VEÐURSTOFA ÍSLANDS
THE ICELANDIC METEOROLOGICAL OFFICE

EVAPORATION AND POTENTIAL EVAPOTRANSPIRATION IN ICELAND

BY

MARKÚS Á. EINARSSON

REYKJAVÍK 1972

CONTENTS

EVAPORATION AND POTENTIAL EVAPOTRANSPIRATION IN ICELAND

BY

MARKÚS Á. EINARSSON

(THE ICELANDIC METEOROLOGICAL OFFICE)

1. INTRODUCTION

Although knowledge of evaporation and potential evapotranspiration is of importance in many scientific fields such as agricultural research and water management, almost no measurements or computations of these elements have been performed in Iceland so far. Only in summartime during the last three years a class "A" pan has been operated at Reykjavík. A consideration of the problem has therefore been urgently needed.

The following investigation is an attempt to give estimates, with the aid of Penman's equation, of evaporation from an open water surface (E_o) and potential evapotranspiration (E_p) from a grass covered surface and to discuss the distribution of the same. The calculations are based on distribution maps for global radiation previously found by the author for the period 1958–1967 (Einarsson, 1969) and meteorological data from 28 weather stations for the same period. The distribution of E_o for the year and of E_p for the periods May–August, April–September and the year are mapped. Further the potential water balance ($P-E_p$) is calculated and mapped according to the values of E_p and precipitation normals (P) for the period 1931–1960.

The WMO Technical Note No. 83 (1966) gives the following definitions of the terms evaporation and potential evapotranspiration:

Evaporation: "Emission of water vapour by a wet or a free surface of water, in liquid or solid state, at a temperature below boiling point".

Potential evapotranspiration: "Maximum quantity of water capable of being lost, as water vapour, in a given climate, by a continuous stretch of vegetation covering the whole ground when the soil is kept saturated. It thus includes evaporation from the soil and transpiration from the vegetation from a specified region in a given time interval".

Potential evapotranspiration is mainly controlled by meteorological factors such as radiation, temperature, wind and saturation deficit, and many empirical formulae have been introduced to calculate it from different factors, since direct measurements are difficult to make. The most widely used methods are probably those of Thornthwaite and Penman. The former is based on climatological correlations with monthly mean air temperatures, while the Penman formula is a combination of aerodynamic and energy-balance approaches to the problem, and seems to have a rather sound physical basis. Several authors have compared the two methods. Van Wijk, De Vries and Van Duin (1953) found a reasonable agreement in yearly values, while monthly values show a shift in phase of about one month. Penman's values are found to be nearly in phase with solar radiation while those according to Thornthwaite are in phase with temperature. If advective heat transfer is not important the former view is favoured by theory according to the authors.

In a later paper (Van Wijk and De Vries, 1954) these results are confirmed. The conclusion is, that a method based on monthly temperatures cannot be supposed to have sufficient general validity under varying meteorological conditions. It is not theoretically permissible to use temperature as an indication of the energy available for evaporation. Thornthwaite's formula cannot therefore be used to calculate monthly values of potential evapotranspiration. If the values are right in spring they are much too high in winter.

The Penman formula on the other hand incorporates available energy, and only a part of the equation is in phase with temperature. Evaporation is therefore somewhat retarded in comparison with solar radiation, but the effect is generally small, especially in summer.

Aslyng (1960) has made comparisons between measurements with evaporimeters and estimates according to Thornthwaite's and Penman's formulae. His results are similar to the above mentioned. Penman's method gives values of the same order as the evaporimeters during the first five months of the year whereas for the last seven months it yields lower values. Thornthwaite's method gives too low figures during the first five and too high during the last five months of the year.

As Penman's method seems to give the most reliable results according to the quoted papers it has been adopted in this investigation. It may also be mentioned that the method has already been used in several investigations in the other Nordic countries (Aslyng 1960 and 1965, Utaaker 1963 and Wallén 1966), and already for this reason it is advisable to use for the sake of regional comparison or mapping.

2. ADOPTION OF PENMAN'S METHOD

In this paper Penman's equation is used in the general form:

$$E = \frac{\Delta/\gamma \cdot H + E_a}{\Delta/\gamma + 1}$$

where the symbols have the following meaning:

E: evaporation, E_o, or potential evapotranspiration, E_p, (depending on the value of the reflection coefficient r) in $mm \cdot day^{-1}$.

Δ: the slope (de/dT) of the saturation vapour pressure curve at air temperature T_a, in $mb \cdot {}^\circ K^{-1}$.

γ: the "psychrometer constant", $\gamma = 0.65\ mb \cdot {}^\circ K^{-1}$.

H: the net radiation given in equivalent $mm \cdot day^{-1}$.

$$H = L^{-1} \cdot [G \cdot (1-r) - \sigma \cdot T_a^4 \cdot (0.56 - 0.078 \cdot \sqrt{e_d}) \cdot (0.1 + 0.9 \cdot S/S_o)].$$

L: latent heat of evaporation, $L = 59.5\ cal \cdot cm^{-2} \cdot mm^{-1}$.

G: global radiation in $cal \cdot cm^{-2} \cdot day^{-1}$.

r: reflection coefficient. When calculating evaporation from a free water surface $r = 0.05$, but for calculations of potential evapotranspiration from a grass covered surface it is $r = 0.20$, a value confirmed by measurements.

σ: Stefan-Boltzmann's constant, $\sigma = 117.2 \cdot 10^{-9}\ cal \cdot cm^{-2} \cdot day^{-1} \cdot {}^\circ K^{-4}$.

T_a: mean air temperature at about 2 metres height in °K.

e_d: vapour pressure in mb at mean air temperature T_a.

S/S_o: relative duration of sunshine.

E_a: a measure of the drying power of the air (Penman's new expression).

$$E_a = 0.26 \cdot (e_a - e_d) \cdot (0.5 + 0.54 \cdot u_2) \text{ in } mm \cdot day^{-1}.$$

$(e_a - e_d)$: saturation deficit at mean air temperature T_a, in mb.

u_2: wind velocity at 2 metres height in $m \cdot sec^{-1}$.

Originally Penman (1956) introduced a so-called "stomatal day length term" in the equation for potential evapotranspiration, but later he omitted it (WMO, Technical Note No. 83, 1966). The equations for evaporation from a free water surface and for potential evapotranspiration therefore have exactly the same form, the only difference being a different value of the reflection coefficient. Also in Nordic investigations there is some confusion concerning the use of the "stomatal day length term". Wallén (1966) includes it, while Aslyng (1960 and 1965) and Utaaker (1963) omit it. Some other authors do not recommend the use of such a term and it has therefore not been used in this study. At the same time it should also be mentioned that heat flux in soil has not been considered either.

