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POTENTIAL EVAPOTRANSPIRATION AND WATER BALANCE IN ICELAND

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The paper describes the results of estimations of potential evapotranspiration (E_p) in Iceland using Penman's equation. The calculations are based on distribution maps for global radiation for the period 1958–1967 previously developed by the author, and meteorological data from 28 weather stations for the same period. The distribution of E_p for the year and for the summer (April–September) are mapped. Further, the difference between precipitation and potential evapotranspiration ($P–E_p$) is calculated and mapped for the year as a whole and for the two periods April–September and May-August according to the values of E_p and precipitation normals (P) for the years 1931–1960.

POTENTIAL EVAPOTRANSPIRATION

So far almost no measurements or computations of evaporation or potential evapotranspiration have been performed in Iceland. Only during summertime in the last four years has a class A pan been operated at Reykjavík. A consideration of the problem has therefore been urgently needed.

Since Penman's method is probably one of the most widely used for computing potential evapotranspiration and is generally considered to give reliable results, it was adopted in this investigation. Further, the method has already been used in several investigations in other Nordic countries (Aslyng 1960, 1965, Utaaker 1963, Wallén 1966), and therefore it is expedient to use it also for the sake of regional comparison.

The equation in its first original form given by Penman (1956) was

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

where the symbols have the following meanings:

E_p : potential evapotranspiration 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 $mm \cdot day^{-1}$.
$H = L^{-1} \cdot [G \cdot (1-r) - \sigma \cdot T_a^4 \cdot (0.56 - 0.078 \cdot \sqrt{e}) \cdot (0.1 + 0.9 \cdot S/S_0)]$.
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, $r = 0.20$.
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 2 m height in °K.
e : vapour pressure in mb at mean air temperature T_a.
S/S_0 : relative duration of sunshine, where S is actual hours of sunshine and S_0 maximum possible hours of sunshine.
E_a : a measure of the drying power of the air (Penman's new expression).
$E_a = 0.26 \cdot (e'-e) \cdot (0.5 + 0.54 \cdot u_2)$ in $mm \cdot day^{-1}$.
$(e'-e)$: saturation deficit at mean air temperature T_a, in mb.
u_2 : wind velocity at 2 metres height in $m \cdot sec^{-1}$.

Estimated monthly values of G in Iceland for the period 1958–67 (Einarsson 1969) were used in the calculations. 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. Some stations could not be included because they lacked observations of one or more of the elements needed. The value of the reflection coefficient was chosen, $r = 0.20$.

It may be mentioned that evaporation from an open water surface (E_0) with the value of the reflection coefficient $r = 0.05$ was calculated for the same stations. The ratio E_p/E_0 turned out to be on the order of 0.81–0.87; the average yearly value for all stations was 0.84 (Einarsson 1972).

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 lie 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 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, where G_0 is the maximum possible global radiation (Einarsson 1966). These equations were revised later (Einarsson 1969) and used together with similar equations between G/G_0 and cloudiness to compute the global radiation. Now the equations including S/S_0 have been used in the opposite way, i. e. to get monthly mean values of S/S_0 from the values of G and G_0 which are available. The values calculated in this way are exact for those stations which recorded sunshine, and a good approximation for other stations.

At all stations the net radiation has been computed according to Penman's equation, as no direct measurements are available for the period in question. At Reykjavík, however, measurements of net radiation were made later, i. e. during the summer months May–September 1968–1970, with a Schulze radiation balance meter. It was found useful for the sake of comparison to calculate also the net radiation according to Penman for this short period. The result of the comparison showed that the measured values were about 10 % higher than the computed ones when looking at the period May–September as a whole. Potential evapotranspiration calculated from Penman's equation for the same months will accordingly be some 6–7 % lower than if measured values of net radiation were used (Einarsson 1972). In winter the energy part of the equation is of little importance. Strictly the above comparison applies only to the Reykjavík area.

Only 12 out of the 28 stations in question have anemometers, while 16 stations have to estimate the wind according to the Beaufort scale. The measured values were reduced to 2 metres height, whereas estimated values were considered representative for the 2 metre level.

