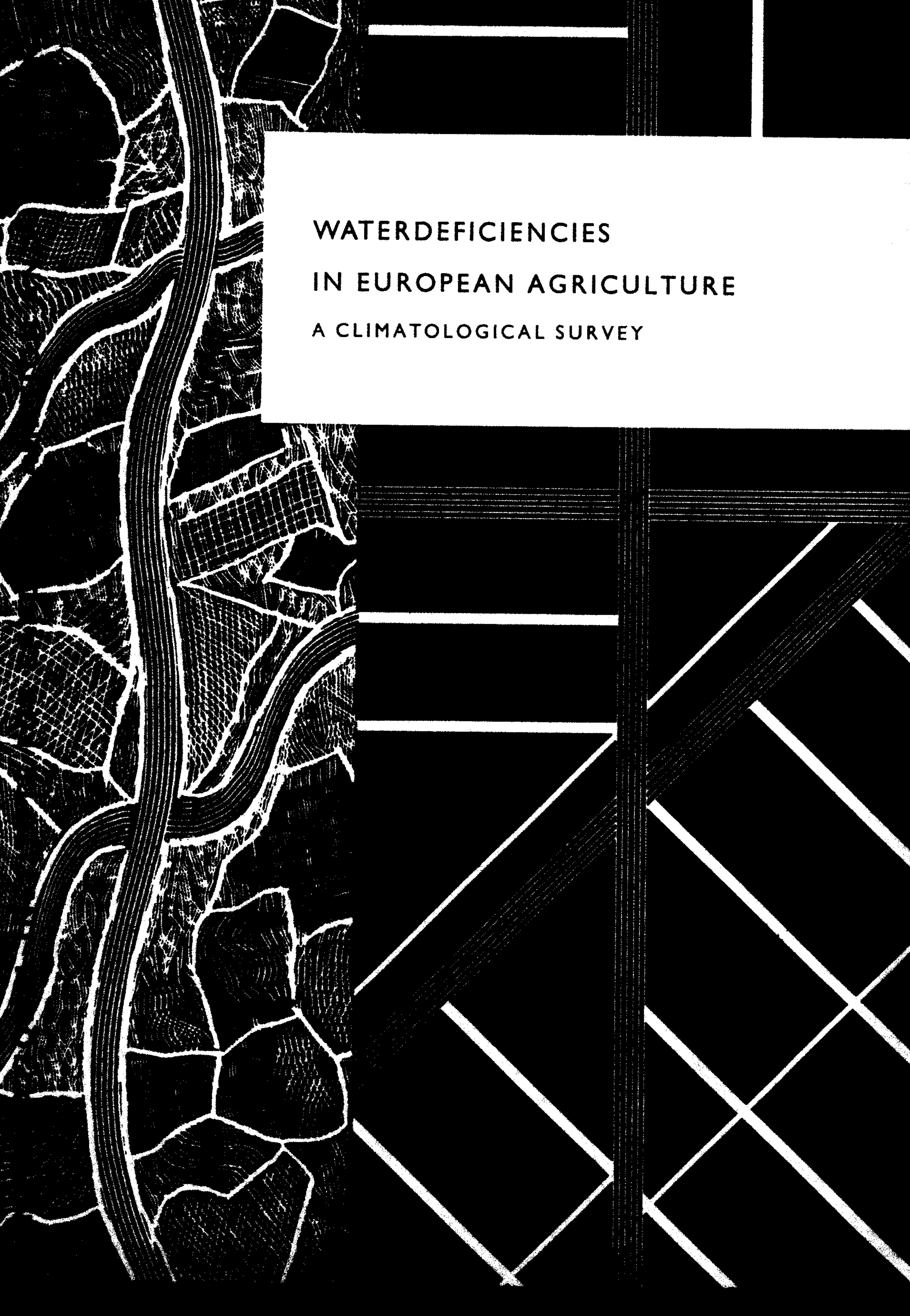
WATERDEFICIENCIES IN EUROPEAN AGRICULTURE

A CLIMATOLOGICAL SURVEY



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WATERDEFICIENCIES IN EUROPEAN AGRICULTURE

A CLIMATOLOGICAL SURVEY

DÉFICITS EN EAU DANS L'AGRICULTURE EUROPÉENNE
CARTOGRAPHIE CLIMATOLOGIQUE

WASSERDEFIZIT IN DER EUROPAEISCHEN LANDWIRTSCHAFT
EINE KLIMATISCHE KARTIERUNG

DEFICIENCIAS DE AQUA EN LA AGRICULTURA EUROPEA
CARTOGRAFIA CLIMATOLOGICA

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TABLE OF CONTENTS

To this publication are added ten separate maps, numbered I, Ia, Ib, Ic, II, III, IV, Va, Vb and Vc.

1. INTRODUCTION

1.1 The importance of irrigation

There is a growing interest in Europe in the prospects opened up by the use of (supplemental) irrigation. It is being realised that in many regions agricultural productivity can be substantially increased by overcoming the water shortages that occur for shorter or longer periods during the growing season.

It will be obvious that artificial watersupply will have its maximum effect where the precipitation deficiency is large and of frequent occurrence and where there is only a small amount of moisture available in the soil. But not only the precipitation deficiency and the type of soil and crop determine the useful effect of supplemental irrigation. If there are other inhibiting factors than the watersupply – for instance a low state of fertility of the soil or bad production techniques – it is certain that supplying water will lead to a less satisfactory result than if the general level of these production factors were high and it was only the water shortage that prevented a high level of production from being reached.

In certain cases supplemental irrigation may render more effective the use of fertilizer and this may stimulate a further increase in productivity.

In addition to climate, soil conditions and production technique, there are other factors which are equally important for the applicability and profitability of supplemental irrigation. Thus the management pattern of the agricultural holding, viz. the ratios in which the production factors are applied, and the external production factors, also determine the place of supplemental irrigation and its profitability.

When we consider the development of agriculture and the place occupied therein by supplemental irrigation it will be found, that great changes have occurred during recent decades.

Before the development of large-scale manufacture of fertilizers and the growth of agricultural knowledge in the sphere of plant breeding, water management, etc., a country's production capacity could only be increased by cultivating new areas which were generally less fertile. Since moreover production technique was at a comparatively low level (supplemental) irrigation could only be of importance where the soil was naturally very fertile and the climate very dry, and where in addition large amounts of water could be supplied by comparatively easy means, as for instance in the fertile valleys in the Mediterranean area.

With the turn of the century, however, increasing amounts of fertilizers and new, highly productive crops were made available to farmers, so that there could be a gradual improvement in production technique. Moreover food scarcities were a great stimulus to increasing the production capacity. In many cases the process went so far that soils were cultivated having a potentially low level of production. Owing to the use of fertilizers and improved production methods it was possible to achieve what under the prevailing economic conditions was a reasonable level of productivity on these less fertile soils. But as a result shortage of water was increasingly felt as a factor limiting production, especially on soils with a lower water holding capacity. It is as a result of these conditions that the technique of supplemental irrigation has been developed during the last twenty years, often in the form of sprinkler irrigation.

Recently, however, certain changes have been noticed in this development. In many European countries food shortages have given way to a situation in which the population has become self-supporting as regards certain products, while market surpluses have arisen of other products which were traditionally export products. Moreover thanks to labour costs, high capital investments, high fertilizer prices, etc., cost prices have reached unprecedented levels. Hence in many areas the aim of increasing the total production capacity has already been replaced by the objective of reducing the cost prices of agricultural produce. Since the factors of labour and capital in particular have a great effect on this cost price, there is a tendency to employ the available labour and capital in a more economic way and to concentrate them on the best soils; the marginal soils can then only be used extensively, or even entirely taken out of agricultural production and afforested. But as a result of this development higher demands will be made on the watersupply on the better soils. If techniques may succeed in simplifying the application of supplemental irrigation to a minimum of required labour and capital, it will be very tempting, from the standpoint of the farmer, to raise productivity of the land by supplemental irrigation. So long as, however, the problem of the surpluses of agricultural products is not solved, the application of supplemental irrigation will be less desirable, from the macro-economical standpoint.

When we look towards the future we see that a continuous increase in population is to be expected and that the present production level will ultimately prove inadequate to supply the increased needs of the industrial centres. But it does not seem likely that it would then again be an economic proposition to bring poorer soils into cultivation once more. The tendency, already present, to intensify the use of the good soils, will then hold to an even greater degree. Although under present conditions many of these soils in northern and central Europe require no supply of water for most crops, the future desirability of increasing productivity will eventually lead to very high demands being made on water-supply.

The economic integration of European countries may be expected to be of predominant importance to the development of agriculture. The question immediately arises as to which areas are suitable for increasing production and what direction this development should take. This problem is obviously a very complex one and comprises many different factors. One of these is of a hydrological kind, viz. to what extent can a shortage of water in agriculture be a limiting factor, and what amounts should be supplied and in what frequency in order to reach an optimum level of production? The answer to this problem is a matter of universal interest; the possibilities of supplemental irrigation should be examined over the entire area of Europe, it being assumed that it will be possible to raise the other production factors to their optimum development, and also assuming that, with the increase in population to be expected, increasing the productivity of European agriculture will continue to be a matter of essential importance in the future as well.
In the following chapters further attention will be given to these problems, the emphasis being placed on climatic conditions. The data supplied may constitute a starting point for increasing our knowledge of the problems and may prove useful in determining the policy to be followed.

1.2 Supplemental irrigation

Irrigation practice in humid areas is designated by the term 'supplemental irrigation'. By this is meant the supplying of water for the benefit of agricultural crops for comparatively short and usually irregular periods of drought during the growing season so as to overcome a shortage of soil moisture. This shortage of moisture occurs when the water removed by evapotranspiration is so much greater than the precipitation that the to the vegetation available water stored in the soil becomes exhausted.
The irregular need of water supply is a typical feature of supplemental irrigation, unlike the irrigation practice in arid and semi-arid regions where water has to be regularly supplied to the crops during the growing period or the greater part thereof. If there is no such possibility of supplying water, there can be no question of arid regions bearing a crop of any significance. In semi-arid regions, however, agriculture may be possible without irrigation, but is always a marginal occupation. In humid regions, which make up the greater part of the agricultural land area of Europe, agriculture does not directly depend on artificial supply of water, but it is often possible to increase the production level considerably by applying supplemental irrigation.
The classic type of irrigation has evolved in the course of centuries in the typically arid regions of the world. During recent decades however, irrigation also found important fields of application in the humid regions, and is continuing to do so at an increasing rate. It is noticeable that these are the very areas in which modern techniques such as sprinkler

irrigation have been developed and that also in the arid regions the possibilities afforded by these techniques have been a powerful stimulus to a more up-to-date set-up of a great many new irrigation projects.