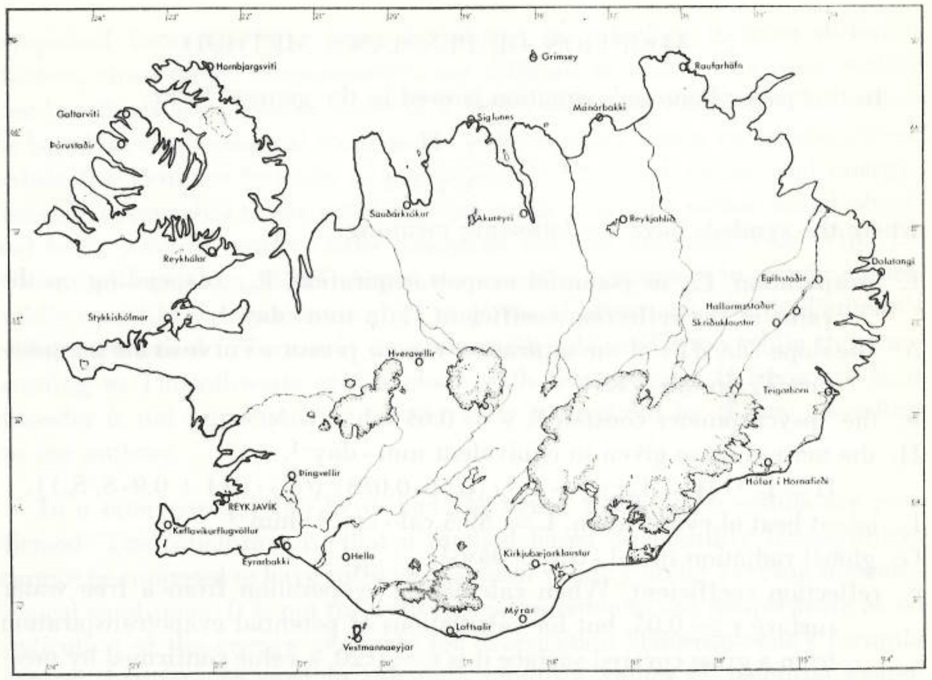

Fig. 1: Weather stations used in the calculations.

A few remarks concerning the different factors of the equation are of interest. Monthly mean values of T_a, u_2 as well as relative humidity were calculated for the period 1958–1967 for 28 weather stations in Iceland (fig. 1). More stations could not be included because they were lacking observations of one or more of the elements needed.

The part of the equation representing energy available for evaporation (H), contains global radiation G. The author has in a former publication (Einarsson, 1969) given monthly values of global radiation in Iceland for the period 1958–1967, and these have been used in the present investigation.

The value of r given in the literature for green vegetation varies usually between 0.20 and 0.26 (Rijtema, 1966). Wallén (1966) uses $r = 0.25$ for a grass covered surface, Utaaker (1963) uses $r = 0.20$ and Penman (1956) mentions the same value for "fresh green vegetation". Here the value $r = 0.20$ has been adopted, as it seems to be used by many authors. Furthermore albedo measurements made over short grass at Reykjavík during the short period 12th August–22nd September 1970 gave almost the same result. A generally accepted value of r for a free water surface is $r = 0.05$.

The part of H describing the long wave radiation contains among other factors the relative duration of sunshine S/S_0. It is then possible that different authors use a different definition of S_0, the duration of sunshine on clear days. In our case S_0 has been found by plotting all clear day values of S_0 on a diagram and drawing a curve in such a way that the majority of the single values are lying on or below the curve (Einarsson, 1969).

The use of S/S_0 in the equation creates a problem, as only 7 of the 28 weather stations do have recordings of S. This has been solved in the following way:

In a former investigation the author computed equations of regression between relative global radiation G/G_0 and S/S_0 (Einarsson, 1966). These equations were revised later (Einarsson, 1969) and used together with similar equations between G/G_0 and cloudiness to compute and map the global radiation in Iceland. Now the equations including S/S_0 have been used in an opposite way, i.e. to get monthly mean values of S/S_0 from values of G and G_0 which are available. The values calculated in this way are exact for those stations having recordings of sunshine, but a good approximation for other stations.

At all stations the net radiation has been computed according to Penman's equation, as no measurements are available for the period in question. At Reykjavík, however, measurements of net radiation have been performed later, i.e. during the summer months May–September 1968–1970 with a Schulze radiation balance meter. It has been found useful for the sake of comparison to calculate also the net radiation according to Penman for this short period. The comparison gave the following results (table 1):

TABLE 1

Difference between measured and computed net radiation for May–September 1968–70, in per cent of measured values.

	difference, %
May	16.6
June	6.0
July	5.9
August	9.4
September	22.6

All the months May–September taken together give the mean difference 9.8%. As can be seen from the table the difference is always positive, i.e. the measured values are higher than the computed ones, and the percentage difference is rather great in May and September but much lower in the summer months June–August. Assuming that the measured values are closer to the truth we find that potential evapotranspiration with computed net radiation is too low, although the percentage difference will be less than in table 1.

Considering E_a as a constant, a change dH in net radiation will cause a change in potential evapotranspiration E_p, given by:

$$dE_p = dH \cdot \frac{\Delta/\gamma}{\Delta/\gamma + 1}.$$

With representative values for Δ and H and applying the differences given in table 1, one can accordingly calculate for each month how much the values of E_p would increase if measured values were used instead of computed ones.

In May measured values of net radiation H, were in the mean 16.6% higher than the computed ones. If the measured figures are used the values of E_p would increase about 12%. In June and July a 6% difference in H leads to 4% higher values in E_p, and in August 9.4% difference in H to 6% higher values of E_p. In September the difference was as much as 22.6%, and yet the E_p-values will only increase by 9%. The reason for this is, that in autumn the importance of the energy term of Penman's equation diminishes and is in fact small during the winter. A rather great inaccuracy in H is therefore of relatively little importance in that season.

The conclusion of this comparison is then, that during the months in which E_p is high, the use of Penman's equation for H will give values of E_p, which are within some 10% lower than values which would result from measured net radiation. For the whole period May–September the values will only be 6–7% lower in the mean. Strictly, however, this only applies to the Reykjavík area, where the measurements were performed.

In Penman's equation the factor E_a is a measure of the drying power of the air and is expressed as a function of the saturation deficit, $(e_a – e_d)$, and the wind velocity at 2 metres height, u_2. In selecting wind velocity data some problems arise. Only 12 out of 28 stations used in the study have anemometers, while 16 stations have to estimate the wind according to the Beaufort scale. This gives rise to individual differences in the figures. Secondly the mean values for wind velocity are not based on the same number of observations each day, and in the third place the anemometers are usually at 8–12 metres height, and the wind must consequently be reduced to 2 metres.

As a result of the first problem two stations were omitted already before the calculations started, because of improbable and unreliable values of wind velocity, and as a matter of fact also of relative humidity.

