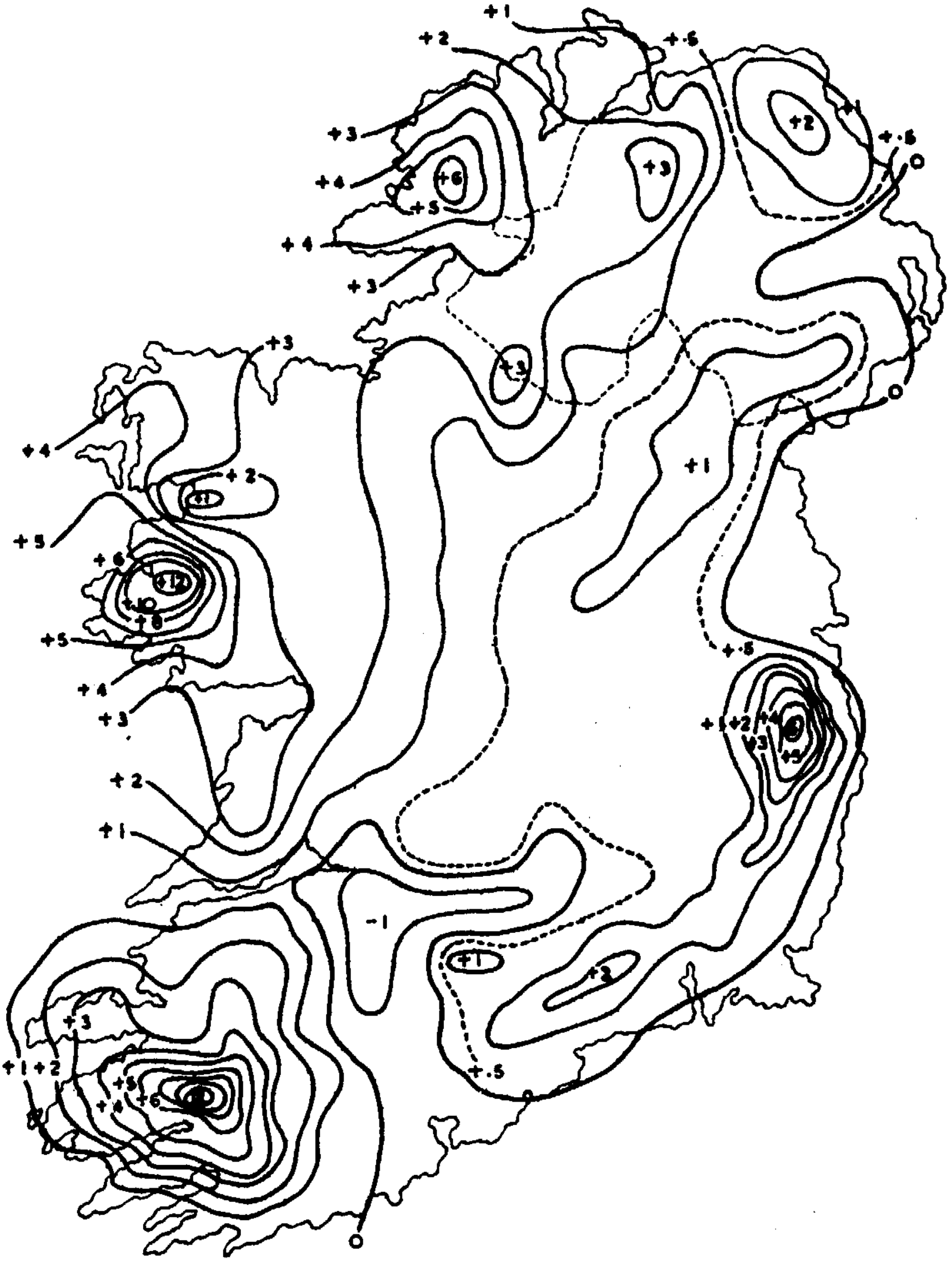


+ — *Excess water to be drained off*
− — *Withdrawals from soil moisture reserves*

FIG. 8.