Before presenting the results, it should be stressed that the calculations are only approximate. In the first place the constants in Penman's formula originally were determined for climatic conditions different from those in Iceland, and this makes the results somewhat 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_0, 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. And finally, inaccuracies

Table 1.
Potential evapotranspiration, E_p, 1958–1967 (mm)

	Jan.	Feb.	March	April	May	June
Reykjavík	7	12	28	50	86	92
Stykkishólmur	6	9	21	40	73	88
Reykhólar	7	9	23	42	73	93
Þórustaðir	3	5	16	35	72	93
Galtarviti	14	15	26	43	72	90
Hornbjargsviti	20	22	28	42	64	83
Sauðárkrókur	2	6	16	40	76	99
Siglunes	12	18	26	42	65	83
Grímsey	18	20	27	41	61	82
Akureyri	–2	1	12	34	70	95
Reykjahlíð	3	6	20	41	78	106
Mánárbakki	10	12	21	37	68	99
Raufarhöfn	6	8	17	36	60	82
Egilsstaðir	–2	1	16	40	76	105
Hallormsstaður	10	5	20	44	76	100
Skriðuklaustur	11	7	17	44	81	107
Dalatangi	9	12	24	39	58	75
Teigarhorn	11	11	31	50	82	98
Hólar í Hornafirði	7	8	28	50	81	90
Kirkjubæjarklaustur	2	7	23	49	81	88
Mýrar	–1	6	21	50	90	96
Loftsalir	5	11	29	49	88	102
Vestmannaeyjar	23	31	47	64	93	93
Hella	–1	5	23	46	89	95
Hveravellir[x)]	0	6	13	29	67	77
Eyrarbakki	5	13	28	49	88	92
Þingvellir	–6	2	17	40	78	86
Keflavíkurflugvöllur	8	15	32	51	86	89

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.

As mentioned in the introduction, measurements by means of evaporation pans have up to now been very scarce in Iceland. Only since 1968 has a class

July	Aug.	Sept.	Oct.	Nov.	Dec.	Year	Apr.–Sept.
97	72	36	13	6	13	512	433
88	61	35	14	11	15	461	385
93	63	33	10	8	10	464	397
86	55	27	9	6	5	412	368
83	56	34	16	17	14	480	378
72	50	32	19	24	30	486	343
87	56	31	7	5	5	430	389
72	50	32	14	19	19	452	344
68	46	27	15	19	26	450	325
87	56	29	5	0	2	389	371
90	56	30	6	8	11	455	401
83	54	30	12	16	14	456	371
70	45	24	6	10	16	380	317
89	58	30	7	2	5	427	398
90	58	32	11	10	4	460	400
96	64	37	12	8	2	486	429
71	50	30	14	13	12	407	323
88	66	38	14	13	13	515	422
84	63	34	12	5	6	468	402
97	68	34	8	–1	3	459	417
98	67	31	6	–2	–2	460	432
101	74	38	11	1	0	509	452
96	78	45	28	27	29	654	469
102	72	32	5	–4	–3	461	436
76	50	26	7	2	0	353	325
100	75	38	14	7	2	511	442
94	64	28	5	–3	–4	401	390
99	75	39	16	12	17	539	439