Although technical developments have followed more or less parallel paths in the United States and Europe, supplemental irrigation holds a more important place in American agriculture than in European.
This can be illustrated as follows. In the eastern states (viz. the humid part of the United States) only some 39,000 acres were being irrigated in 1939, the traditional view being that except for certain crops there was no need of irrigation. The picture was entirely different in 1957, when we find some 650,000 acres under irrigation, or nearly 17 times as much, in a period of less than 20 years. Whereas in the five-year period from 1949 to 1954 the irrigated area in this part of the United States increased by 70 %, the area under irrigation in the arid western part of the United States only increased by 10 % in the same period. These figures show what enormous strides have been made in irrigation in the humid regions of America, with the result that the irrigated area in these parts is catching up on its arrears.
Although the use of supplemental irrigation in Europe has hitherto been a more gradual process, it may be anticipated that here too supplemental irrigation will play a more important part in the future.

2. SOIL MOISTURE CONDITIONS IN RELATION TO PLANT GROWTH

It was pointed out in the preceding chapter that the object of irrigation is to replenish any shortage of moisture in the soil. In this chapter we shall investigate how far the available soil moisture has to be depleted that the resultant decrease in the supply of water from the soil to the plants becomes the limiting factor in plant growth. For this purpose we must consider the interrelations between soil, moisture and plant growth.

During periods of rain, water infiltrates into the soil from the surface, the top layer being moistened first. As a result of capillary forces the infiltrating water is retained in this layer until a certain degree of moistness has been reached, which is termed field capacity. Should more water be applied to the soil after this point has been reached, it will percolate through the top layer into the subsoil. In this way the soil is brought to field capacity from the soil surface downwards. Surplus water, not retained by the soil, seeps down to a greater depth and eventually reaches the phreatic level where it joins the free ground water. Owing to the evapotranspiration – viz. the evaporation of water from the soil plus the transpiration from plants – moisture is extracted from the root zone. If this extraction is not offset by precipitation or irrigation, the moisture content will decline to a point at which the plants are no longer able to extract the remaining moisture from the soil. At this point the moisture tension in the soil is in equilibrium with the suction power of the roots. Thus the soil reaches a degree of moistness – known as the permanent wilting percentage – at which the plants are incapable of absorbing any further moisture.
Hence of all the water stored in the soil, the only soil moisture available for absorption by plants is that intermediate between field capacity and the permanent wilting percentage This amount of available moisture is largely determined by the type of soil. It ranges, for instance, from about 7.5% by volume of soil in the case of humus-poor sandy soils, up to a maximum of 20% by volume in the case of a good clay loam or a lighter textured, but humus-rich soil.
For many years there has been a lively controversy as to whether the 'available moisture'

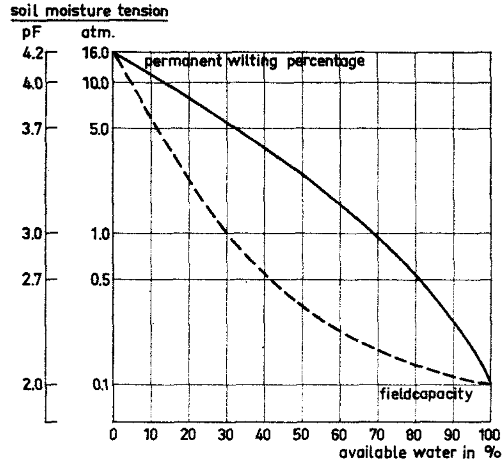
is equally available for plant growth or only available with such increasing difficulty that plant growth functions are retarded before the wilting point is reached. The different viewpoints have been summarised in review articles by VIEHMEYER and HENDRICKSON (1950), by RICHARDS and WADLEIGH (1952) and by HAGAN (1955).

According to VIEHMEYER and HENDRICKSON *et al.*, the water uptake of the plant is unchanged between field capacity and the permanent wilting percentage. They also observed that the rate of growth was not diminished over the entire available range of soil moisture.
On the other hand, it has been maintained by MAKKINK (1956), SLATYER (1956) *et al.*, that under certain conditions plant growth diminishes progressively as the soil moisture content falls below field capacity, and ceases at the permanent wilting percentage.
According to RICHARDS, VAN BAVEL *et al.*, plant growth is related to the tenacity with which water is held by soil. Their experiments show that plants can readily absorb water up to a certain moisture tension which is lower than the wilting point. Consequently it is not the range between field capacity and wilting point that determines the amount of readily absorbable moisture, but the moisture retention characteristics of the soil.

These different viewpoints, each supported by experimental results, have led to a somewhat confusing situation. This is due to the different conditions under which the various experiments were conducted, so that the said opinions are not so conflicting as would appear at first sight.
In the following, we shall consider briefly the three major factors which influenced the experimental results, viz. rate of moisture consumption, soil moisture retention characteristics, and root density distribution.
In order to maintain the optimum rate of growth plants have to consume soil moisture at a rate equal to the 'potential evapotranspiration'. This quantity is determined by such meteorological factors, as solar radiation, temperature, humidity and wind speed (see also chapter 3). Hence if the atmosphere has a great evaporative power, so that moisture consumption is also high, the water supply may limit plant growth even when soil moisture tension is low (MAKKINK, 1956).
The second factor is illustrated by the soil moisture retention characteristics shown in figure 1. It can be seen from the curves that the sandy loam releases nearly 70% of the available water at tensions lower than one atmosphere, whereas the clay loam only releases 30%. Moreover it should be noticed that soil moisture tension determines both the amount of energy required by roots for moisture absorption and the rate at which water flows from the surroundings to the absorbing root surface.
If we consider the whole depth of the root zone it will be obvious that the distance water has to flow to the absorbing root surfaces, and hence the rate of moisture absorption, must be related to the root spacing density. Most of the root mass will usually be found in the top layer of soil, the root density decreasing in downward direction. Although the density of the roots may vary widely under different conditions, the root density distribution in the root zone can be shown diagramatically by a downward pointed triangle. This means that if the rate of moisture consumption is so high that plant growth is retarded even before the available water in the top layer of soil has been absorbed, only less than 50% of all moisture available within the root zone can be readily absorbed. On the other hand, if the rate of moisture consumption is very low, it may happen that despite the wide spacing of the root system within a part of the root zone nearly all moisture available in the root zone is still absorbed without plant growth being retarded.

It is apparent from this brief discussion that the amount of moisture within the root zone which is readily available for plant growth depends on various factors, e.g. crop rooting, soil moisture characteristics, and potential evapotranspiration.

Fig. 1. Curves illustrating the soil moisture retention characteristics of a sandy loam (- - - -) and a clay loam (———)



Although it was not possible to provide a defenite solution to this problem, for the purpose of the present investigation it was assumed that only 50% of the total amount of available moisture in the whole root zone could be readily absorbed by the plants at a rate equal to the potential evapotranspiration. In irrigation practice it is also often assumed that water should be supplied as soon as 50% of the amount of moisture available has been extracted from the soil.

This quantity of readily available moisture will hereinafter be termed the 'soil-root value'. This value may be rather too low under conditions of low potential evapotranspiration and in cases in which the soil moisture tension remains low over a considerable range between field capacity and wilting point (see fig. 1: curve of sandy loam). Vice versa, the soil-root value may be rather too high. The term has been chosen as a variant of the well-known 'root-constant' defined by PENMAN (1956). PENMAN's theories are based on the behaviour of deep soils in which the quantity of available moisture is not limited by the depth of soil but only by the depth to which roots have time to penetrate. In the present investigation however, both crop-rooting and moisture-holding capacity are taken into consideration. For a given type of soil and vegetation, the soil-root value can be determined and expressed in the thickness of a layer of water, in the same way as precipitation and evapotranspiration.

A soil which has a high moisture-holding capacity and is deeply penetrated by roots will have a high soil-root value, which means that a great amount of water can be stored in the soil and is readily available to plants. Such a high soil-root value is conducive to plant growth since during dry periods the need of a supply of water is less frequent than it would be if the soil-root value were low, indicating a poor moisture-holding capacity and/or shallow root-penetration of the soil. In order to afford some idea of the possible

TABLE I: TYPE OF SOIL – DEPTH OF ROOT ZONE – SOIL-ROOT VALUE

Depth of the root zone in a deep, homogeneous and permeable soil:
Class I: shallow-rooted market-garden crops, or seedlings 10– 50 cm;
Class II: grassland and moderately deep-rooted crops 50–100 cm;
Class III: deep-rooted crops, including trees 100–200 cm.

Type of soil	Distribution	Max.% available water	Depth of the profile	Soil-root value (50% of the available water in the root zone)		
				Class I	Class II	Class III
Glacial deposits	Approximately the entire region north of latitude 52 and the Alpine area + margin, (regions covered by glaciers during the ice age)					
loamy (including boulder clay)		15%	50 – > 200 cm	10 – 40 mm	40 – 75 mm	40 – 150 mm
sandy		10%	50 – > 200 cm	5 – 25 mm	25 – 50 mm	25 – 100 mm
Cover sand	Small strip south of the boulder clay area, approx. between latitudes 51 and 52	15%	50 – > 200 cm	10 – 40 mm	40 – 75 mm	40 – 150 mm
Loess (Chernozems)	Strip varying in width south of the boulder clay and cover sand region up to latitudes 45 to 50; wider in eastern Europe than in western Europe.	20%	50 – > 200 cm	10 – 50 mm	50 – 100 mm	50 – 200 mm
Mediterranean soils (e.g. terra rossa)	South of latitude 45, along the Mediterranean sea	20%	25 –100 cm	10 – 50 mm	25 – 100 mm	25 – 100 mm
Shallow soils (including mountain ranges and degraded soils)	Coastal strip in western Scandinavia; central European mountain ranges; Alps, Apennines, Pyrenees, etc.	17.5%	0 – 45 cm	0 – 45 mm	0 – 45 mm	0 – 45 mm
Alluvial and marine soils	Scattered along rivers and coasts					
clayey		20%	50 – > 200 cm	10 – 50 mm	50 – 100 mm	50 – 200 mm
sandy		10%	50 – > 200 cm	5 – 25 mm	25 – 50 mm	25 – 100 mm
Peat soils	Scattered	25%	50 – > 150 cm	12 – 60 mm	60 – 125 mm	60 – 180 mm

size of the soil-root value in various parts of Europe, an approximate survey has been compiled, (see Table I).[1])

In the column headed soil-root value the low figures indicate the possible value under unfavourable conditions, e.g. disturbing layers, poor structural condition and the like; the high figures denote the possible value under favourable conditions, viz. deep soils, good structural condition and the like.
It should be strongly emphasised that these data are very approximate their only purpose being to give an idea of the distribution of various types of soil with respect to their readily absorbable store of moisture. It should be noted that no usual pedological classifications (e.g. great soil groups) are employed, but chiefly quaternary geological data (FLINT, 1958), since it has been found that the latter give a better idea of the moisture-holding capacity of the soil profile.