RAINFALL – EVAPOTRANSPIRATION (CMS)
(MEANS 1881 – 1915)

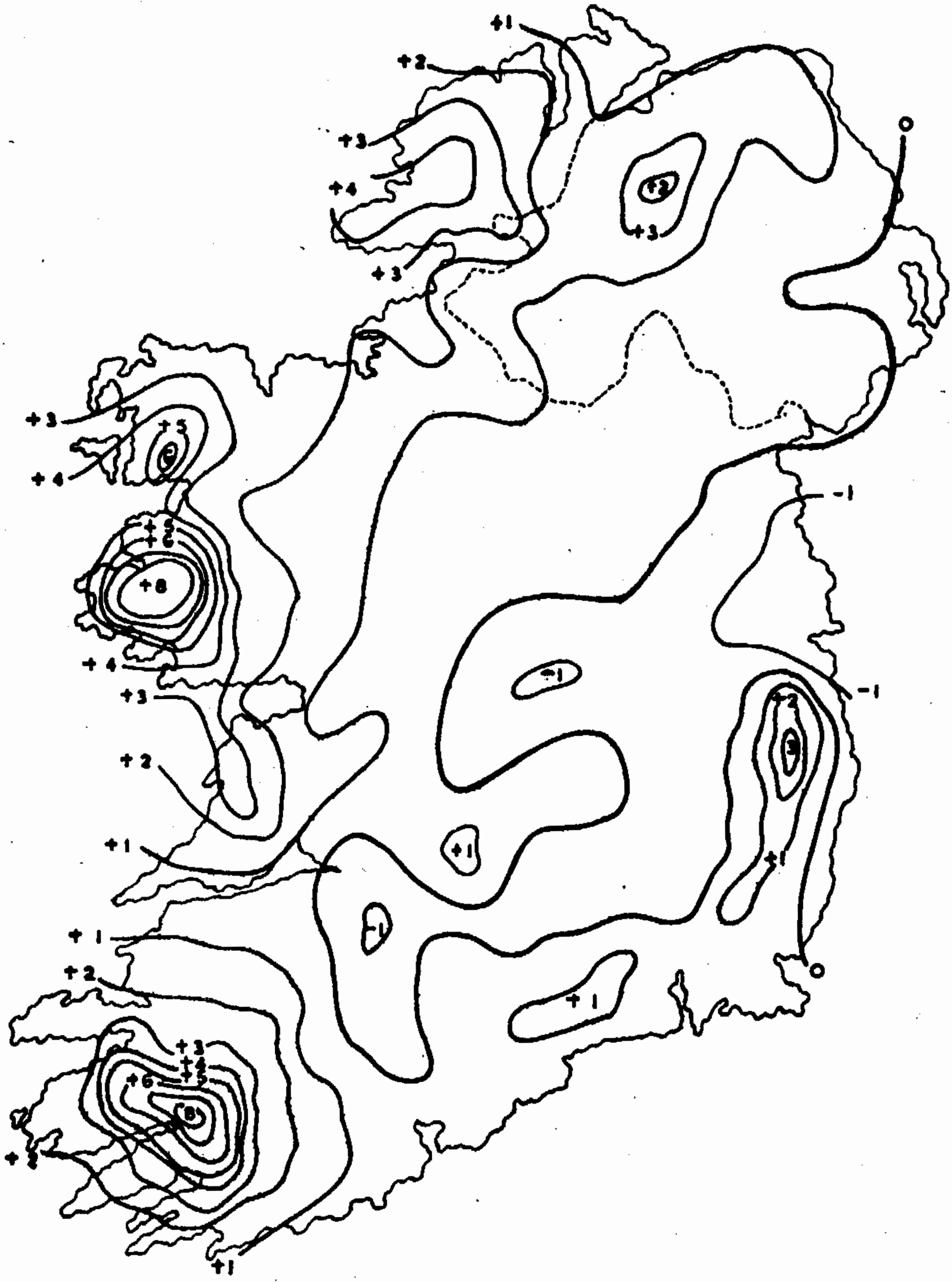
AUGUST



\+ = *Excess water to be drained off*
\- = *Withdrawals from soil moisture reserves*

FIG. 9.