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

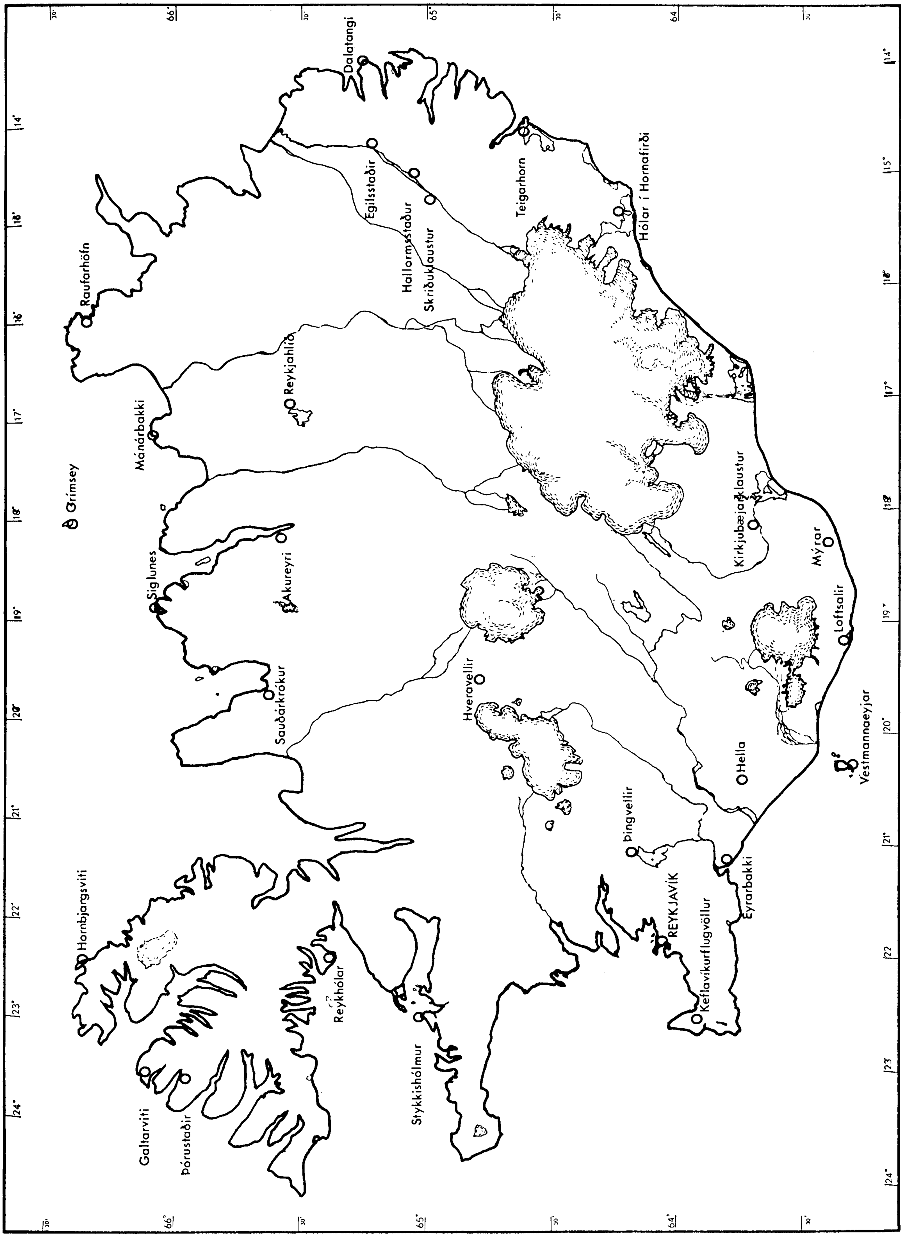

Fig. 1.
Weather stations used in the calculations.

A pan been in use at Reykjavík during the summer months. Comparisons between potential evapotranspiration calculated according to Penman and measured values for the months June–September 1968–1970 showed that the ratio, class A/E_p, for the summer as a whole averaged 1.10, with the value being 1.00 in June and increasing towards autumn (Einarsson 1972). This is in reasonable agreement with comparisons made by Heldal (1969).

In Fig. 1 are shown the 28 weather stations in Iceland for which values of E_p were calculated for the period 1958–1967. Table 1 shows the results for each month, for the year and for the summer half of the year, April–September. The Table shows, as may be expected, that by far the greatest part of the potential evapotranspiration, or some 70–95 %, takes place in the period April–September. Maximum monthly values occur in June or July. In midsummer the energy part of the Penman equation is usually three times the value of E_a or more, and therefore the month of maximum global radiation will generally also be the month of maximum evaporation. In SW-Iceland, global radiation for the period 1958–1967 had a maximum in July instead of June (Einarsson 1969), and consequently the maximum value of E_p in that area is also found in July. In other parts of the country E_p is highest in June. The Table shows that the highest monthly values reach 100 mm in places.

It is seen that small negative values of E_p appear in winter, at 5 stations in January and 4 stations in November and December. Most of these stations are situated some distance from the coast. Compared with values from Scandinavia, however, surprisingly few stations in Iceland have negative values 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 coast. It is considered doubtful whether negative values of E_p can be considered correct.