[1]) The capillary rise of water from the phreatic level in low-lying lands may considerably enlarge the amount of available moisture; this applies to great parts of the Netherlands. However, this particular aspect has not been taken into account in the present investigation.

3. COMPILING A GEOGRAPHICAL SURVEY OF THE WATER DEFICIENCIES IN EUROPE

It will be sufficiently clear from what has been stated above that water is an extremely important factor in growth; our next task is to examine what deficiencies should be taken into account in the natural watersupply to crops in Europe.

It was shown in section 1.2 that for a plant to achieve optimum growth the reduction in moisture available in the root zone should not exceed the soil-root value. Under such conditions the evapotranspiration from the plant is equal to the potential evapotranspiration of which the magnitude is determined by climatic conditions.

During a period in which evapotranspiration exceeds precipitation (climatological precipitation deficit) the readily available soil-moisture, which is at most equal to the soil-root value, will eventually become exhausted. At this point commences the physiological period of drought which is terminated as soon as precipitation again exceeds evapotranspiration; consequently the moisture deficit will then have risen to its maximum value.

The magnitude of any water deficiency is determined by the water balance, which in the case of a given period may be written:

$E_{pot} - (P + R) =$ water deficiency, E_{pot} = potential evapotranspiration;
P = precipitation;
R = available soil moisture (up to a max. value equal to the soil-root value).

In irrigation practice it is not unusual for the variations in the soil moisture content to be checked daily, but in order to obtain an approximate survey of the irrigation needs in a given area there is little point in making the calculation for periods of less than one month. At the commencement of the period in which the climatological precipitation deficit occurs, the available soil moisture stored in the soil usually corresponds to the soil-root value. This value can be determined with sufficient accuracy in case of a known soil type and crop, but there are often such great local variations in the magnitude as to render it impossible to include reliable soil-root values in the geographical survey of irrigation needs. Consequently in this survey only the climatological precipitation deficit has been determined, viz. only the factors 'precipitation' and 'potential evapotranspiration':

$$E_{pot} - P = \text{climatological precipitation deficit.}$$

A geographical survey of the climatological precipitation deficit can now be obtained by calculating this balance for each separate month over a large number of representative places, and mapping the maximum precipitation deficit obtained by summing the results. By subsequently including the soil-root value one obtains the water shortage with which crops have to deal in a particular instance. In order to determine whether or not supplemental irrigation would be an economic proposition it is also necessary to calculate the frequency at which a particular precipitation deficit will occur. In this manner, employing the calculations set out in detail in the following paragraph, a general survey is obtained of the average water shortages in Europe and of the shortages which occur with a given frequency.

3.1 CALCULATION OF THE CLIMATOLOGICAL PRECIPITATION DEFICIT

The climatological precipitation deficit is calculated over the annual climatological deficit period, this period being characterised by the fact, that the water balance shows a precipitation deficit for each month.

Starting from the monthly precipitation and the monthly potential evapotranspiration averaged over a large number of years, the average annual maximum climatological precipitation deficit is obtained by summing the precipitation deficit over all months in the deficit period.

As an illustration of the calculation of the average annual maximum precipitation deficit from the water balance, drawn up separately for each month, table II shows the calculation for Helsinki, Paris, Athens and de Bilt (Holland) from average meteorological data over thirty years, and also from data for 1919 in the case of de Bilt.

These calculations were made in respect of 287 European meteorological stations regarded as being representative of their vicinity. The average monthly precipitation figures could be taken from the annual records of the meteorological departments concerned, but potential evapotranspiration values could not be arrived at by direct observations and had to be calculated with the aid of known meteorological data.

Determination of the potential evapotranspiration

Despite the fact that an evapotranspiration formula on a physical basis is nowadays available, no one has yet succeeded in drawing up a formula wholly derived from theoretical considerations. Since evapotranspiration is affected by numerous factors, such a formula would moreover be of such a complex type as to be virtually useless in practice. Many research-workers have therefore compiled formulae which have a more or less

TABLE II. WATER BALANCES DRAWN UP FOR SOME PLACES IN EUROPE[1])

	Helsinki:				Paris:				Athens:				De Bilt:				De Bilt 1919:			
	P	E_p	$P-E_p$	$\Sigma (P-E_p)$	P	E_p	$P-E_p$	$\Sigma (P-E_p)$	P	E_p	$P-E_p$	$\Sigma (P-E_p)$	P	E_p	$P-E_p$	$\Sigma (P-E_p)$	P	E_p	$P-E_p$	$\Sigma (P-E_p)$
J	55	0	55	—	39	8	31	—	53	29	24	—	57	7	50	—	50	6	44	—
F	43	0	43	—	31	13	18	—	40	50	– 10	– 10	44	10	34	—	40	6	34	—
M	43	0	43	—	41	24	17	—	30	76	– 46	– 56	50	22	28	—	66	18	48	—
A	42	14	28	—	42	63	–21	– 21	20	103	– 83	–139	46	51	– 5	– 5	65	40	25	—
M	48	60	–12	– 12	53	88	–35	– 56	21	139	–118	–257	52	89	–37	– 42	22	103	–81	– 81
J	51	95	–44	– 56	59	110	–51	–107	16	162	–146	–403	61	99	–38	– 80	46	108	–62	–143
J	59	111	–52	–108	56	122	–66	–173	4	181	–177	–580	79	111	–32	–112	129	94	35	–143
A	83	89	– 6	–114	55	102	–47	–220	8	173	–165	–745	88	89	– 1	–113	48	100	–52	–160
S	72	47	25	,,	50	82	–32	–252	16	144	–128	–873	70	68	2	,,	40	85	–45	–205
O	74	11	63	,,	59	49	10	,,	40	113	– 73	–946	77	29	48	,,	63	22	41	,,
N	68	3	65	,,	46	14	32	,,	66	65	1	,,	64	12	52	,,	58	6	52	,,
D	62	0	62	,,	45	8	37	,,	69	50	19	,,	72	7	65	,,	115	8	107	,,
Tot:	700	430	384	–114	576	683	145	–252	384	1285	44	–946	760	593	279	–113	742	597	351	–205
	Deficit period: May to August (5–8)				Deficit period: April to Sept. (4–9)				Deficit period: Febr. to Oct. (2–10)				Deficit period: April to Aug. (4–8)				Deficit period: May to Sept. (5–9)			

[1]) all values expressed in mm.

pronounced empirical basis. It was usually possible to give them a comparatively simple form since use was made of the interrelationships existing between a number of meteorological factors such as incoming radiant energy, temperature, precipitation, saturation deficiency of the atmosphere and evapotranspiration, but the relationship between these factors is not identical for different climatic regions. The usefulness of these empirical formulae is therefore largely determined by the climatic conditions of the region for which the formula is drawn up.

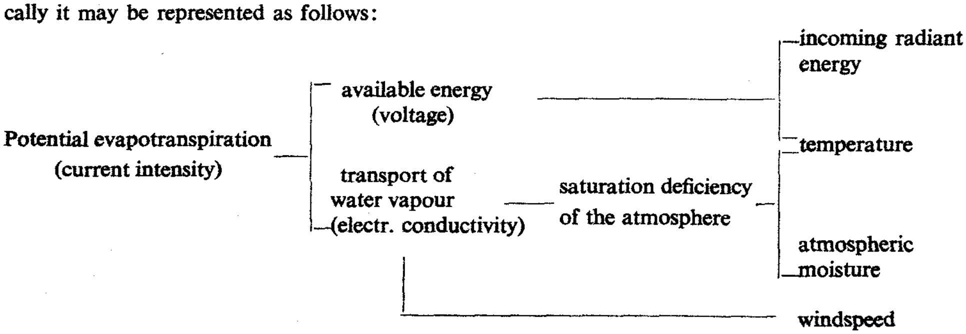
Moreover in evaluating these formulae it is very important to examine to what extent account was taken of the most important meteorological factors determining evapotranspiration. What these factors are, will be briefly discussed below.

Energy is required for the evapotranspiration of water; this energy is derived from the incoming solar radiation, but not all incoming radiant energy is available for evapotranspiration at the moment of irradiation. Part of it is used to increase the temperature of the air and may subsequently become available for evapotranspiration. The energy thus stored may also be entrained by air currents to regions which have different meteorological conditions (adjective heat). From this it follows that the temperature, although closely correlated to the incoming radiant energy, should occupy such a position in the evapotranspiration formula as to enable the said effects to time and place to be taken into account.

But it is not enough for there to be sufficient energy available to evaporate the water; there must also be a regular transport of water vapour to make possible fresh evapotranspiration. If a plentiful transport of water vapour is possible the evapotranspiration will be greatly determined by the available energy. However, in case there should only a limited transport of water vapour be possible, the available energy will not be fully employed for evapotranspiration, resulting in an evapotranspiration being smaller than in the first instance. Recent investigations have shown that the withdrawal of water vapour is a very complex process. In fact, the rate at which water vapour is transported at a given moment is not determined by the comparatively simple diffusion process, but by wind speed, turbulence and convection. When, however, we take into consideration the amount of water vapour drawn off in a given period (e.g. a week), this will not primarily depend on the above factors but on the saturation deficiency of the atmosphere, viz. the absorption capacity of the air for water vapour. This is why the saturation deficiency of the air is very important in the empirical formulae when the evapotranspiration has to be calculated over a period of a week or a month. The size of this saturation deficiency is closely correlated to the temperature and humidity of the air.

It may be desirable to include windspeed in the empirical formula when one wants to apply the calculations to regions between which there are considerable differences in the mean wind speed.

The evapotranspiration process shows some similarity to the law in the theory of electricity. Schematically it may be represented as follows:



The most suitable evapotranspiration formulae for calculating the climatological precipitation deficit will be considered in greater detail.

PENMAN's (1956) formula is based on an energy balance for the incoming radiant energy. Temperature, cloudiness, wind speed and relative humidity occur in the equation representing the energy balance. In order to draw up an evapotranspiration formula for practical use we require some empirical coefficients in a number of terms of the balance. These empirical coefficients are calculated from the meteorological data of a specific region, so that for climatically different regions we need other empirical coefficients, but few if any of these have been published to date. Moreover the meteorological data required to use the formula are only available in the case of a limited number of meteorological stations. Except for such drawbacks, which made it impossible to employ Penman's formula for the present investigation, it must be considered one of the most reliable and theoretically sound formulae.