RAINFALL – EVAPOTRANSPIRATION (CMS)
(MEANS 1881 – 1915)
SEPTEMBER

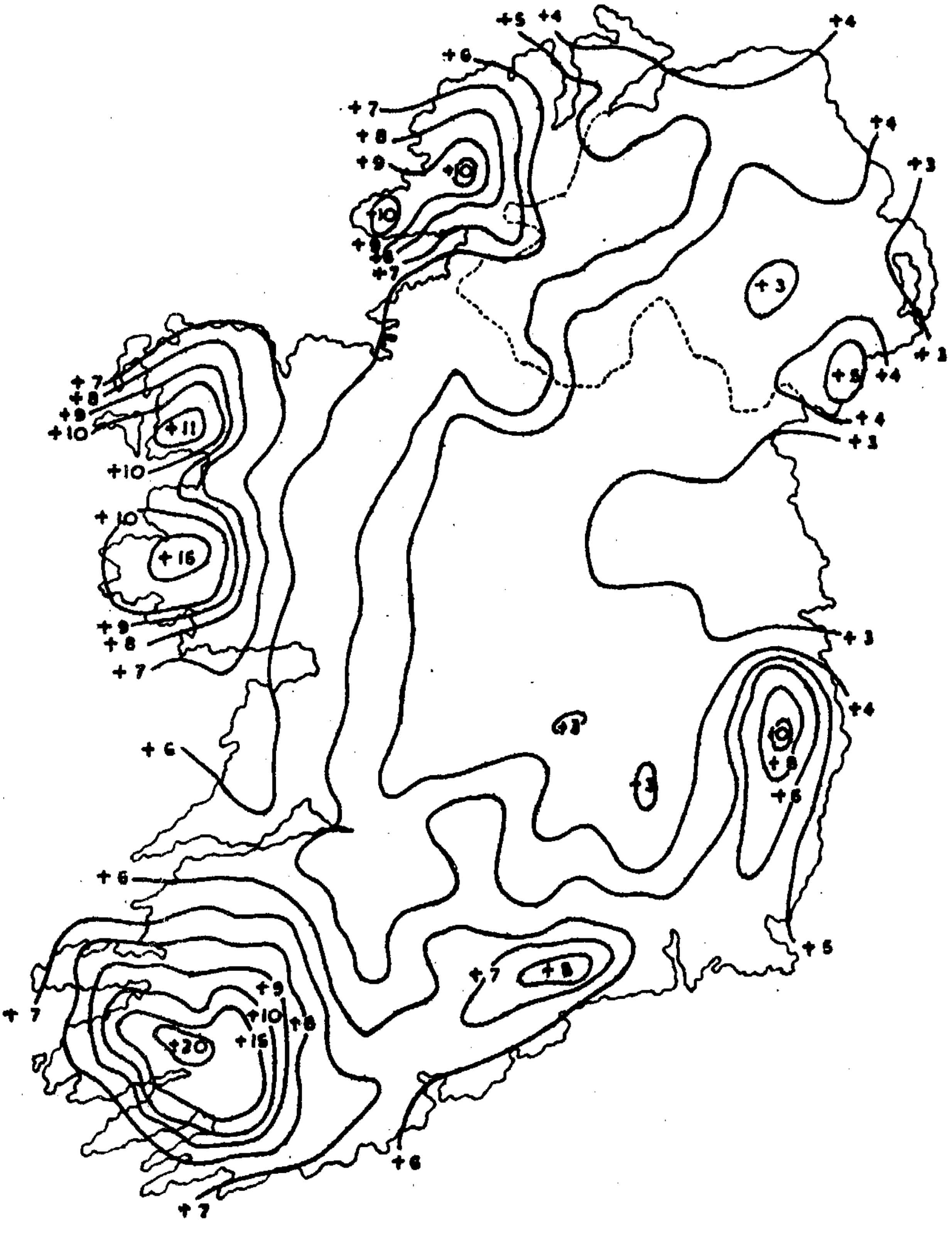


+ = *Excess water to be drained off*
– = *Withdrawals from soil moisture reserves*

FIG. 10.