Sigurðsson (1955) has calculated mean wind velocities for Reykjavík 1949–1953 at different times of the day. Using his figures one can show, that only in midsummer can there be a difference in mean values based on different observation times of the order of 10% (owing to sea breeze effect), but in most cases it is much less. It has therefore been assumed, that the effect of different observation times is less than possible inaccuracies due to individual estimates of wind, and as it is difficult to find applicable corrections the values have not been corrected in this respect.

The measurements of wind velocity must be reduced to 2 metres height, whereas estimated values are considered representative for the 2 metres level. These reductions have been made according to formulae given by Hellmann (1917) and later Carruthers (1943).

Before presenting the results the approximate character of the calculations should be stressed. In the first place the constants in Penman's formula are originally determined for climatic conditions different from those in Iceland, and this makes the results to some degree uncertain, although the use of the formula has given quite reliable results in neighbouring countries. In the second place there may be some doubt about some of the factors included in the equation. In the radiation term the global radiation has been taken from distribution maps, which in turn were based on regression equations between G/G_o and sunshine and cloudiness respectively at Reykjavík, and consequently obviously not as accurate in other parts of the country. In the third place comparisons with measured values already mentioned indicate that the radiation term of Penman's equation gives values, which are a little too low. Lastly, inaccuracies in humidity measurements are almost certain to occur in winter at freezing temperatures, when made by means of dry and wet bulb thermometers.

In spite of these shortages the calculations should give a valuable first picture of the evaporation conditions in Iceland. It is to be hoped that increased measurements will improve that picture in near future.

3. EVAPORATION FROM AN OPEN WATER SURFACE

Calculations of evaporation from an open water surface, E_o, are based on existing weather conditions at the 28 weather stations in question during the ten years period 1958–1967, conditions, which are not quite the same, as if there had been a real water surface. The value of the reflection coefficient is $r = 0.05$. The results for each month separately, the year as a whole and the two periods April–September and May–August are given for all stations in table 2, and the distribution of annual values is shown in fig. 2.

Table 2 shows as is to be expected, that by far the greatest part of the yearly evaporation, or some 75–95%, takes place in the period April- September. Maximum values are found in June or July. In summer the energy part of the Penman equation is usually three to five times the value of E_a, and therefore the month of maximum global radiation will generally also be the month of maximum evaporation. In SW-Iceland global radiation had for the period 1958–1967 a maximum in July instead of June and consequently the maximum evaporation in the area is also found in this month.

TABLE 2. *Evaporation from open water surface, E_0, 1958–1967 (mm).*

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year	Ap-S	May-Aug.
Reykjavík	7	13	33	60	104	109	117	88	44	16	6	13	610	522	418
Stykkishólmur	7	10	26	49	88	105	106	73	41	16	11	15	547	462	372
Reykhólar	8	10	28	51	89	112	112	76	39	13	8	10	556	479	389
Þórustaðir	3	6	20	44	87	112	104	67	34	11	7	5	500	448	370
Galtarviti	15	16	30	51	87	109	101	69	40	18	17	14	567	457	366
Hornbjargsviti	20	23	32	50	77	99	87	60	38	20	24	30	560	411	323
Sauðárkrókur	2	7	20	50	92	119	105	69	38	10	5	5	522	473	385
Siglunes	12	20	31	50	78	100	87	61	38	16	19	19	531	414	326
Grímsey	18	21	31	48	74	98	82	56	33	16	19	26	522	391	310
Akureyri	–2	2	16	43	85	114	105	68	35	7	0	2	475	450	372
Reykjahlíð	3	8	24	50	94	127	109	69	38	9	8	11	550	487	399
Mánárbakki	10	13	25	45	83	121	102	67	38	14	16	14	548	456	373
Raufarhöfn	6	9	21	43	73	99	85	56	30	8	10	16	456	386	313
Egilsstaðir	–2	2	21	49	91	124	106	70	38	10	3	5	517	478	391
Hallormsstaður	10	7	24	53	92	119	108	70	40	14	10	4	551	482	389
Skriðuklaustur	12	9	22	54	97	127	114	77	44	15	9	2	582	513	415
Dalatangi	9	13	29	47	71	92	86	61	36	16	14	12	486	393	310
Teigarhorn	11	13	36	60	99	117	105	79	45	17	14	13	609	505	400
Hólar í Hornafirði	7	10	33	59	97	108	102	77	42	15	6	6	562	485	384
Kirkjubæjarklaustur	3	9	28	59	98	105	118	84	42	11	0	3	560	506	405
Mýrar	0	8	27	61	107	114	118	82	39	9	–2	–1	562	521	421
Loftsalir	5	13	35	60	107	124	124	91	47	15	2	0	623	553	446
Vestmannaeyjar	23	33	52	74	110	110	116	93	53	31	27	29	751	556	429
Hella	–1	7	28	56	107	112	122	88	40	8	–3	–2	562	525	429
Hveravellir*)	0	7	17	36	80	91	91	60	32	9	3	0	426	390	322
Eyrarbakki	6	15	33	58	104	109	119	89	45	17	8	2	605	524	421
Þingvellir	–5	4	22	50	96	103	114	79	35	8	–2	–4	500	477	392
Keflavíkurflugvöllur	8	17	37	60	102	104	118	89	46	19	13	17	630	519	413

*) Values were estimated from only 3 years of observations.

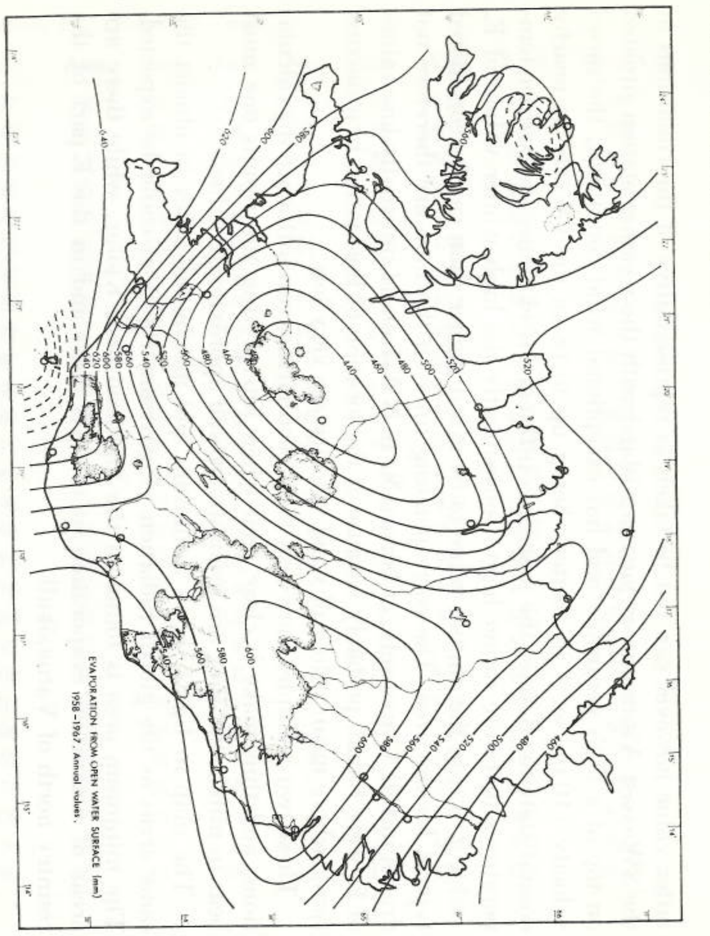

Fig. 2: Distribution of evaporation from open water surface (mm) 1958–1967. Annual values.