THORNTHWAITE's (1948) and BLANEY–CRIDDLE's (1950) formulae are mainly based on the relationship between temperature and evapotranspiration, but some account is also taken of incoming radiant energy by applying a correction for the day-length. But the phase difference between temperature and incoming radiant energy is not adequately reflected in these formulae (VAN WIJK and DE VRIES 1954).
In Thornthwaite's formula a factor is inserted which enables it to be applied to different climatic conditions insofar as they are reflected in the trend of the mean monthly temperatures. Both formulae were evolved in the United States and appear to be succesfully used in southern Europe. Hitherto there have been no indications that these formulae would also give reliable results in other parts of Europe.

HAUDE's (1955) formula is based on the relationship between evapotranspiration and saturation deficiency of the air. This formula is employed in Germany instead Penman's. Penman's formula includes too many meteorological data for practical use, while according to reports from Germany, in the case of areas which have a more continental type of climate the formula places too little emphasis on the effect of the saturation deficiency of the air. But Haude's formula does not include incoming radiant energy and moreover has only been tested in Germany, so that it would not yet be advisable to employ it in other parts of Europe.

TURC's (1953; 1954) formula is primarily based on the dependence of evapotranspiration incoming radiant energy and temperature. At the same time it lays some emphasis on precipitation and hence indirectly on atmospheric humidity, so that limited allowance is made, via the temperature, for the saturation deficiency of the water vapour in the air. The empirical coefficients are determined from observations with lysimeters and water balances of river basins throughout the world. Although Turc's formula has only little been used to date, it may be expected to find practically universal application. Moreover the formula is very practical for agriculture as it is possible to take into account the type and stage of development of the crop and the amount of moisture actually stored in the soil.

Of the five formulae mentioned for the calculation of the potential evapotranspiration, that of TURC (see appendix I) has been selected for the purpose of this investigation, having particular regard to the following advantages:

- the meteorological data required for the calculation are known in the case of practically every observation station;
- allowance is made for the two factors determining the energy available for evaporation, viz. incoming radiant energy and temperature; moreover atmospheric humidity is taken into account by means of the precipitation;
- the empirical coefficients are determined from numerous water balance observations throughout the world.

In the course of this investigation the evapotranspiration values calculated with the use of Turc's formula were compared as far as possible with water balance observations or with empirical calculations, which have been found reliable. The result did in fact confirm the applicability of Turc's formula to various climatic regions within Europe.
The fact that Turc's formula takes no account of wind speed may be a disadvantage, although wind speed will only be an important factor when the evapotranspiration has to be calculated over very brief periods or when extreme values occur for the mean wind speed.
For the 287 meteorological observation stations included in the calculation the temperature data were taken from the annual meteorological records and data on incoming radiant energy from BLACK's (1956) maps.

The results of the calculations were made clear by mapping them in various ways. From this the following map data were obtained:

Map I : Average annual maximum precipitation deficits;
„ Ia : Average annual precipitation deficits at the end of June;
„ Ib : Average annual increase in precipitation deficits during July-August-September;
„ Ic : Average annual maximum precipitation deficits during the growing period of winter wheat;
„ II : Average annual maximum precipitation surpluses;
„ III: Average annual period of precipitation deficit;
„ IV: Average annual potential evapotranspiration.

The meteorological stations are shown and numbered on map III. The names of the observation stations can be found in appendix II by means of these numerals. This table also shows the average annual precipitation, the average annual potential evapotranspiration, the average annual maximum precipitation deficit and the average annual maximum precipitation surpluses.
The network of observation stations was usually dense enough to make it possible to compile fairly detailed and reliable maps. Only in regions with steep contours the number of observation stations was inadequate. In these regions precipitation will in fact show marked local variations and the evapotranspiration, which depends on the altitude, will also vary from place to place. Owing to this, the precipitation deficit in mountainous regions (indicated on the map by a special symbol) showed a highly varied pattern which could only be approximately reduced to map form. In compiling the maps use was also made of precipitation and altitude maps to plot the boundaries.

3.2 CALCULATION OF THE FREQUENCY OF THE WATER SHORTAGES

As well as determining the magnitude of the average climatological precipitation deficit it is also necessary to determine the frequency with which a water shortage occurs. These

data are in fact indispensable if we are to discover whether or not supplemental irrigation would be an economic proposition.
In order to calculate the frequency of the water shortages we must first know the frequency distribution of the precipitation deficit. This can be calculated from the monthly precipitation and potential evapotranspiration figures over a great number of years. But in view of the degree of accuracy aimed at in this investigation it is preferable to avoid such an exacting method of calculation. It was found possible to greatly simplify the method of calculation without the frequency distribution of the climatological precipitation deficit showing an error of more than 25 mm (ignoring a few exceptions).

In the method followed it was possible to limit the calculation to graphically determined frequency distributions of the precipitation for 46 meteorological observation stations, from which data the frequency distributions of the precipitation, and consequently the precipitation deficit could also be deduced for the remaining places.

The simplification was obtained by starting from the following assumptions:
- there is no clear correlation between precipitation and potential evapotranspiration over the deficiency period; hence the variability in the precipitation deficit has not been increased or reduced by a correlation between precipitation and potential evapotranspiration;
- the annual variability in the precipitation is many times greater than in the potential evapotranspiration.

It follows from these two assumptions that in order to calculate the frequency distribution of the precipitation deficit it is only necessary to calculate the frequency distribution of the precipitation.[1])
It was also found that:
- the variability in the total precipitation over a particular period of the year can be calculated from the variability in the total precipitation over a more or less overlapping period, provided the characteristic pattern of the rainfall does not differ widely in the two periods. This relationship can be expressed as follows:

$$\frac{\text{variability in the precipitation over period I}}{\text{variability in the precipitation over period II}} = \sqrt{\frac{\text{Average precipitation in period II}}{\text{Average precipitation in period I}}}$$

Tests have shown that using this rule does not lead to any great deviation even when the two periods are taken into consideration for different meteorological stations, provided the characteristic patterns of rainfall also show close similarity in this case. From the precipitation distribution it was possible to select 46 representative meteorological stations for which the frequency distribution of the precipitation was determined from the annual data. From this the amounts of precipitation were calculated graphically at different probabilities. For 18 of the 46 stations selected it was found that the characteristic pattern of precipitation in the deficit period differed considerably from the pattern of the annual precipitation. Hence the frequency distribution for these 18 stations had to be calculated from the precipitation data over the actual deficit period in stead of using the total annual precipitation. For this purpose it was therefore necessary to have at our disposal the monthly precipitation figures for a great number of years.

[1]) In the Netherlands the variability in the precipitation is about five times as great as in the potential evapotranspiration. In this case, if we ignore the variability in the evapotranspiration, the resulting error in the calculated variability in the precipitation deficit is only 2%.

From the 46 frequency distributions calculated it was then possible to deduce all required frequency distributions for the remaining meteorological stations of which only the average annual precipitation was known. These stations were accordingly first divided into 46 groups according to the pattern of precipitation, one calculated frequency distribution being representative of each of these groups. In deducing the frequency distributions required use was made of the above-mentioned relationship between the average amount of precipitation and the variability in the precipitation. The number of years included in the calculations varied from 30 to 70.

Hitherto only the frequency distribution of the precipitation deficit had been calculated, but in order to determine in how many years out of ten there might be a shortage of water for the plant we should also include the soil-root value as a credit item. Since, as was stated earlier, no geographical survey of the soil-root value is available, the calculations for the whole of Europe were made for three different soil-root values, viz. 50 mm, 100 mm and 200 mm.

In order to obtain a conspectus of the results obtained, three maps were compiled:

Maps Va, Vb and Vc: Frequency of precipitation deficits of
50, 100 and 200 mm respectively.

The mountainous regions also caused difficulties in compiling these maps. In particular, the central Alpine regions showed such a varying pattern (changing from one valley to the next), that it was even found impossible to show approximate frequency lines in this region. The Central Alps are therefore left blank on maps Va, b and c.

4. INDICATIONS PROVIDED BY THE MAPS

4.1 SURVEY OF THE MAPS COMPILED

The results of the calculations made according to chapter 3 had to be arranged in such a way as to be of the maximum worth in practice.
To this end various maps were compiled which provided the completest possible survey of the incidence of water shortages in agriculture in Europe.
Before entering into a discussion of the maps we should once again make it quite clear that these maps cannot provide any solution to the problem as to whether or not supplemental irrigation would be profitable. The maps supply information only on the very important question as to what water shortage should be taken into account by farmers in the various parts of Europe. In conjunction with this it might be possible to examine whether supplemental irrigation would be economically important taking into consideration such factors as:

- the availability of water and its costs;
- the availability of labour and capital;
- the level of agriculture;
- the possibility of changing over to more intensive crop growing;
- the possibility of marketing agricultural produce;
- the cultivation of drought-resistant crops;

and so on.

Put briefly, the maps only supply information on the need of supplemental irrigation from the point of view of climate, not directly on the importance of supplemental irrigation from an economic standpoint.

In the first place a map (I) was made showing the size of the *average annual maximum precipitation deficits*. This is the size to which the climatological precipitation deficit increases in the course of the annual deficit period. But there are two drawbacks attaching to this map:

- the duration of the deficit period varies very considerably as between the north and south of Europe, for example, and will generally not coincide with the growing period of the various crops, but be shorter or longer. In the latter case the actual water shortage is less than would appear from the map;
- the potential evapotranspiration is calculated with the use of Turc's formula, a value of 70 being assumed for the crop factor (see appendix I). According to Turc this represents the potential evapotranspiration of a luxuriant crop entirely covering the ground. But certainly not all crops cover the soil completely during the entire deficit period. Hence for such a case map I also shows an excessive water shortage.

In order to obviate these drawbacks as far as possible, maps Ia, Ib and Ic have been compiled respectively showing the precipitation deficits to the end of June, for July–August–September, and for the entire growing period of winter wheat.

It is very important that the *precipitation surplus* built up outside the deficit period should be great enough to supplement entirely the soil moisture storage. The calculation is made in exactly the same manner as that of the precipitation deficit. These results are incorporated in map II.

It was also found desirable to show the *duration of the deficit period* in a separate map (map III) so that it can be ascertained whether the growing season of a particular crop wholly or partly coincides with the deficit period. With the aid of these five maps it is now possible to draw more detailed conclusions regarding the possible need of supplemental irrigation.

The results of the calculation of the *frequency of the water shortages* are incorporated in three different maps (Va, Vb and Vc) showing the number of years of a decade in which a climatological precipitation deficit of 50, 100 and 200 mm respectively is exceeded.

If in a particular instance there is a soil-root value of 100 mm, it is possible to ascertain from map Vb the number of years out of the ten in which supplemental irrigation will be needed. If it has also been possible to determine that in this particular case it is only profitable to overcome a water shortage of, say, 200 mm, it can be ascertained from map Vc in how many years supplemental irrigation will be an economic proposition.