RAINFALL – EVAPOTRANSPIRATION (CMS)
(MEANS 1881 – 1915)

OCTOBER



\+ = *Excess water to be drained off*
\- = *Withdrawals from soil moisture reserves*

FIG. 11.

ACCUMULATED WITHDRAWALS OF MOISTURE FROM SOIL RESERVES AT END OF

JUNE

(MEANS 1881 – 1915)

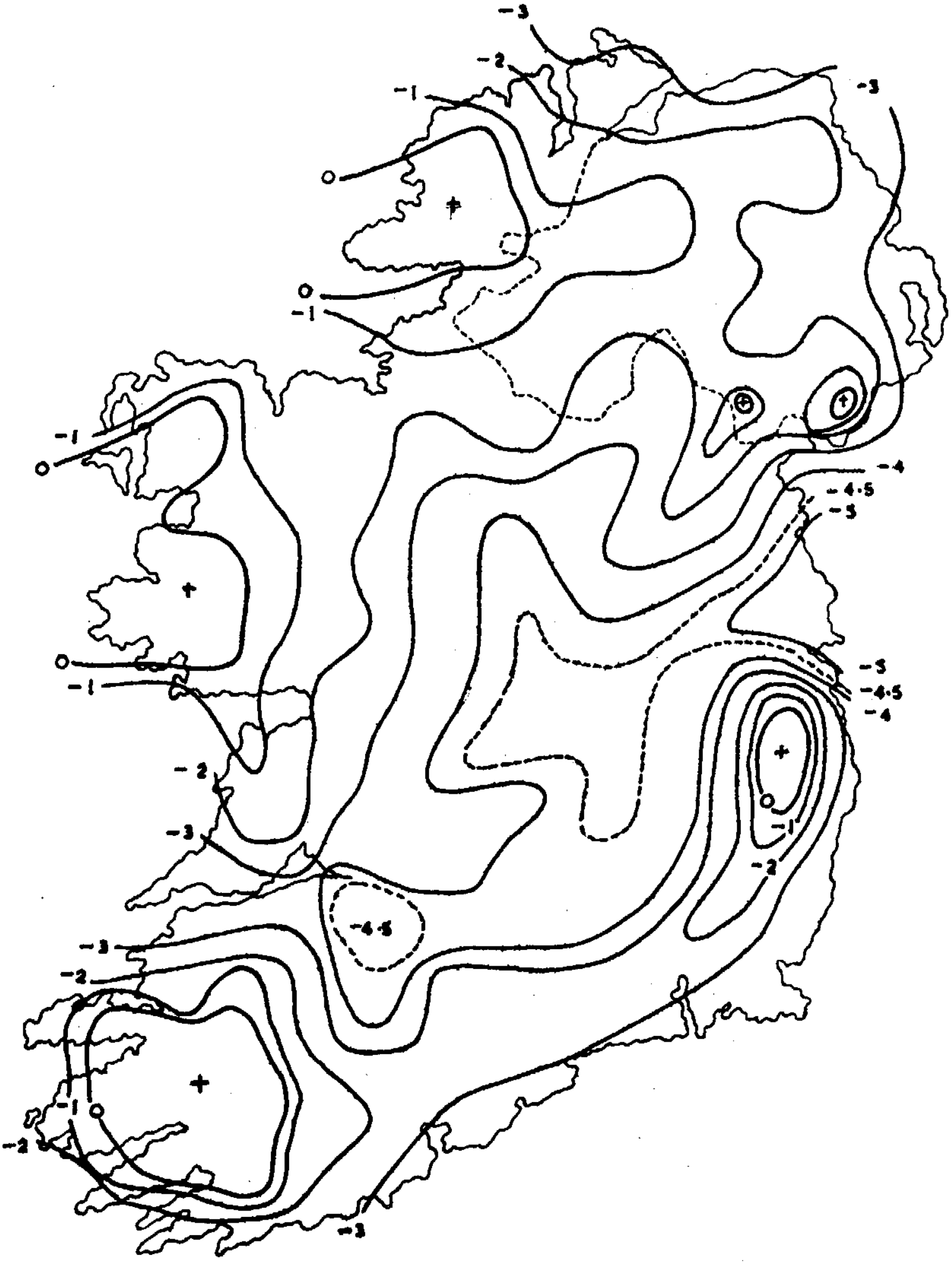


FIG. 12.