In other parts of the country E_0 is highest in June. Monthly values of E_0 in the two extreme months differ slightly from one station to another, but are mainly between 100 mm and 120 mm, the highest value being 127 mm.

In winter evaporation is small and even negative values appear. Some of the factors in Penman's equation are rather uncertain during this season. Global radiation is then small and the measurements rather inaccurate, and the relative humidity determined with dry and wet bulb thermometers is in many cases too high, when temperature is below freezing as already mentioned. For these reasons it is doubtful whether negative values of E_0 can be considered correct. Surprisingly few stations in Iceland have negative evaporation, however, compared with values from Scandinavia, where they are almost the rule in winter. This is probably due to the fact that wind velocity is much higher on the average in Iceland than on the continent. Mean velocities in winter of the order 5–7 $m \cdot sec^{-1}$ are common, especially at the coasts. The results show, that in January only four stations, situated some distance from the coast, have small negative values, and three in November and December.

Fig. 2 presents the distribution of annual evaporation. The values vary generally between about 440 mm and 620 mm, the minimum value being 426 mm at Hveravellir and the maximum 751 mm at Vestmannaeyjar. This latter value however can not be taken as representative of the conditions at the SW-coast. Vestmannaeyjar is an island with the weather station situated on top of a high peninsula and has exceptional wind conditions, the mean velocity (10 m · sec^{-1} in winter) being up to twice the velocity at nearby coastal stations. Besides the maritime influence is extreme, and winter temperatures therefore rather high. Consequently the high winter values of E_0 (table 2) cause the annual value to be much higher than can be considered typical for the area. The corresponding lines on the map are therefore not drawn in full. Conversely, at Þórustaðir in NW-Iceland unusually low values of E_0 were found, probably because of the location of the station in a narrow fjord, where mean values of wind velocity are very low.

These two examples show how local peculiarities can influence the calculations, and thus make it clear, that when interpreting the results one must bear in mind, that they are preliminary and approximate values.

The map in fig. 2 shows minimum and maximum zones in almost the same areas as the global radiation (Einarsson, 1969) as could be expected. The minimum area is found in the highland near Kjölur, while there are areas of maximum evaporation at the SW-coast and in the E-part of the country north of Vatnajökull.

4. POTENTIAL EVAPOTRANSPIRATION

The formula for potential evapotranspiration, E_p, from a grass covered surface has exactly the same form as that of E_0, the only difference being the value of the reflection coefficient, which now is $r = 0.20$, as previously mentioned. The results of the calculations for all stations are presented in table 3, for each month separately, for the year as a whole and the two periods April–September and May–August. The distribution of annual values and of values for April–September and May–August is shown in fig. 3–5.

In general similar explanations apply for E_p as for E_0. The values of E_p are lower than those of E_0, because of the difference in reflection coefficients, and the ratio E_p/E_0 turns out to be of the order 0.81–0.87, the average value for all stations being 0.84 for the year and 0.83 for the two shorter periods.

Table 3 shows, that monthly maximum values of E_p, which in 1958–1967 occur in July at the SW-coast, but in June elsewhere, reach 100 mm in places, the highest value being 107 mm at Skriðuklaustur in June. In the case of E_p small negative values appear at 5 stations in January and 4 stations in November and December, most of them situated some distance from the coast.

Fig. 3 shows the distribution of annual potential evapotranspiration. The values lie mainly in the range 360–540 mm the extreme values being 353 mm at Hveravellir and 654 mm at Vestmannaeyjar according to table 3. As already explained the latter figure cannot be taken to be representative for

TABLE 3. *Potential evapotranspiration, E_p, 1958–1967 (mm).*

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year	Ap-S	May-Aug
Reykjavík	7	12	28	50	86	92	97	72	36	13	6	13	512	433	347
Stykkishólmur	6	9	21	40	73	88	88	61	35	14	11	15	461	385	310
Reykhólar	7	9	23	42	73	93	93	63	33	10	8	10	464	397	322
Þórustaðir	3	5	16	35	72	93	86	55	27	9	6	5	412	368	306
Galtarviti	14	15	26	43	72	90	83	56	34	16	17	14	480	378	301
Hornbjargsviti	20	22	28	42	64	83	72	50	32	19	24	30	486	343	269
Sauðárkrókur	2	6	16	40	76	99	87	56	31	7	5	5	430	389	318
Siglunes	12	18	26	42	65	83	72	50	32	14	19	19	452	344	270
Grímsey	18	20	27	41	61	82	68	46	27	15	19	26	450	325	257
Akureyri	–2	1	12	34	70	95	87	56	29	5	0	2	389	371	308
Reykjahlíð	3	6	20	41	78	106	90	56	30	6	8	11	455	401	330
Mánárbakki	10	12	21	37	68	99	83	54	30	12	16	14	456	371	304
Raufarhöfn	6	8	17	36	60	82	70	45	24	6	10	16	380	317	257
Egilsstaðir	–2	1	16	40	76	105	89	58	30	7	2	5	427	398	328
Hallormsstaður	10	5	20	44	76	100	90	58	32	11	10	4	460	400	324
Skriðuklaustur	11	7	17	44	81	107	96	64	37	12	8	2	486	429	348
Dalatangi	9	12	24	39	58	75	71	50	30	14	13	12	407	323	254
Teigarhorn	11	11	31	50	82	98	88	66	38	14	13	13	515	422	334
Hólar í Hornafirði	7	8	28	50	81	90	84	63	34	12	5	6	468	402	318
Kirkjubæjarklaustur	2	7	23	49	81	88	97	68	34	8	–1	3	459	417	334
Mýrar	–1	6	21	50	90	96	98	67	31	6	–2	–2	460	432	351
Loftsalir	5	11	29	49	88	102	101	74	38	11	1	0	509	452	365
Vestmannaeyjar	23	31	47	64	93	93	96	78	45	28	27	29	654	469	360
Hella	–1	5	23	46	89	95	102	72	32	5	–4	–3	461	436	358
Hveravellir*)	0	6	13	29	67	77	76	50	26	7	2	0	353	325	270
Eyrarbakki	5	13	28	49	88	92	100	75	38	14	7	2	511	442	355
Þingvellir	–6	2	17	40	78	86	94	64	28	5	–3	–4	401	390	322
Keflavíkurflugvöllur	8	15	32	51	86	89	99	75	39	16	12	17	539	439	349

*) Values were estimated from only 3 years of observations.