In order to determine the need of supplemental irrigation, this being the main purpose of the present investigation, one should therefore read 'need of supplemental irrigation at a soil-root value of 50, 100 and 200 mm, respectively' instead of climatological precipitation deficit of 50, 100 and 200 mm respectively.

The resultant maps provided an indispensable supplement to maps I, II and III, which only relate to the mean situation.

In conclusion, for a number of places it was also found desirable to set out the results clearly in graph form. For this purpose fourteen places were selected from various parts of Europe.

The size of the potential evapotranspiration, the precipitation, and the resultant climatological precipitation surplus or deficit are set out month by month in the form of a block diagram in appendix III. The frequency of the precipitation deficit with the chances in 1 to 9 out of 10 occasions are set out in diagram in appendix IV.

4.2 AVERAGE ANNUAL MAXIMUM PRECIPITATION DEFICITS (MAP I)

This survey clearly shows in the first place that precipitation deficits occur throughout Europe, although generally to a lesser extent in the clearly defined mountainous regions, where however, agriculture is usually less important.

Although there are wide variations in the general pattern, we can nevertheless distinguish different classes according to the size of the precipitation deficit; the following main classification may be adopted:

< 50 mm — *very slight deficit:* water shortage only occurs with low soil-root values (0–50 mm).

regions:

- extreme north of Europe: Northern Scandinavia and northern Russia;
- westerly, mainly steeply contoured coastal strips where the depressions from the Atlantic are intercepted: Norway, Scotland, Ireland, the west of England;
- precipitation centres of the mountain ranges and their foothills: the Tatra and Alpine massif and the hills situated to the north thereof.
  It is particularly noticeable that the centre with a small precipitation deficit is shifted somewhat to the north of the Alpine massif. This may be connected with the fact that most summer rains are brought in from the region north of the Alps. At the other hand certain valleys lie in the rain shadow and there – also as a result of the low moisture holding capacity of the gravelly soil – irrigation is proving very valuable (e.g. western Tirol, south-west Norway).

50–100 mm — *slight deficit:* water shortages also occur with somewhat higher soil-root values (0–100 mm).

regions:

- predominantly in northern Europe: west Russian and north Russian ridge, Finland, central and northern Sweden, south-east Norway, central England;
- around the precipitation centres of the mountain ranges and their foothills (Alps), and also the Pyrenees, the Central Massif, the Taunus, the Erzgebirge, the Sudeten, Carpathian and Transsylvanian Alps.

100–200 mm — *moderate precipitation deficit:* water shortages occur with moderate and occasionally even with high soil-root values (0–200 mm).

regions: – north of latitude 50: central Russia, Baltic states, north-west Poland, southern Sweden, southern Finland, Denmark, the Bothnian Gulf, north-west Germany, the Benelux-countries, south-east England;
– south of latitude 50: only in mountainous districts or areas bordering the latter, e.g. the Central Massif, the foothills of the Pyrenees, a part of the southern and western Alps, the mountain areas of southern Jugoslavia and the Rumanian highlands.

200–400 mm *high precipitation deficit:* severe water shortages occur in this category, even where there is a high soil-root value (0–200 mm).

regions: – Poland (both western and central Poland), east central Germany, London and vicinity, central, south-west and southern France (with exception of the Central Massif), north-west Spain, the Po plain, the Apenines, the Danube plain.

400–600 mm *very high precipitation deficit:* irrigation very important.

regions: – transition areas in central Spain, central Portugal, central Italy, Corsica, Rumanian lowland plain, Macedonia, western Greece.

>600 mm *extreme precipitation deficit:* irrigation essential.

regions: – southern Portugal, southern, central and eastern Spain, Sardinia, Sicily, south-eastern Italy, eastern Greece.

Thus, as we might have expected, the general tendency is for the deficit to increase from north to south. In northern and north-west Europe, where there are fairly large amounts of summer precipitation and relatively little evapotranspiration, the deficit varies from very slight to moderate. In central and eastern Europe, viz. in regions with a land climate, the summer precipitation is generally high, as is also the summer temperature, the result being a moderate to fairly high precipitation deficit. Districts bordering the Mediterranean obviously have a high to extremely high precipitation deficit, the summers here being both warm and dry.
The general pattern is disturbed by mountain ranges with a relatively slight precipitation deficit, in many cases excentrically situated, and by the lowland plains and river valleys with a relatively high precipitation deficit.

4.3 AVERAGE ANNUAL PRECIPITATION DEFICITS AT THE END OF JUNE (MAP Ia)

The general tendency is for the regions north of latitude 45 to have at the end of June a precipitation deficit usually varying from 50 to 100 mm. An exception is formed by the mountain ranges and their foothills, the western coastal districts of the British Isles, as well as the greater part of the northern European countries, where the precipitation deficit is lower, and also the central area of Germany and Poland, the central areas of France, and the Hungarian-Jugoslavian Danube plain where the precipitation deficit is higher.

The conclusion to be drawn from this general situation is that irrigation is not required in the spring and early summer provided the soil-root value is moderate to high (> 100 mm), viz. provided the soils in question have a good moisture-retaining capacity and already possess a well-developed root system (perennial and winter crops). In many cases, however, supplemental irrigation will be beneficial to crops sown in the spring, particularly on soils with a poorer moisture-retaining capacity.

The regions south of latitude 45, with the exception of the mountain areas, have a precipitation deficit at the end of June which is already higher than 100 mm. In the extreme south the deficit has already increased to about 400 mm. By this time, however, the winter crops in these areas are substantially ripe, and further to the south they have even been harvested. Generally speaking for these crops supplemental irrigation, will only be of importance if there is only a small amount of moisture stored in the soil at the commencement of the dry period (see map II). Crops sown in the spring will usually remain very poor if no irrigation is applied.

4.4 AVERAGE ANNUAL INCREASE IN THE PRECIPITATION DEFICITS DURING JULY–AUGUST–SEPTEMBER (MAP Ib)

Broadly speaking this survey is very similar to map Ia, which shows the situation as it has developed up to the end of June.

In large parts of Europe the precipitation deficit at the end of June is of about the same order of magnitude as the further increase during July, August and September. The German-Polish area, with an increase of over 100 mm, is larger, however, and this is also true of the central and south-western area of France. On the other hand regions in which the summer depressions are intercepted, particularly the western coastal districts of the British Isles and Scandinavia, have an increase in the precipitation deficit which is less than the precipitation deficit at the end of June.

Towards the south the increase in the precipitation deficit ranges from amounts of 100 mm south of the Alps and the east European mountains up to 400 mm and over in the extreme south. Consequently this increase is somewhat greater than the precipitation deficit in these regions up to the end of June.

Although in the spring situation it is still possible to make use of the available soil moisture corresponding to the soil-root value, this is no longer the case in the summer situation, and the whole of the further increase in the precipitation deficit has to be made up by irrigation. Thus except for the above-mentioned coastal districts and certain mountain areas of central Europe where the increase in the deficit is very small, need of irrigation is everywhere where crops still not entirely ripe, are in the open. The further south we go the more important this becomes, although we should take into account the fact

that crops ripen increasingly earlier in a southern direction, enabling the irrigation period to be reduced.
For this reason the total shortage of water is by no means always as great as that indicated on the maps. Thus on map Ib this is due to the above reason, on map Ia to the amount of available soil-moisture corresponding to the soil-root value, and on map I to both reasons.

4.5 AVERAGE ANNUAL MAXIMUM PRECIPITATION DEFICITS DURING THE GROWING PERIOD OF WINTER WHEAT (MAP Ic)

This map illustrates the climatological precipitation deficit throughout the growing period of winter wheat[1]). From this map it is possible to ascertain whether or not the natural supply of water in the various agricultural regions of Europe is sufficient for the cultivation of winter wheat.
In interpreting this map both the size of the precipitation deficit and that of the soil-root value should be taken into account. For very good soils the maximum value to be observed for this purpose is 150 mm. Thus where the precipitation deficit exceeds 150 mm, no optimum yields may be expected without supplemental irrigation.
It should also be remembered that in addition to an adequate supply of moisture and proper tendance, other factors are also important in wheat-growing, e.g. the temperature and relative humidity during the growing period. Having regard to the two latter factors, which are the main determinants of the quality of the wheat, it is possible to divide Europe into three areas:

- the north-west, which has a temperate climate, viz. wet, fairly cool summers, and wet, mild winters;
- the south, which has a Mediterranean climate, viz. dry, warm summers and wet, mild winters;
- the south-east, which has a continental climate, viz. damp, warm summers and dry, cold winters.

The continental climate is the most suited to the cultivation of good quality wheat, unlike the temperate climate where the quality of the wheat is generally middling. There may, however, be great variations from place to place in the size of the yield; this is found to be due, among other causes, to the natural supply of water. It can be ascertained from map Ic.

High yields predominate in the north-western part of Europe, e.g. the well-known districts with soils having a high moisture-holding capacity in Denmark, the Netherlands and eastern England (alluvial soils), and Germany, Belgium and northern France (mostly loess soils). The greater part of these districts comes within the region having a precipi-

[1]) The data on the length of the growing period of winter wheat and the yields in the various wheat-producing regions are taken from the 'Atlas of World Resources', part I: 'The agricultural Resources of the World', by William van Royen (1954).

tation deficit of from 100 to 150 mm, in other words in the region where the natural water supply is just sufficient provided the soil has a high moisture-holding capacity. It will be clear that substantially poorer yields will be obtained in central and southern France where the deficit exceeds 150 mm.

Owing to the high precipitation deficit the yields in southern Europe are generally poor. The Duero river plain in the neighbourhood of Valladolid, which is the most important wheat-growing district in Spain has a deficit of about 200 mm, which is less than for the rest of Spain with the exception of the north-west, where for other reasons wheat-growing is of no importance.

In Italy the Po plain is a well-known wheat-producing district with very high yields. Here indeed good soils and a good deal of warmth are accompanied by a relatively low precipitation deficit of from 50 to 150 mm. More towards the south the yields decline with a simultaneous increase in the deficit.

In the south-east of Europe wheat-growing is concentrated in the fertile plains and valleys such as the Hungarian Danube plain, Walachia, Moldavia and the Ukraine. In this instance also productivity is found to be correlated to the size of the precipitation deficit. The Hungarian plain with a deficit of from 100–150 mm gives very good yields except on the sandier soils between the Danube and the Tizza which have a poor moisture-retaining capacity. The yields in Walachia are lower than in Hungary but better than in Moldavia and the Ukraine where the deficit is of the order of 200 mm.

Thus this approximate survey demonstrates the usefulness of this map for the comparison of various wheat-producing districts with respect to the natural supply of water.

4.6 AVERAGE ANNUAL MAXIMUM PRECIPITATION SURPLUSES (MAP II)

Except for the extreme south-east of Spain – in the neighbourhood of Murcia – the whole of Europe has a precipitation surplus for one or more months (See also map III).