ACCUMULATED WITHDRAWALS OF MOISTURE FROM SOIL RESERVES AT END OF

JULY

(MEANS 1881 – 1915)

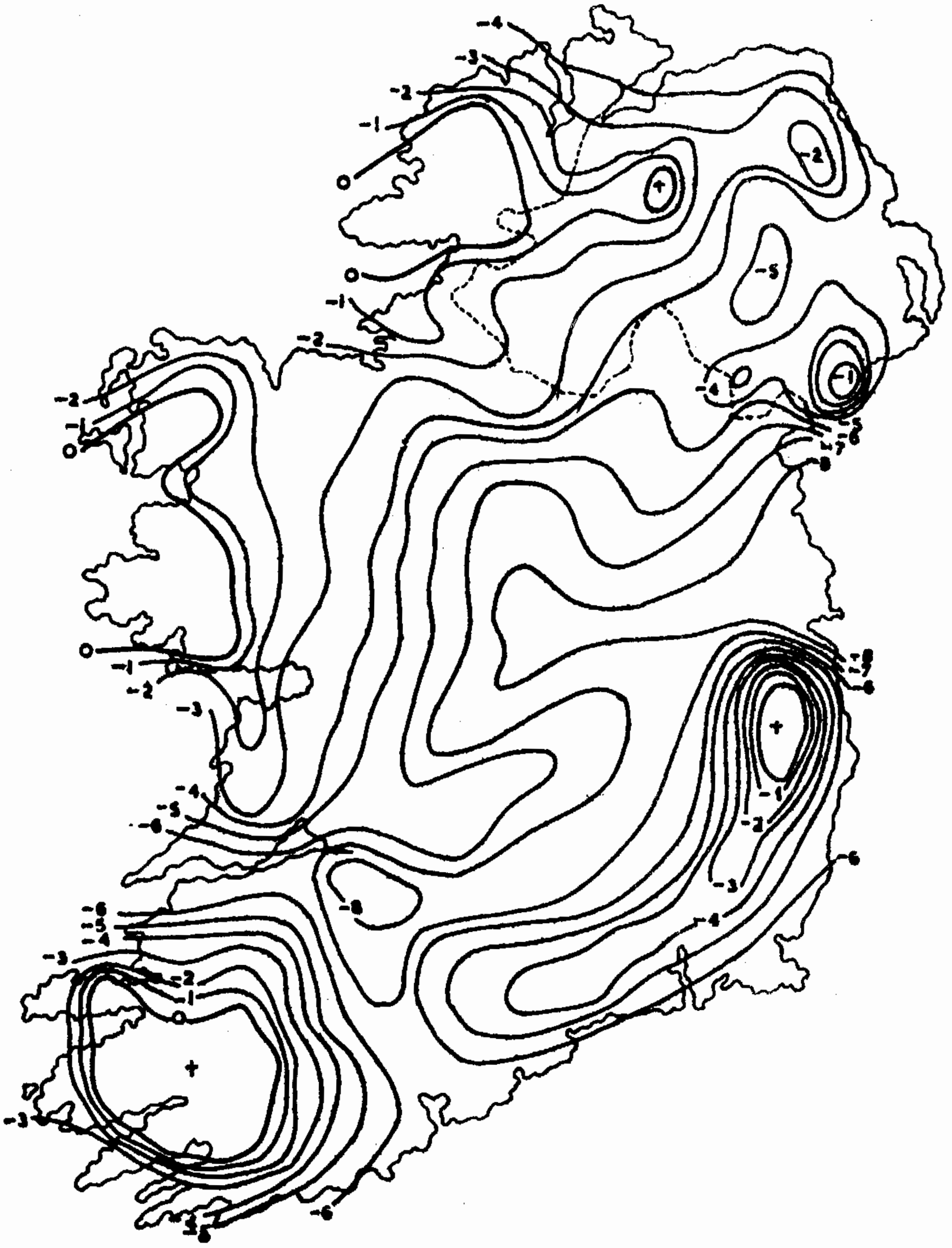


FIG. 13.