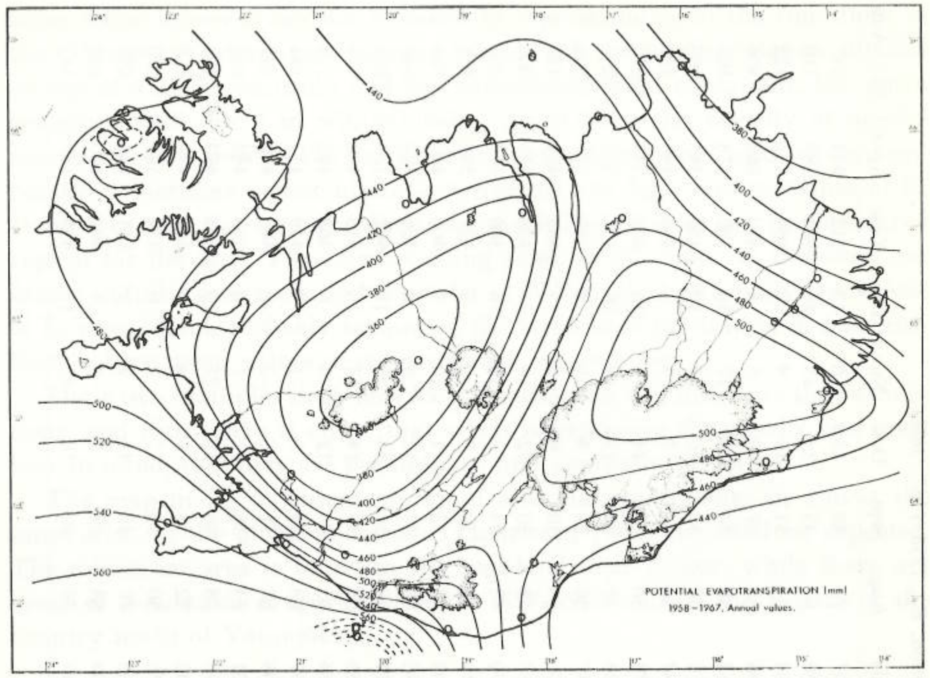

Fig. 3. Distribution of potential evapotranspiration (mm) 1958–1967. Annual values.

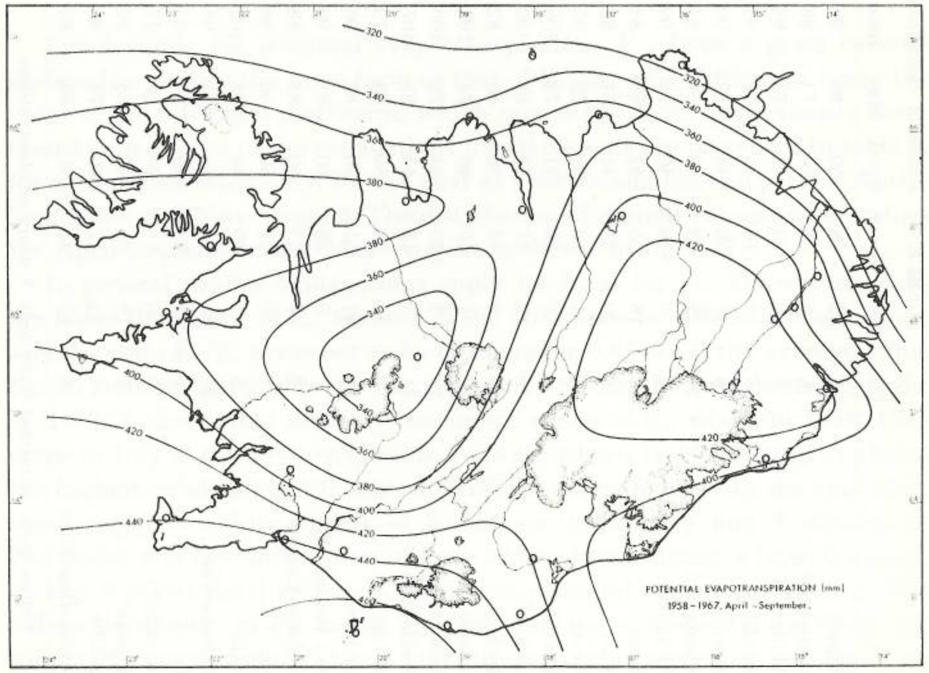

Fig. 4. Distribution of potential evapotranspiration (mm) 1958–1967. April–September.

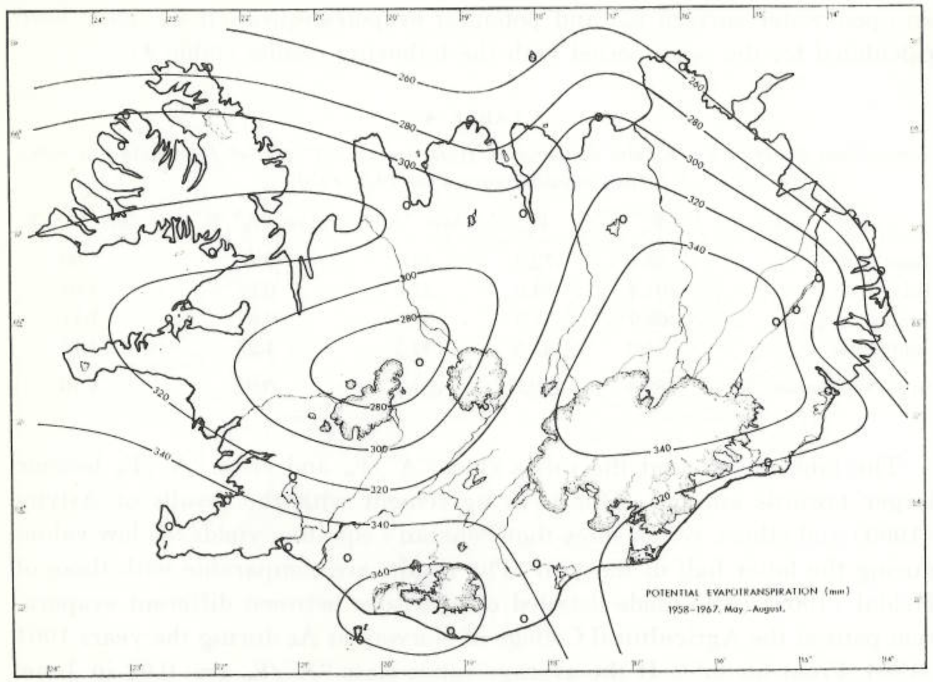

Fig. 5. Distribution of potential evapotranspiration (mm) 1958–1967. May–August.

the area. Maximum and minimum zones are evidently found in the same areas as for E_0, i.e. a minimum zone in the highland near Kjölur and maximum areas at the SW-coast and north of Vatnajökull.