In Map II five classes are distinguished, according to whether or not there is a sufficient precipitation surplus to make up the soil-root value:

> 300 mm — more than sufficient for all soils.

regions:
- predominantly in the mountains and along the west coasts of the Ocean and the Baltic as well as the Mediterranean.
  It is remarkable that the surplus in eastern Europe nowhere exceeds 300 mm; this is due to the maximum precipitation coinciding with the maximum evapotranspiration.

200–300 mm — precipitation surplus generally sufficient to supplement the water storage, but locally inadequate after a dry winter.

regions:
- predominantly north of latitude 52;
- also the Benelux countries, north-western France, the greater part of western Germany, the vicinity of the mountain ranges;

- finally, south of latitude 45, where narrow strips occur behind the regions with a surplus of more than 300 mm.

100–200 mm — an insufficient precipitation surplus for supplementing the water storage in areas with a high soil-root value.

regions:
- only occurring south of latitude 54;
  Largest region: East-Germany, Poland, southern Russia, Rumania, Bulgaria, Hungary, eastern Jugoslavia and a part of Czechoslovakia;
- also south-east England; the Rhine plain at Bingen-Strassburg, central France;
- narrow strips in the Mediterranean countries: Spain, Italy, Greece and the island of Sicily.

50–100 mm — only sufficient for areas with a small soil-root value.

regions:
- central and south-west Spain adjoining Portugal;
- also the eastern coasts of Sardinia, southern Italy, Greece, Bulgaria, Rumania, and the south of the Ukraine.

$<$ 50 mm — an absolutely insufficient precipitation surplus.

regions:
- large areas of Spain: the entire eastern part plus the Balearic islands, the plain around Valladolid and the south-west adjoining the extreme south of Portugal;
- also a small area around Athens.

4.7 AVERAGE ANNUAL PERIOD OF PRECIPITATION DEFICITS (MAP III)

Map III shows approximately in which month the precipitation deficit begins and in which month it ends, or in which month the precipitation surplus ends and in which month it begins.

It is particularly noticeable that in practically the entire central region of Europe between about latitudes 53 and 43 the precipitation deficiency begins between mid-March and mid-April and ends between mid-September and mid-October, so that this period lasts about five to seven months. An exception is formed by the mountain ranges in which the deficit period is naturally of much shorter duration; in some places it is even less than a month. The details of these variations cannot, however, be seen on the map, although they are marked separately with each meteorological station.

In the regions north of latitude 53 the deficit period does not begin until the end of April or the beginning of May. Noticeable is the effect of the ocean which delays the beginning of the deficit period owing to the high monthly rainfall (Scandinavia, British Isles).

But also in regions such as Russia where the land climate is the major influence, the line indicating the beginning of the deficit period (about 15th April) is shifted to the south for

about three degrees of latitude. This is to be attributed to the potential evapotranspiration which is still very slight in the spring and in which no change occurs until the end of April.
In southern Europe, approximately south of latitude 42 to 44, the deficit period commences as early as the beginning of March or even earlier. Of particular interest are the considerable differences in Spain where the further south-east we proceed the earlier the period begins; it even commences as early as the beginning of January along the east coast. This is to be attributed to the influence of the north African climatic zone. On the other hand, along the western coastal areas of Spain, Italy and Greece the effect of the Mediterranean is felt in the form of winter rains which delay the commencement of the deficit period.
The influence of the sea is also felt at the end of the deficit period, although not everywhere in the same way. The Baltic has a strong tendency to prolong the deficit period in the surrounding regions. On the other hand the Atlantic Ocean, the western part of the North Sea, the Mediterranean and the Adriatic, have a curtailing effect on the length of the deficit period.
Here again the eastern coast of Spain occupies an exceptional position owing to the warm dry wind coming from the south. At some places there is even a precipitation deficit throughout the year in this area.
Owing to the land climate also the final dates of the deficit period are shifted to the north; this is clearly illustrated by the trend of the line for 15th October in eastern Europe.

4.8 AVERAGE ANNUAL POTENTIAL EVAPOTRANSPIRATION (MAP IV)

With regard to the pattern shown by the map of the average annual evapotranspiration, only a few remarks are required.
Going from north to south the evapotranspiration gradually increases, viz. from 300 mm in Norway and Finland to about 1300 mm in southern Spain and southern Greece. The farther south we go the greater is this increase and the clearer the differences are seen over relatively short distances. Whereas in the north the distances between the evapotranspiration lines 100 mm apart extend over some five degrees of latitude, in the south this is only in the order of about one degree of latitude.
An exception to the comparatively regular trend is formed by the central European mountain ranges which have a relatively lower evapotranspiration.

4.9 FREQUENCY OF PRECIPITATION DEFICITS (MAP Va, Vb, Vc)

The geographical survey of the frequency with which the water shortages occur is calculated for three assumed soil-root values, viz. 50, 100, and 200 mm. These values represent the situation which occurs under normal soil-root conditions (50–100 mm) and the upper limit (200 mm) which in practice occurs far less frequently.
A comparison of the three maps clearly illustrates the effect of the magnitude of the soil-root value on the frequency of the water shortage.

For cases in which the soil-root value is only 50 mm, no place could be found anywhere on the map where a water shortage occurs less than once in ten years. On the other hand at a soil-root value of 100 mm in the case of part of Scandinavia, Scotland, England and Ireland the frequency of the water shortage is already less than once in ten years. At a soil-root value of 200 mm we find the above situation over the whole of northern Europe, Scotland, Ireland, the greater part of England, the west coast of Denmark, White Russia, and extensive areas in the neighbourhood of the mountains.
A comparison of the various regions which have a water shortage in more than nine years out of ten shows the same pattern.
Broadly speaking, at a soil-root value of 50 mm, this area coincides with the area south of latitude 53, with the exception of the Benelux countries and northern France where the water shortage is somewhat smaller, and Denmark and south east Sweden where a shortage also occurs in more than nine years out of ten. At a soil-root value of 100 mm the entire area is clearly shifted to the south. At a soil-root value of 200 mm the boundary, in general, already coincides with latitude 45.

We can clearly distinguish a number of areas on the three maps in which there is a noticeable difference from the general situation. Firstly, areas with a less frequent water shortage. These chiefly coincide with the mountain ranges and the foothills to the north there of. The mountains in Great Britain are also an obvious example of areas with a low frequency of water shortage.
Of greater interest are the areas with a more frequent water shortage. In general these areas are somewhat warmer and in particular drier than their vicinity. They are mainly lowland plains, so that these are also the very areas where the best agricultural districts are found, e.g. central France, eastern Germany, the Danube plain, the Rhine plain at Bingen-Mannheim, and the vicinity of Prague. The frequent water shortage in south-east

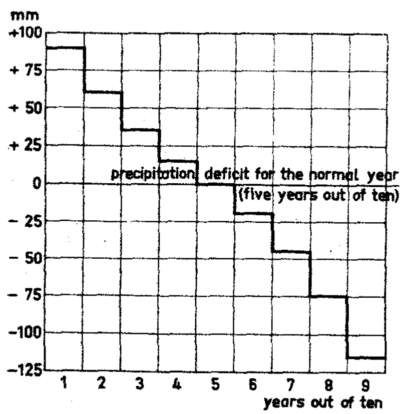


Fig. 2. Graph of the mean frequency pattern for Europe, calculated from the data given in appendix IV

England, eastern Denmark and southern and eastern Sweden is also noticeable. The reason is to be sought in the fact that these areas lie in a rain shadow and in addition are heated by the ocean which is relatively warm at this latitude.

The frequency of the precipitation deficit for a number of places in Europe is shown in graph form in appendix IV.
It is possible to read from these graphs in how many of a period of ten years a precipitation deficit of a given size or more may be anticipated. In the case of Paris, for example, in three out of ten years the precipitation deficit is found to exceed 300 mm, and in eight out of ten 195 mm. Compared to the great differences in the precipitation deficit existing between various places at a given frequency (e.g. 5 years out of 10), the differences between the frequency patterns themselves, viz. in the size of the stages, are very small. For this reason it was obvious to draw a mean graph from this frequency pattern (fig. 2) which is very useful for estimating the frequency of the precipitation deficit of places of which only the mean situation is known.
To make such an estimate one may proceed as follows:
The precipitation deficit for the normal year for the place in question – or a place in the vicinity – is found in appendix II. If it is now required to know what precipitation deficit should be allowed for in three of the ten years a value of 35 mm is found in the graph, which value, added to the precipitation deficit for the normal year (x mm), gives the required value (x + 35 mm).
If, on the other hand, the average precipitation deficit was 245 mm, for example, the graph also learns that a precipitation deficit of 200 mm or more may be expected in seven years out of ten.

5. FINAL OBSERVATIONS

This investigation shows how an analysis can be made of the size of the precipitation deficit in agriculture from the water balance:

$$E_{pot} - P = \text{precipitation deficit.}$$

This method is most applicable to Europe since a dense system of meteorological observation stations is available. If, however, it is desired to analyse regions where this is not the case, it may be possible to obtain an approximate idea of the precipitation deficits by studying maps showing soil types, natural vegetation, total annual precipitation and distribution of precipitation, altitude, land use, or possibly other available data. Even where the water balance method can be employed, these maps are useful for adding the boundaries in the precipitation deficits maps.

The calculation of the water balance for 287 places in Europe led to the compilation of ten maps which give an approximate idea of the natural supplies of water in Europe. Only regions of the order of magnitude of 1,000,000 ha or more can therefore be compared with respect to the need of irrigation. In the case of smaller regions, however, or regions with steep contours, the conclusions become uncertain because precipitation in particular may vary considerably from place to place.

If therefore it is required to make an accurate analysis of a particular region it will first of all be necessary to calculate the water balance for the greatest possible number of observation stations. The accuracy of the analysis may also be increased by such means as:

- calculating the potential evapotranspiration for various crops and according to their stage of development (factor V in Turc's formula).
- accurately determining the size of the soil-root value and including it in the water balance;
- calculating the water balance per decade;
- possibly employing another evapotranspiration formula, provided it has proved reliable where it has to be employed.

The most important conclusion to be drawn from the maps compiled is that supplemental irrigation is capable of increasing the crop yield throughout Europe with the possible exception of the extreme north and a number of mountainous districts of minor importance to agriculture. Even on the very best soils supplemental irrigation will repeatedly be able to increase the yield in the greater part of Europe (see map Vc).
It will depend, however, on the benefits anticipated whether or not supplemental irrigation is used. It should be remembered that the calculations are made for a luxuriant stand of vegetation, but in practice conditions have been substantially adapted to insufficient water supply by means of crop selection or extensive cultivation. Under these conditions, if supplemental irrigation is to be an economic proposition, it should be accompanied by a modified choice of crops and intensification of cultivation, or in other words by a modification of the entire system of farming (BAARS, 1958). But the problems attaching to the determination of the cost/benefit ratio with the use of supplemental irrigation have by no means yet been solved.
Hence for the time being this investigation may serve to give an idea of the extent to which irrigation is needed in the various regions under otherwise optimum production conditions. The investigation may also stimulate others to carrying out more detailed analyses of the water requirement in a particular region and a more detailed study of the cost/benefit problem with the use of supplemental irrigation.