ACCUMULATED WITHDRAWALS OF MOISTURE FROM SOIL RESERVES AT END OF

AUGUST

(MEANS 1881 – 1915)

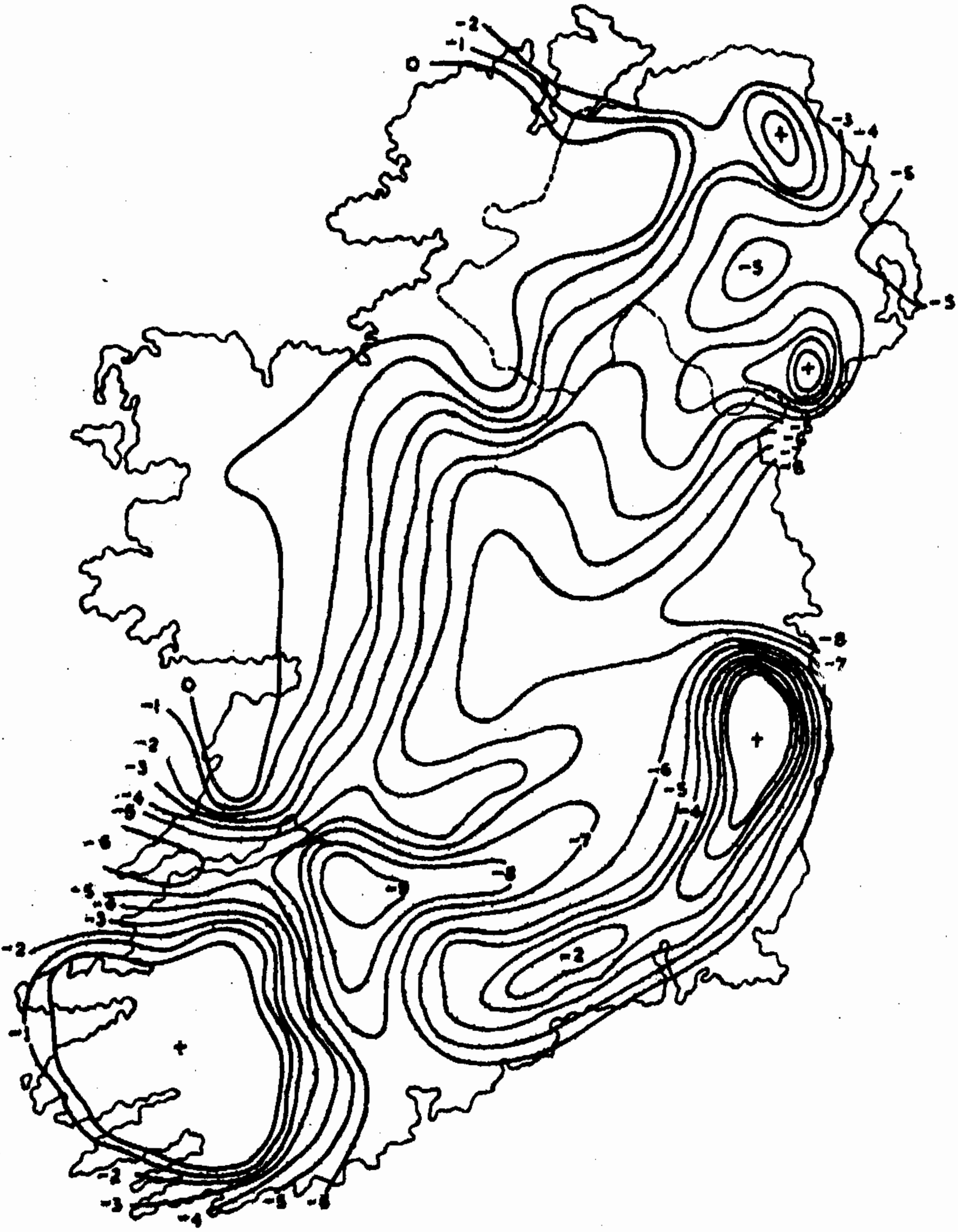


FIG. 14.