Fig. 2 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 1. This latter value, however, cannot be taken as representative of the conditions at the SW-coast. Vestmannaeyjar is an island with the weather station situated on the top of a high peninsula and has exceptional wind conditions, the mean velocity (10 $m \cdot sec^{-1}$ in winter) being up to twice the velocity of nearby coastal stations. Further, the maritime influence is extreme and winter temperatures are therefore rather high. Consequently, the high winter values of E_p 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_p were found, probably because of the location of the station in a narrow fjord where mean values of

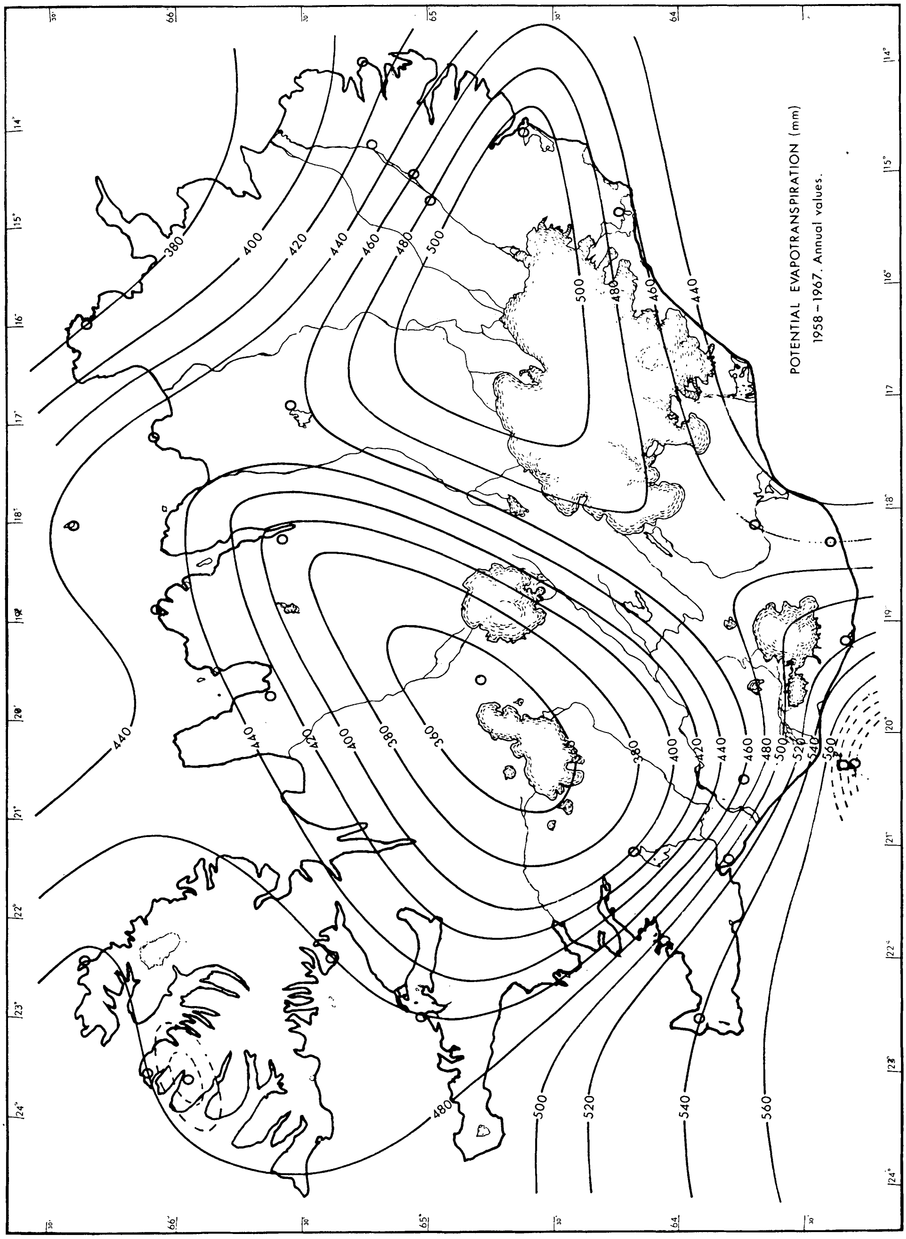

Fig. 2.