APPENDIX I

TURC'S FORMULA FOR CALCULATING THE POTENTIAL EVAPOTRANSPIRATION

General TURC formula for calculating the evapotranspiration of a vegetation covered soil:

$$E = \frac{P + a + V}{\sqrt{1 + \left(\frac{p+a}{L} + \frac{V}{2L}\right)^2}}, \text{ in which:}$$

E = evapotranspiration in mm of water per 10-day period;
P = precipitation in mm of water per 10-day period;
L = evaporation capacity of the air:

$$L = \frac{(t + 2)\sqrt{i}}{16}, \text{ in which:}$$

t = mean temperature of the air in a sheltered location during the 10-day period, in degrees centigrade,
i = total incoming radiant energy in cal./sq. cms per day;
a = column of water that may evaporate from a bare soil, disregarding precipitation, at the expense of the water contained in the soil, in mm. per 10-day period;

$$a = 35 - \Delta, \quad \text{with a maximum value of 10 mm;}$$

Δ = depletion of the soil moisture;
V = effect of the vegetation cover on the evapotranspiration, viz. further decrease of the soil moisture;
for each 10-day period, V is the smaller of:

$$25\sqrt{\frac{Mc}{Z}} \text{ or } \left(30 + 1.5\,Mc\,\frac{z}{Z}\right) - \Delta, \text{ in which:}$$

M = production of dry matter in 100 kg per ha (dried at 105°C);
Z = length of the growing season in 10-day periods;
z = the position of the 10-day period under consideration;
c = coefficient indicating the drying-capacity of a given crop, in relation of the transpiration coefficient established for wheat.

In case of calculating the potential evapotranspiration, that is the evapotranspiration of a luxuriant growing vegetation which is never lacking of water, the formula becomes:

$$E_{pot} = \frac{P + 80}{\sqrt{1 + \left(\frac{P + 10}{L} + \frac{70}{2L}\right)^2}} \qquad \text{for } L > 10$$

and

$$E_{pot} = \frac{P + 10}{\sqrt{1 + \left(\frac{P + 10}{L}\right)^2}}, \qquad \text{for } L < 10$$

in which is taken:
$E = E_{pot}$; potential evapotranspiration in mm of water per 10-day period;
$a = 10$; maximum value of a (for humid soils);
$V = 25\sqrt{\frac{Mc}{Z}} = 70$; this corresponds, attributing to c an average value of 1, to $\frac{M}{Z} = 8$, or a production of 'harvestable' dry matter equivalent to 800 kg per 10-day period per ha; or to $c = 4/3$ (maximum value) and $\frac{M}{Z} = 6$.

APPENDIX II

LIST OF THE METEOROLOGICAL OBSERVATION STATIONS IN RESPECT OF WHICH THE CALCULATIONS WERE MADE

	Station	Annual precipi-tation	Annual potential evapotrans-piration	Annual deficit	Annual surplus	Country
1	Inari	453	231	10	232	Finland
2	Kajaani	604	312	42	334	,
3	Vaasa	585	365	88	308	,
4	Kuopio	627	361	72	338	,
5	Tampere	611	423	96	284	,
6	Helsinki	700	430	114	384	,
7	Gällivare	472	268	50	254	Sweden
8	Haparanda	533	317	115	331	,
9	Östersund	509	343	56	222	,
10	Härnösand	632	383	84	343	,
11	Uppsala	545	460	138	223	,
12	Karlstad	628	476	117	269	,
13	Falun	549	450	103	202	,
14	Borås	905	452	48	501	,
15	Västervik	547	499	184	232	,
16	Visby	514	502	214	226	,
17	Växjö	583	484	135	234	,
18	Malmö	572	528	177	221	,
19	Bodö	852	285	16	583	Norway
20	Trondheim	764	322	48	490	,
21	Röros	449	240	35	244	,
22	Lillehammer	676	361	62	377	,
23	Oslo	768	452	80	396	,
24	Bergen	1944	404	—	1540	,
25	Kristiansand	1297	446	42	893	,
26	Dalen	831	405	43	469	,
27	Grenaa	583	509	160	234	Denmark
28	Viborg	643	489	123	277	,
29	Esbjerg	678	507	131	302	,
30	Odense	630	528	166	268	,
31	Köbenhavn (Copen-hagen)	579	541	190	228	,
32	Nakskov	579	536	177	220	,
33	Skagen	625	484	133	274	,
34	Glasgow	961	431	9	539	Great Britain
35	Armagh	821	444	13	390	,
36	Blacksod Point	1285	455	2	832	Ireland
37	Birr Castle	839	463	30	406	,

	Station	Annual precipi-tation	Annual potential evapotrans-piration	Annual deficit	Annual surplus	Country
38	Aberdeen	763	425	34	372	Great Britain
39	Malin Head	827	432	19	414	Ireland
40	Dublin	715	463	48	300	,
41	Valencia	1454	526	—	928	,
42	Dumfries	987	444	8	551	Great Britain
43	Cork Cape	1053	531	33	555	Ireland
44	Shields	635	451	62	246	Great Britain
45	York	628	539	123	212	,
46	Liverpool	726	512	75	289	,
47	Nottingham	583	532	157	208	,
48	Buxton	1265	423	—	842	,
49	Yarmouth	635	541	158	252	,
50	Cambridge	560	572	190	178	,
51	Greenwich	609	618	212	203	,
52	Dungeness	631	593	221	259	,
53	St. Anns Head	912	523	69	458	,
54	Southampton	800	624	170	346	,
55	Falmouth	1127	592	62	597	,
56	Birmingham	666	513	113	266	,
57	Oxford	645	563	157	239	,
58	Southend	497	622	265	140	,
59	Cardiff	1043	548	55	550	,
60	Torquay	842	633	183	392	,
61	Wick	774	382	19	411	,
62	Den Helder	657	562	162	257	Netherlands
63	Groningen	721	567	106	260	,
64	De Bilt	760	594	113	279	,
65	Maastricht	669	670	193	194	,
66	Goes	714	656	131	231	,
67	Uccle	835	623	118	330	Belgium
68	Kaliningrad (Könings-berg)	707	534	119	292	U.S.S.R.
69	Szczytno (Ortelsburg)	611	519	112	204	Poland
70	Klaipeda (Memel)	710	515	146	341	U.S.S.R.
71	Gdansk (Danzig)	546	541	176	181	Poland
72	Koszalin (Kösslin)	737	519	83	301	,
73	Szczecin (Stettin)	561	573	205	193	,
74	Bydgoszcz (Bromberg)	506	591	236	151	,
75	Rostock	603	533	160	230	Eastern Germany
76	Waren	594	576	197	215	,
77	Flensburg	804	526	93	371	,
78	Hamburg	740	576	112	276	Western Germany
79	Bytom	732	577	81	236	Poland
80	Wroclaw (Breslau)	582	622	206	166	,

	Station	Annual precipitation	Annual potential evapotranspiration	Annual deficit	Annual surplus	Country
81	Zielona Gora (Grünberg)	636	573	169	232	Poland
82	Görlitz	706	572	123	257	Eastern Germany
83	Berlin	587	644	246	189	,
84	Magdeburg	508	635	279	152	,
85	Erfurt	506	592	221	135	,
86	Hannover	644	602	166	208	Western Germany
87	Herzberg	802	533	68	337	,
88	Dortmund	740	599	113	254	,
89	Siegen	923	523	56	456	,
90	Trier	714	645	172	241	Western Germany
91	Kassel	595	591	189	193	,
92	Frankfurt	604	653	249	200	,
93	Dresden	667	631	152	188	Eastern Germany
94	Altenburg	544	597	197	144	,
95	Scheibe	1094	444	—	650	,
96	Meiningen	641	563	154	232	,
97	Bingen	514	686	330	158	Western Germany
98	Mannheim	528	690	280	118	,
99	Buchen	745	561	124	308	,
100	Stuttgart	662	686	191	166	,
101	Freudenstadt	1519	567	—	952	,
102	Biberach	805	585	13	283	,
103	Landau	694	626	150	218	,
104	München (Munich)	904	578	1	325	,
105	Nürnberg	585	642	221	164	,
106	Gaildorf	887	599	73	361	,
107	Emden	738	565	107	280	,
108	Dunkerque (Dunkirk)	715	635	166	244	France
109	Arras	676	609	183	250	,
110	Charleville	836	645	167	358	,
111	Romilly s. Seine	584	722	291	153	,
112	Chaumont	874	667	133	340	,
113	Auxerre	602	719	265	148	,
114	Rouen	711	657	179	233	,
115	Cherbourg	863	637	167	393	,
116	St. Honorine du Fay	710	647	179	242	,
117	Ernée	834	650	135	319	,
118	St. Matthieu	809	685	213	337	,
119	Lorient	815	715	220	320	,
120	Nantes	770	735	247	282	,
121	Angers	626	742	281	165	,
122	Châteaudun	580	691	273	162	,
123	Paris	576	683	252	145	,

	Station	Annual precipi-tation	Annual potential evapotrans-piration	Annual deficit	Annual surplus	Country
124	Nancy	796	588	103	311	France
125	Strasbourg	729	686	142	185	,
126	Besançon	1081	685	51	447	,
127	Moulins	615	742	269	142	,
128	Limoges	919	749	155	325	,
129	Poitiers	645	787	307	165	,
130	La Rochelle	640	829	387	198	,
131	Bordeaux	763	849	291	205	,
132	Clermont-Ferrand	647	747	215	115	,
133	Aurillac	1141	689	76	528	,
134	Lyon	796	780	186	202	,
135	Grenoble	1142	808	107	441	,
136	Briançon	588	574	247	261	,
137	Nice	828	941	441	328	,
138	Marseille	574	1003	565	136	,
139	Avignon	644	968	462	138	,
140	Privas	1057	818	187	426	,
141	Montpellier	770	947	403	226	,
142	Perpignan	554	1043	574	85	,
143	Toulouse	660	897	346	109	,
144	St. Martin de Hinx	1402	859	103	646	,
145	Baguères	1404	742	83	745	,
146	Ajaccio	746	1106	572	212	,
147	C. Pertusato	563	1133	700	130	,
148	Moncorvo	525	1027	644	142	Portugal
149	Porto	1157	953	378	582	,
150	Castelo Branco	837	1067	561	331	,
151	Lisboa	629	1155	648	142	,
152	Campo Maior	521	1170	740	91	,
153	Faro	1309	426	886	3	,
154	Satander	840	899	277	218	Spain
155	Oviedo	935	806	231	360	,
156	La Coruña	764	894	366	236	,
157	Santiago	1668	828	173	1013	,
158	Orense	698	977	496	217	,
159	León	353	771	478	60	,
160	Pamplona	705	883	378	200	,
161	Barcelona	528	1153	635	10	,
162	Zaragoza	297	1136	842	3	,
163	Soria	568	780	364	152	,
164	Valladolid	309	902	626	33	,
165	Salamanca	284	937	678	25	,
166	Madrid	425	1035	680	70	,
167	Teruel	387	935	565	17	,