ACCUMULATED WITHDRAWALS OF MOISTURE FROM SOIL RESERVES AT END OF

SEPTEMBER

(MEANS 1881 – 1915)

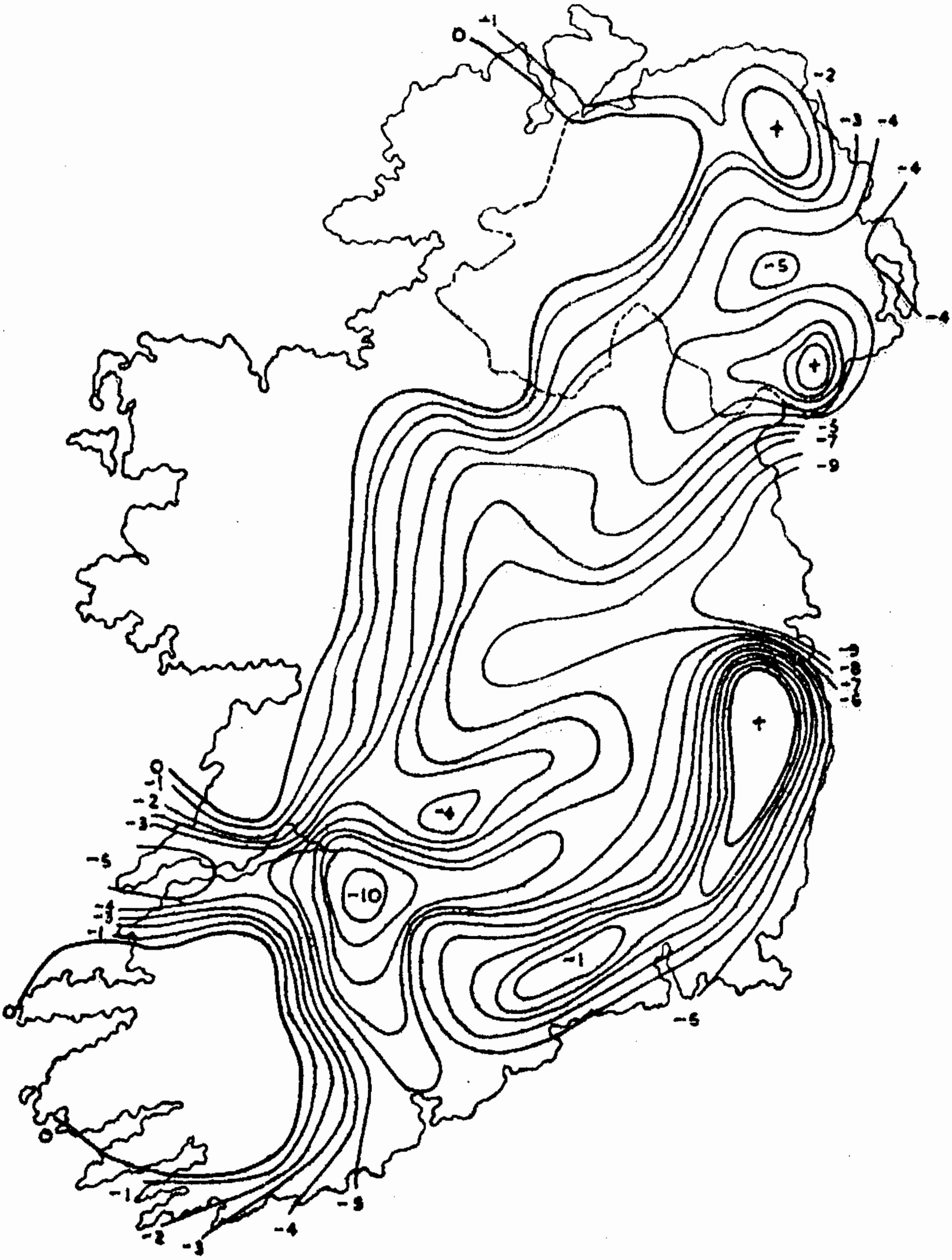


FIG. 15.