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

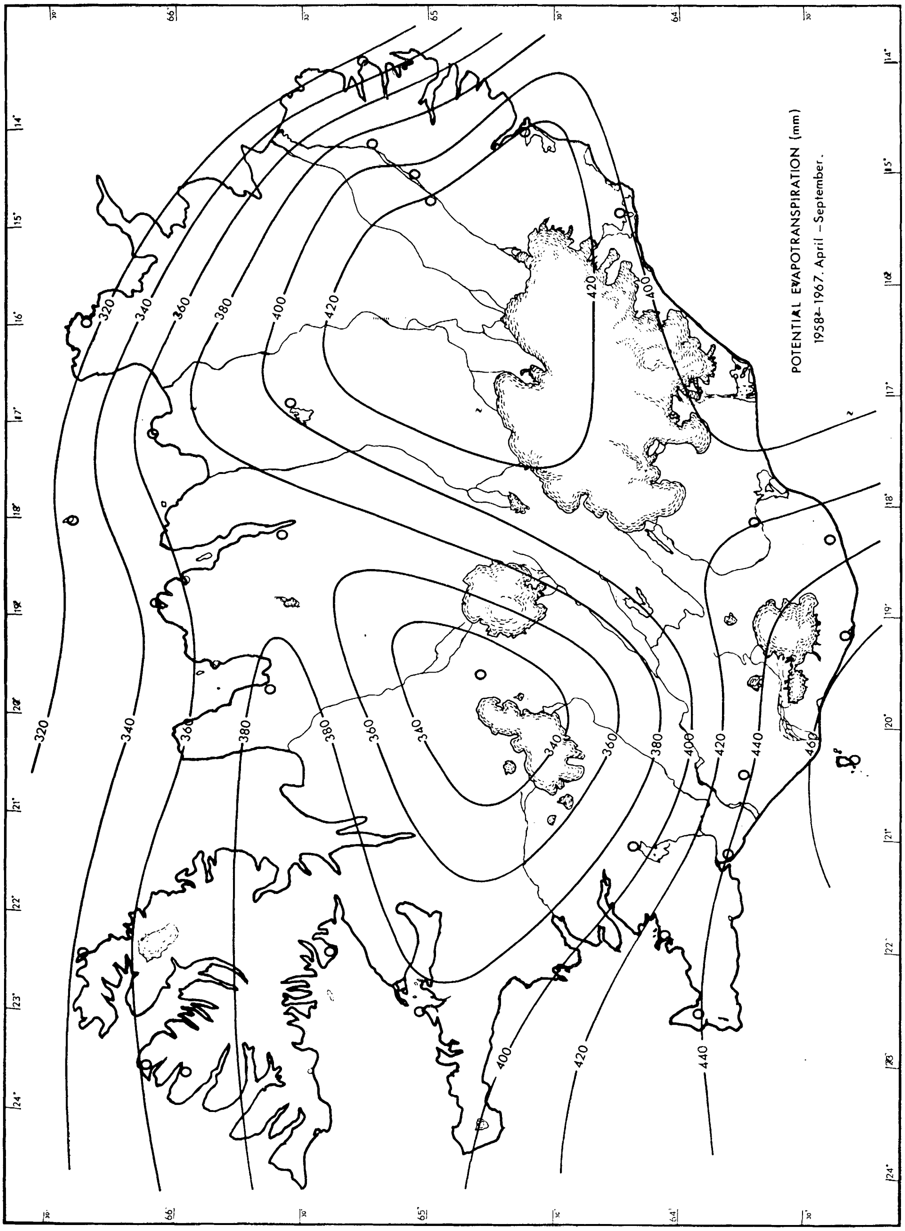

Fig. 3.
Distribution of potential evapotranspiration (mm) 1958–1967. April-September.

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

In general the figure shows minimum and maximum zones in the same regions as might be expected from the corresponding maps for global radiation (Einarsson 1969). The minimum area is in the highland near Kjölur, while there are areas of maximum potential evapotranspiration at the SW-coast and in the E-part of the country, north of Vatnajökull.

Fig. 3 shows the distribution for April–September. 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 this period, thus supporting the suggestion that extreme wind conditions in winter are mainly responsible for the high yearly values at this station.

POTENTIAL WATER BALANCE

The potential water balance, i. e. the difference between precipitation P, and potential evapotranspiration E_p (sometimes also known as the potential net precipitation), 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 may be expected to occur.

In 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). Values of E_p were taken from Table 1 and corresponding maps. With the aid of these values three distribution charts have been prepared in Figs. 4–6, presenting the potential water balance on an annual basis and for April-September and May–August, respectively.