Fig. 4 and 5 show the distribution for the two periods April–September and May–August which are very important for agriculture. It is seen that the greatest part of the potential evapotranspiration occurs in the summer half of the year. Maximum and minimum zones are in the same areas as for the annual values and one notices, that the values for Vestmannaeyjar are not very high in these periods, thus supporting the suggestion that extreme wind conditions in winter are mainly responsible for the high yearly values at this station.

5. COMPARISON BETWEEN E_0, E_p AND EVAPORATION FROM A CLASS "A" PAN

As mentioned already in the introduction measurements by means of evaporation pans have up to now been very scarce in Iceland. Only during the summer months June through September 1968–1970 a class "A" pan has been in use at Reykjavík. For comparison purposes the evaporation from an open water surface E_o, and potential evapotranspiration E_p, have been calculated for the same period with the following results (table 4):

TABLE 4

Comparison between E_o, E_p and evaporation from a class "A" pan at Reykjavík (in mm). Mean monthly values for 1968–1970.

	E_o	E_p	class "A"	class "A"/E_o	class "A"/E_p
June	86.1	72.3	72.0	0.84	1.00
July	101.4	84.0	87.0	0.86	1.04
August	66.9	55.9	62.0	0.93	1.11
September	34.0	27.5	43.3	1.27	1.57
June–September . . .	288.4	239.7	264.3	0.92	1.10

The table shows that the ratios class "A"/E_o and class "A"/E_p become larger towards autumn. This is in agreement with the results of Aslyng (1960) and others, which show that Penman's equation yields too low values during the latter half of the year. The results are comparable with those of Heldal (1969), who made detailed comparisons between different evaporation pans at the Agricultural College of Norway at Ås during the years 1961–1964. From his table II the average ratios class "A"/E_o are: 0.92 in June, 0.91 in July, 0.98 in August, 1.14 in September and 0.95 for the whole period June–September. His values, however, seem to vary more from year to year than ours.

6. POTENTIAL WATER BALANCE

The potential water balance, i.e. the difference between precipitation P, and potential evapotranspiration E_p, has been calculated for the year and the two shorter periods April–September and May–August. Its value gives the water balance as it would be, provided that water was plentiful, so that evapotranspiration could always be maintained at a potential rate. To get the true value of the water balance an estimate of the actual evapotranspiration is needed, but such an estimate is not available at the present time. However the potential water balance is valuable, as it clearly indicates areas, where water deficiency can be expected to occur.

When calculating ($P–E_p$) precipitation normals for the period 1931–1960 for 79 stations were used (Veðráttan, ársyfirlit, 1969), together with a map of annual precipitation in Iceland for the same period (Sigfúsdóttir, A. B., in manuscript. Published in Einarsson, 1971). Values of E_p were taken from table 3 and the maps shown in fig. 3–5. With the aid of these values three distribution charts have been prepared in fig. 6–8, presenting the potential water balance on an annual basis and for April–September and May–August respectively.

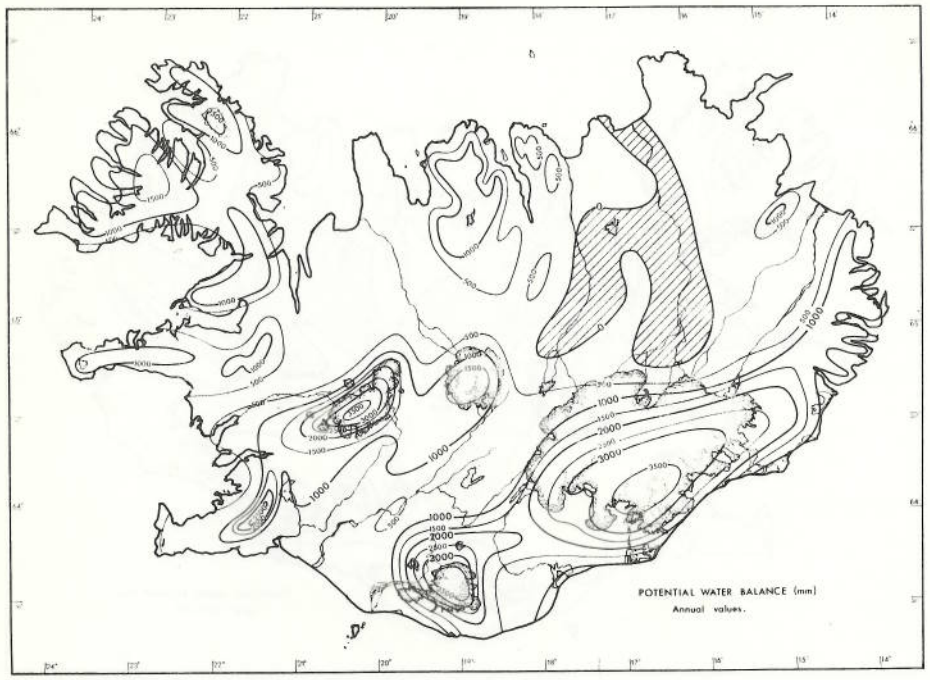

Fig. 6. Distribution of potential water balance (mm). Annual values.

A great part of the precipitation in Iceland falls in southeasterly wind directions and as a consequence the region of maximum precipitation is found in the southeast part of the country, with maximum annual values of more than 4000 mm on the glaciers Vatnajökull and Mýrdalsjökull, and values mainly above 1600 mm in lower areas. As the country is very mountainous, the amount of precipitation varies greatly within the same region. In SW- and W-Iceland the amounts in lowland are of the order 1000–1600 mm at the coast but 700–1000 mm farther inland. The north and northeast parts of the country are the regions of minimum precipitation with values 400–600 mm in lower areas and absolute minimum less than 400 mm in an extensive area north of the huge glacier Vatnajökull.

The main characteristics of the precipitation distribution in Iceland are of course reflected in the distribution of the potential water balance. The maps of E_p were drawn on basis of only 28 stations and without considering possible variations, for example those that might result from varying elevation of the land and its inclination to the sun. It was assumed that the variations in E_p are small compared with the much larger variation of P.