ACCUMULATED WITHDRAWALS OF MOISTURE FROM SOIL RESERVES AT END OF

OCTOBER

(MEANS 1881 – 1915)

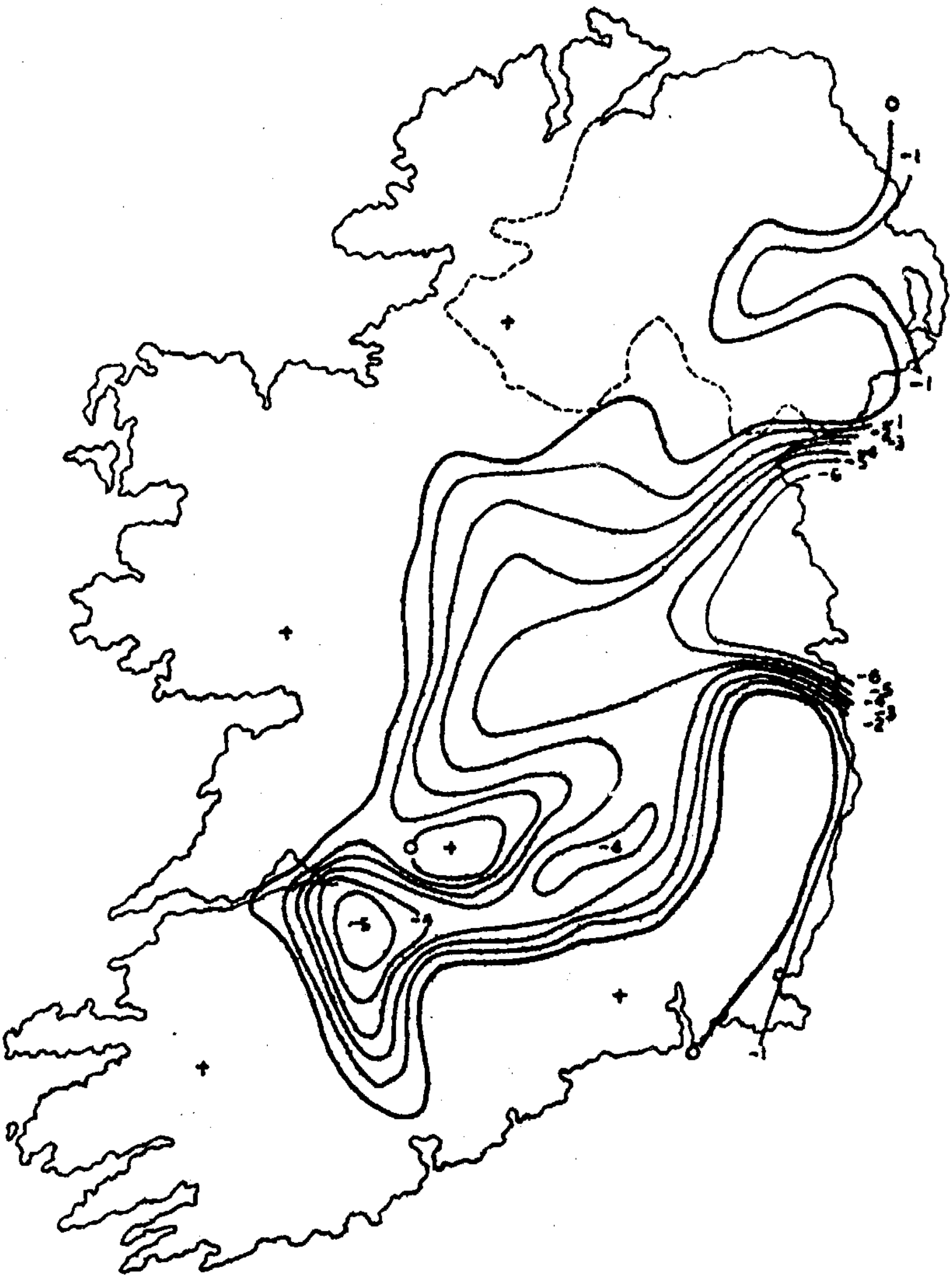


FIG. 16

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