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 southeastern 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 the lowlands are of the order 1000–1600 mm at the coast but 700–1000 mm further inland. The north and northeastern parts of the country are the regions of minimum precipitation, with values 400–600 mm in lower areas and an absolute minimum of 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 the 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. 4 presents the annual potential water balance. By far the largest part of the country has a positive annual balance and as could be expected, the highest values are found in the southeastern part. On the glaciers Vatnajökull, Mýrdalsjökull and Langjökull the potential water balance 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. 5 the potential water balance is shown 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 the precipitation is less in summer than in winter in all parts of the country except in NE-Iceland. No wonder, therefore, that the potential water balance in the summer 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. In addition, some very small areas in the west and southwest parts have negative values. 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. 6, 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 southeastern 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 generally suffer from water deficiency to some extent.

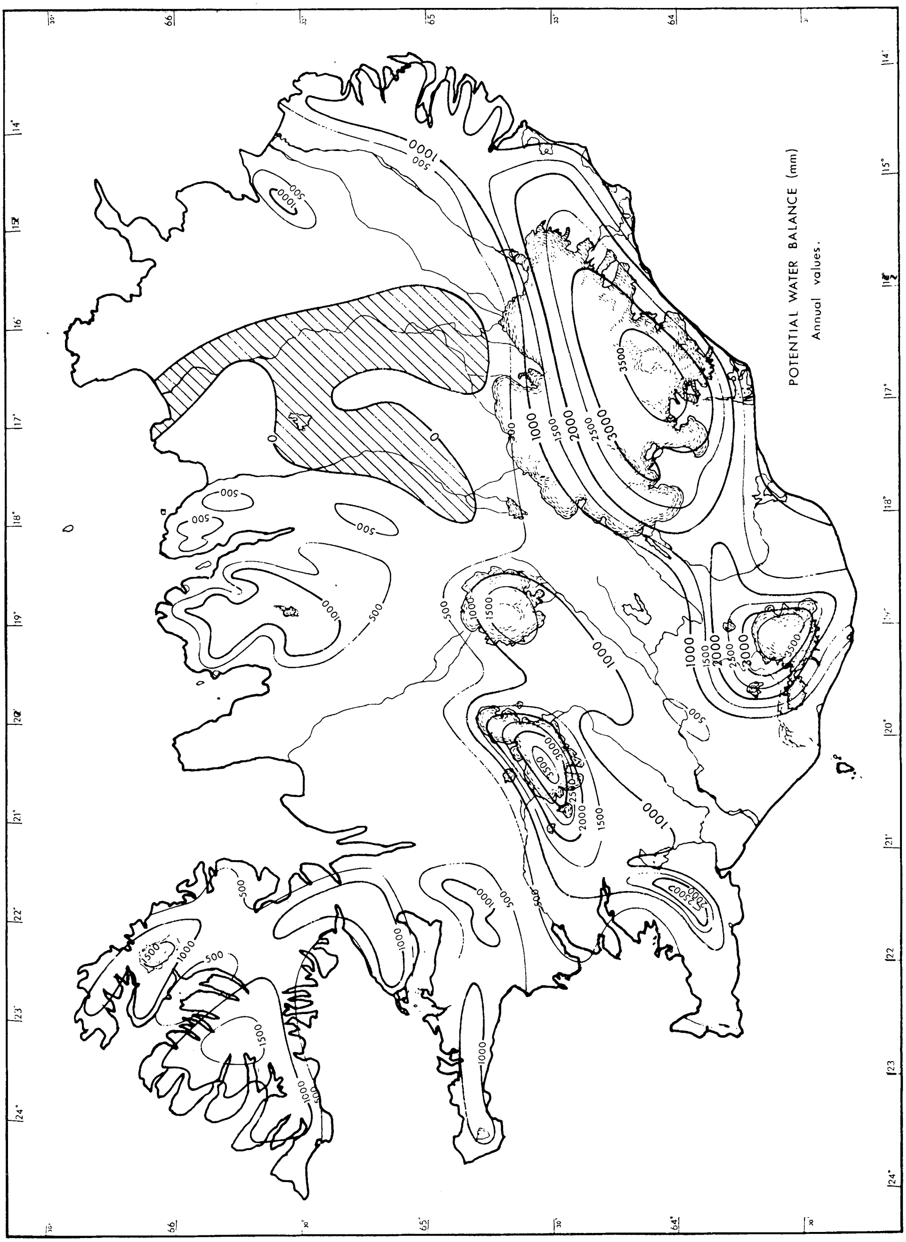

Fig. 4.
Potential water balance (mm). Annual values.