Fig. 6 presents the annual potential water balance. By far the largest part of the country has a positive annual balance and the highest values are found, as could be expected, in the southeast part. On the glaciers Vatnajökull, Mýr-

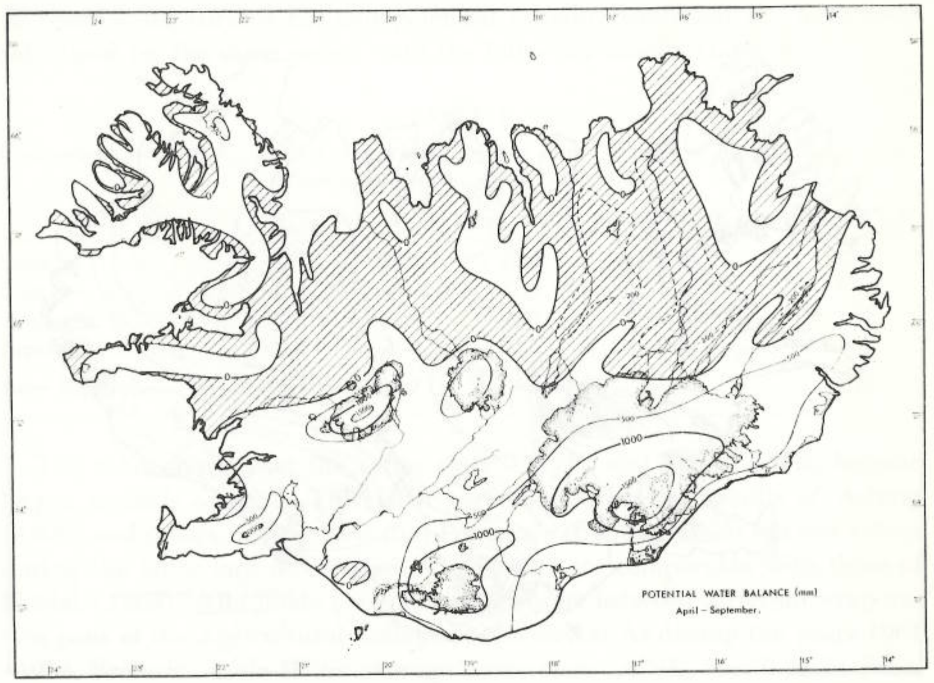

Fig. 7. Distribution of potential water balance (mm). April–September.

dalsjökull and Langjökull it exceeds 3500 mm, but in the lowlands of S-Iceland it is generally between 500 and 1000 mm. In other low regions it is less than 500 mm, and in a rather small area in NE-Iceland north of Vatnajökull, and partly in its precipitation shadow, the balance is negative down to about –100 mm.

In fig. 7 is shown the potential water balance for the period April–September, the summer half of the year. As shown previously the greatest part of the annual potential evapotranspiration takes place in this period, while on the contrary the precipitation is less in summer than in winter in all parts of the country except in NE-Iceland. No wonder therefore, that the water balance is quite different from the annual one. It is seen, that except for some mountainous areas the northern part of the country has a negative balance with the lowest values north of Vatnajökull, a little less than –200 mm. Besides some very small areas in the west and southwest parts have values less than zero. Highest positive balance is found in the same areas as before, and in the southern lowland the values are generally between 0 and 300 mm, in some places up to 500 mm.

Looking at the still shorter period May–August in fig. 8, which in Iceland includes the most important part of the growing season, it is seen, that still new areas show a negative balance. Only the southeast part of the country and several mountainous areas in other regions have positive values, mostly between zero and 500 mm. This means, that most agricultural areas of the country will on average suffer from water deficiency to some extent.

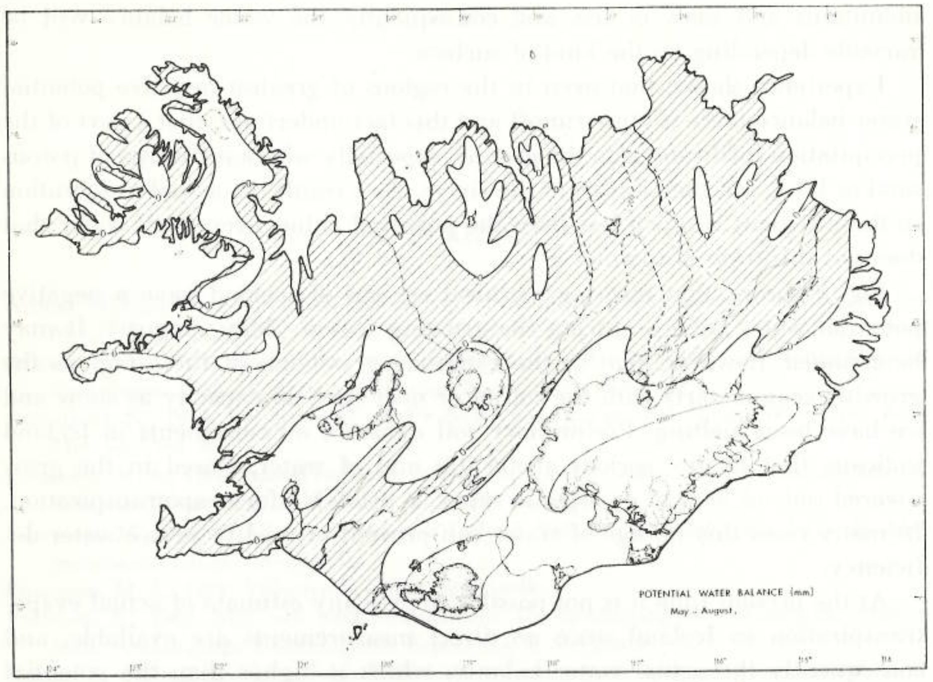

Fig. 8. Distribution of potential water balance (mm). May–August.

There are several things, which must be born in mind, when interpreting the above described potential water balance, some of which will be mentioned in the following:

It is known, that rain gauges, which in Iceland have openings about 1.5 m over the ground, give too low precipitation values, especially where wind velocities are as high as in Iceland, and where a considerable part of the precipitation falls as snow. No systematic investigations have been made in Iceland to clear this point, but preliminary figures indicate, that measured values for rain may as a mean be some 25% too low. This figure is however highly dependent on wind velocity, and a higher value is to be expected for snow (Sigurðsson, F. H., unpublished). Unfortunately no reliable corrections can be applied as yet. If this was however taken into account some of the regions in S-Iceland having negative balance in summer would get positive values.

Further it should be pointed out, that potential evapotranspiration is strictly defined as evaporation and transpiration from a surface covered with grass. However, large parts of Iceland consist of porous sand or lava, bare mountains and snow or ice, and consequently the water balance will be variable depending on the kind of surface.

Experience shows, that even in the regions of greatest negative potential water balance there is some runoff and this fact underlines, that a part of the precipitation infiltrates into the ground, especially where it consists of porous sand or lava, and then drains to the rivers. As a result the actual evaporation in these regions is much less than the potential value, even if all water that does not infiltrate evaporates.