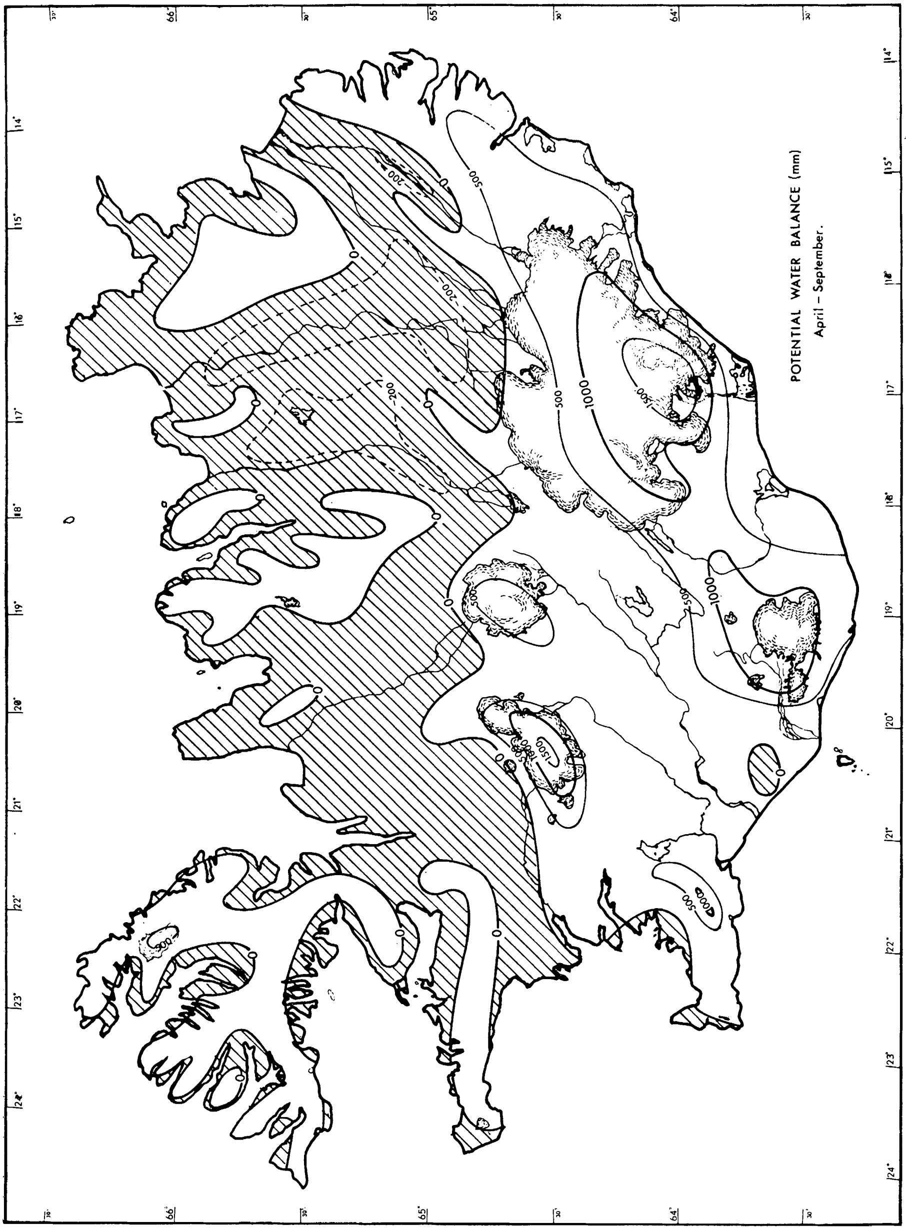

Fig. 5.
Potential water balance (mm). April–September.