Fig. 8 shows, that most agricultural regions of Iceland have a negative potential water balance during the growing season (May–August). It may be assumed, however, that in the extensive grasslands of these regions the growing season starts with the soil at or near its field capacity as snow and ice have been melting. Preliminary soil moisture measurements in Iceland indicate, that in dry periods about 100 mm of water, stored in the grass covered soils of loessial or organic types, is available for evapotranspiration. In many cases this storage of water can prevent or modify severe water deficiency.

At the present time it is not possible to give any estimate of actual evapotranspiration in Iceland since no direct measurements are available, and consequently the actual water balance, which is higher than the potential one, cannot be calculated.

Several authors in neighbouring countries have given values of the ratio actual to potential evapotranspiration E_a/E_p ranging from 0.80 (Aslyng, 1960) down to 0.58 in North-Sweden (Wallén, 1966). The ratio seems to decrease with latitude according to Wallén. In humid areas E_a can in general be assumed to be near to E_p, while in areas with negative water balance, where the surface layers are not capable of storing large quantities of water, E_a will be much less than E_p.

From what has been said it is obvious that further investigations concerning the relations between water storage in soil, runoff and actual evapotranspiration will be needed in the future together with increased evaporation measurements by means of evaporation pans in the different parts of the country.

REFERENCES

Aslyng, H. C., 1960: Evaporation and radiation heat balance at the soil surface. Archiv für Met., Geoph. und Biokl., Serie B, Band 10, Heft 3.

Aslyng, H. C., 1965: Evaporation, evapotranspiration and water balance investigations at Copenhagen 1955–64. Acta Agriculturae Scandinavica 15: 3–4.

Carruthers, N., 1943: Variations in wind velocity near the ground. Quarterly Journal Roy. Met. Soc. Vol. 69.

Einarsson, M. Á., 1966: Global radiation in Reykjavík and its relation to some meteorological elements. Meteorologiske Annaler, Bd. 4, Nr. 20, Oslo.

Einarsson, M. Á., 1969: Global radiation in Iceland. Veðurstofa Íslands (The Icelandic Meteorological Office), Reykjavík.

Einarsson, M. Á., 1971: Veðurfræði, Iðunn, Reykjavík.

Forsman, A., 1969: Mät- och beräkningsmetoder för bestämning av avdunstning. Statens Naturvetenskapliga Forskningsråd, Report No. 4, Stockholm.

Heldal, B., 1969: Evaporation from different evaporation pans in relation to meteorological conditions. Meldinger fra Norges Landbrukshögskole, Vol. 48, Nr. 25.

Hellmann, G., 1917: Über die Bewegung der Luft in den untersten Schichten der Atmosphäre. Met. Zeit. Band 34, 273.

Penman, H. L., 1950: Evaporation over the British Isles. Quarterly Journal Roy. Met. Soc., Vol. 76.

Penman, H. L., 1956: Evaporation: An introductory survey. Netherlands Journal of agricultural Science, Vol. 4, No. 1.

Rijtema, P. E., 1966: Evapotranspiration. Technical Bulletin 47. Institute for Land and Water Management Research. Wageningen.

Sigurðsson, F. H., 1955: De lokale værforhold i Reykjavík. A thesis in meteorology at the University of Oslo.

Utaaker, K., 1963: The local climate of Nes, Hedmark. Universitetet i Bergen, Skrifter nr. 28.

Veðráttan, 1957–1970: Monthly and yearly summaries from the Icelandic Meteorological Office.

Wallén, C. C., 1966: Global solar radiation and potential evapotranspiration in Sweden. Tellus, Vol. 18: 4.

Wijk, W. R. Van, D. A. De Vries and R. H. A. Van Duin, 1953: Potential evapotranspiration. Netherlands Journal of agricultural Science. Vol. 1, No. 1.

Wijk, W. R. Van and D. A. De Vries, 1954: Evapotranspiration. Netherlands Journal of agricultural Science. Vol 2, No. 2.

WMO, Technical Note No. 83, 1966: Measurement and estimation of evaporation and evapotranspiration.

SUMMARY

By means of Penman's equation estimates of evaporation from an open water surface and potential evapotranspiration are given for 28 weather stations in Iceland for the period 1958–1967. The results are used to draw distribution maps. It is shown, that calculated values are in reasonable agreement with pan measurements. Further the potential water balance is calculated and mapped as the difference between precipitation normals for the period 1931–60 and potential evapotranspiration.

Annual values of evaporation from a water surface are of the order 440–620 mm and of potential evapotranspiration 360–540 mm. The distribution maps show, that zones of maximum and minimum evaporation are found in almost the same regions as corresponding areas for global radiation. Minimum is found in the highland near Kjölur, but maximum areas at the SW-coast and in the E-part of the country north of Vatnajökull.

The distribution of potential water balance reflects the main characteristics of the precipitation distribution in Iceland. On an annual basis by far the largest part of the country has a positive balance, while only in a rather small area in NE-Iceland, north of Vatnajökull the balance is negative. During the summer half of the year, April–September, the northern part of the country has a negative potential water balance, except for some mountainous areas, and looking at the still shorter period, May–August, still new areas in W- and SW-Iceland show a negative balance, only the SE-part of the country and several mountainous areas in other regions having positive values.

ÁGRIP Á ÍSLENZKU

Ritgerð þessi fjallar um uppgufun frá vatnsfleti (evaporation) og gnóttargufun frá grónu landi (potential evapotranspiration), sem reiknuð er út fyrir 28 veðurstöðvar á Íslandi á 10 ára tímabilinu 1958–1967. Einnig eru niðurstöður notaðar til að teikna kort yfir uppgufun og gnóttargufun. Reiknuð gildi virðast við samanburð vera í nokkuð góðu samræmi við mælingar með uppgufunarpönnu. Auk þessa er vatnsjöfnuður við gnóttargufun (potential water balance) reiknaður út og kortlagður sem mismunur meðalúrkomu árabilsins 1931–60 og hinnar reiknuðu gnóttargufunar.

Ársgildi uppgufunar frá vatnsfleti reynist vera á bilinu 440–620 mm og gnóttargufunar á bilinu 360–540 mm. Sýna kortin, að hámarks- og lágmarksgildi er að finna í sömu landshlutum og þegar um geislun var að ræða. Lágmark er á Kjalsvæðinu, en hámark við suðvesturströndina og á hálendinu norðan Vatnajökuls.

Dreifing vatnsjafnaðar við gnóttargufun fer að miklu leyti eftir úrkomudreifingunni. Sé litið á árið í heild er vatnsjöfnuður jákvæður í flestum landshlutum, nema á takmörkuðu svæði á Norðausturlandi. Hann verður hins vegar neikvæður á láglendi norðanlands sé einungis litið á sumarhelming ársins, apríl–september, og sé enn styttra tímabil, maí–ágúst, tekið til meðferðar, bætast neikvæð svæði við á láglendi á Vestur- og Suðvesturlandi.