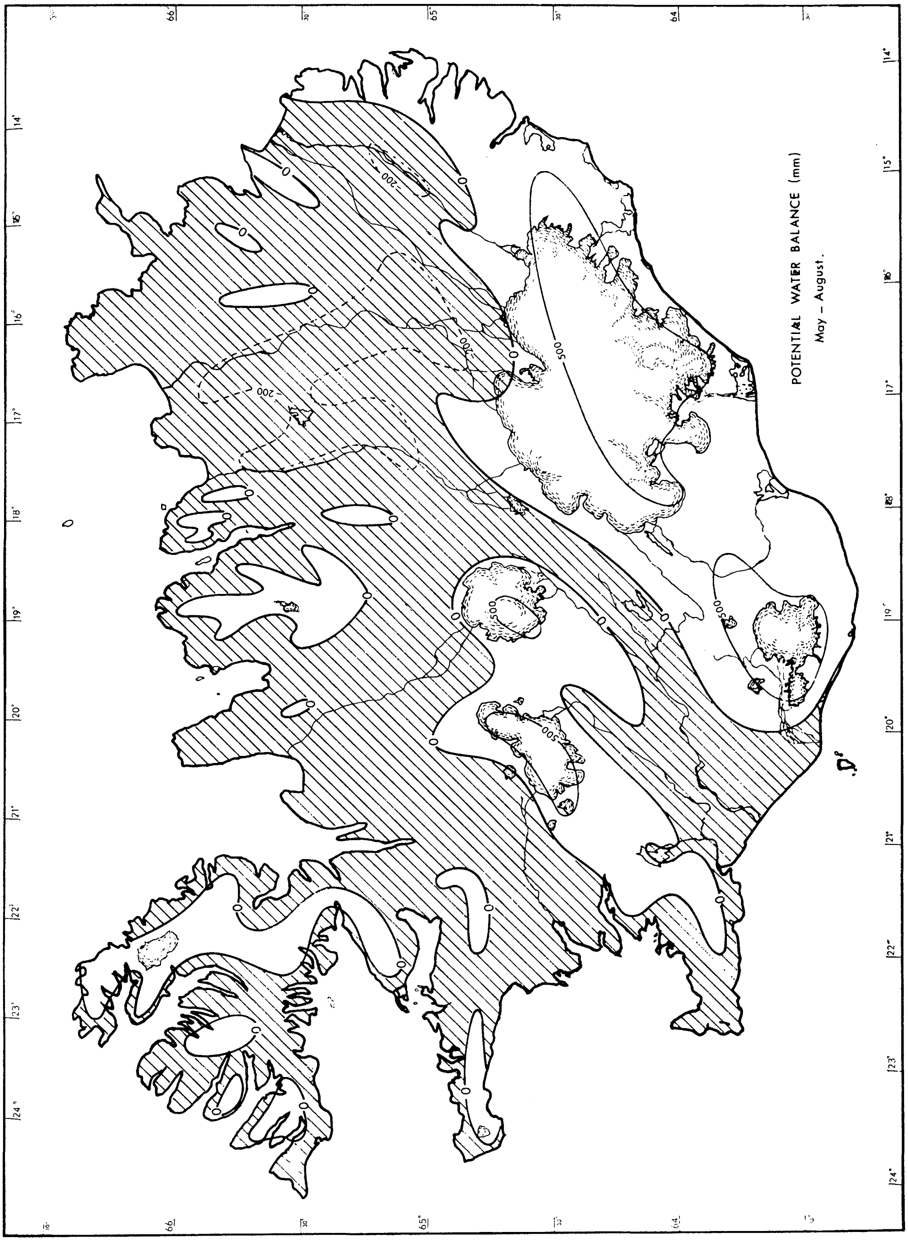

Fig. 6.
Potential water balance (mm). May–August.

There are several things which must be borne in mind when interpreting the potential water balance described above, 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 precipitation values which are lower than they should be, 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 clarify this point, but preliminary figures indicate that measured values for rain are about 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, however, this was taken into account, some of the regions in S-Iceland having a negative balance in summer would get positive values.

Further, it should be pointed out that potential evapotranspiration is usually defined as evaporation and transpiration from a surface covered with grass, when there is no deficit of water. However, large parts of Iceland consist of porous sand or lava, bare mountains and snow or ice, and consequently the water balance will vary 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 underlines the fact 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. 6 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 field capacity because of snow- and ice melt. 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 E in Iceland since no direct measurements are available, and consequently the actual water balance (that is, P–E), which is higher than the potential one, cannot be calculated.

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