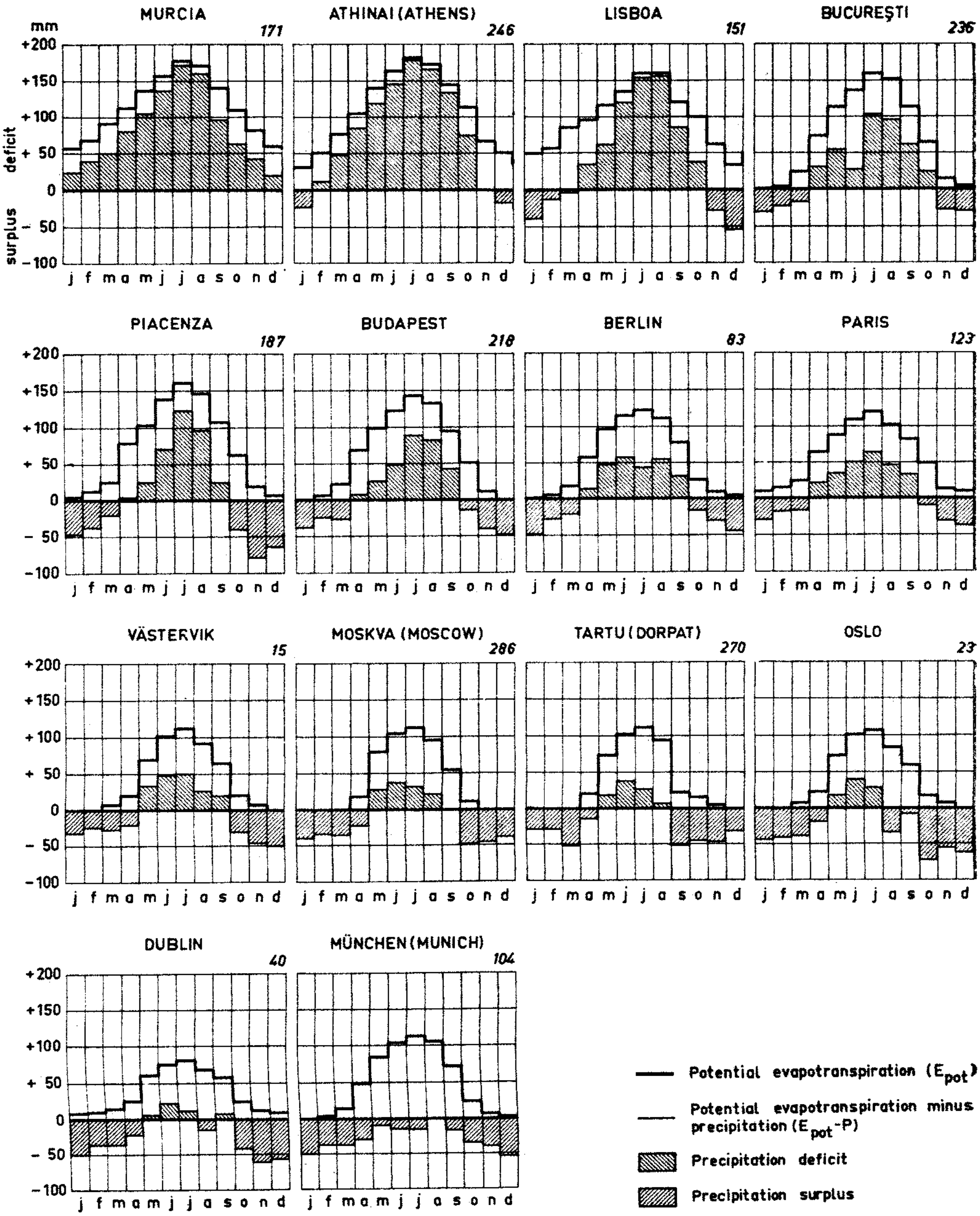
	Station	Annual precipi-tation	Annual potential evapotrans-piration	Annual deficit	Annual surplus	Country
168	Valencia	472	1290	818	—	Spain
169	Ciudad Real	457	1137	732	52	,
170	Albacete	379	1061	696	14	,
171	Murcia	359	1371	1012	—	,
172	Jaén	706	1203	682	185	,
173	Sevilla	499	1405	928	22	,
174	San Fernando	720	1267	701	154	,
175	Málaga	609	1371	826	64	,
176	Palma	467	1320	857	4	,
177	Alicante	440	1351	911	—	,
178	Burgos	560	794	373	132	,
179	Bolzano	738	853	237	122	Italy
180	Sondrio	876	832	203	247	,
181	Udine	1554	850	31	735	,
182	Trieste	1061	921	314	174	,
183	Vicenza	1278	870	158	566	,
184	Venezia	670	937	388	121	,
185	Torino (Turin)	902	858	223	267	,
186	Milano	1071	902	222	391	,
187	Piacenza	841	888	343	296	,
188	Bologna	768	953	409	224	,
189	Ancona	645	1073	563	135	,
190	Genova	1342	1008	285	619	,
191	Perugia	925	926	340	339	,
192	Chieti	694	949	442	187	,
193	Roma	903	1087	517	333	,
194	Foggia	472	1139	729	62	,
195	Napoli	852	1129	546	269	,
196	Gallipoli	526	1230	787	84	,
197	Sassari	612	1154	670	128	,
198	Cagliari	483	1251	826	58	,
199	Messina	797	1307	689	177	,
200	Palermo	748	1271	698	175	,
201	Siracusa	640	1290	801	151	,
202	Apice	740	1053	512	199	,
203	Reggio	535	1298	802	39	,
204	Valletta (Malta)	504	1335	903	66	United Kingdom
205	Beograd (Belgrado)	623	843	354	134	Yugoslavia
206	Niš	588	869	435	154	,
207	Titovo Užice	853	707	152	298	,
208	Vlonë (Valona)	1081	1149	541	473	Albania
209	Shkodër (Skutari)	1455	1018	412	849	,
210	Mostar	1416	1013	364	767	Yugoslavia
211	Skopje (Üskub)	487	937	568	118	,

	Station	Annual precipi-tation	Annual potential evapotrans-piration	Annual deficit	Annual surplus	Country
212	Bihac	1294	795	103	602	Yugoslavia
213	Hvar	790	1105	566	253	,
214	Cres	1044	1006	353	391	,
215	Osijek	664	831	317	150	,
216	Zagreb (Agram)	902	824	192	270	,
217	Sarajevo	890	743	187	321	,
218	Budapest	658	752	293	199	Hungary
219	Debrecen	633	734	274	173	,
220	Hereny	716	722	175	169	,
221	Szeged	563	808	379	134	,
222	Uzhgorod	771	722	204	253	U.S.S.R.
223	Arvavaralja	908	510	—	398	Czechoslovakia
224	Kalocsa	611	824	353	140	Hungary
225	Stalin (Varna)	502	908	498	92	Bulgaria
226	Sofiya	640	801	291	130	,
227	Gabrovo	899	786	127	240	,
228	Petrich	629	1006	630	226	,
229	Plovdiv (Philippopolis)	519	958	540	101	,
230	Chernovtsy (Czerno-witz)	652	655	158	155	U.S.S.R.
231	Sighet	815	661	83	237	Romania
232	Kishinev (Chişinău)	457	782	439	114	U.S.S.R.
233	Focşani	553	800	374	127	Romania
234	Sulina	369	838	539	70	,
235	Turnu Severin	708	877	353	184	,
236	Bucureşti (Bucharest)	592	856	391	127	,
237	Sibiu	702	735	152	119	,
238	Timişoara	659	800	307	166	,
239	Corabia	521	861	449	109	,
240	Lárisa	518	1172	759	119	Greece
241	Thessaloniki (Salonica)	486	1152	728	63	,
242	Lamia	584	1230	775	129	,
243	Toánnina (Yannina)	1253	1044	448	657	,
244	Arta	1080	1198	647	529	,
245	Pátrai (Patras)	707	1278	769	201	,
246	Athínai (Athens)	384	1285	946	44	,
247	Trípolis	809	1083	640	366	,
248	Kalámai (Kalamata)	839	1329	796	307	,
249	Iráklion (Candia)	510	1416	988	82	,
250	Karlovy Vary (Carls-bad)	640	503	133	247	Czechoslovakia
251	Praha (Prague)	493	639	255	109	,
252	Liberec	830	536	44	338	,
253	Tabor	599	595	160	164	,

	Station	Annual precipi-tation	Annual potential evapotrans-piration	Annual deficit	Annual surplus	Country
254	Brno (Brünn)	561	649	225	137	Czechoslovakia
255	Přerov	655	588	102	169	,
256	Innsbruck	917	629	16	304	Austria
257	Zell am See	1011	542	—	469	,
258	Neumarkt	774	500	6	280	,
259	Graz	874	645	15	244	,
260	Wien (Vienna)	670	678	202	194	,
261	Linz	978	635	2	345	,
262	Krems	524	680	219	83	,
263	Basel	818	635	72	257	Switzerland
264	Zürich	1044	628	—	416	,
265	Bern	977	605	8	380	,
266	Genève	889	712	129	306	,
267	Sion	590	758	361	193	,
268	Chur	831	625	57	263	,
269	Tallin (Reval)	611	423	125	314	U.S.S.R.
270	Tartu (Dorpat)	640	427	82	318	,
271	Narva	765	457	77	385	,
272	Ventspils	660	464	124	320	,
273	Riga	583	499	131	215	,
274	Vilnyus	632	519	93	206	,
275	Daugavpils (Dvinsk)	596	499	100	197	,
276	Pinsk	593	558	164	201	,
277	Minsk	657	489	69	237	,
278	Mogilev	647	505	110	252	,
279	Warszawa (Warsaw)	555	595	203	163	Poland
280	Lublin	551	600	197	148	,
281	Lvov	699	605	105	199	U.S.S.R.
282	Piotrków	525	599	230	156	Poland
283	Kraków	737	602	42	177	,
284	Ternopol	571	570	168	169	U.S.S.R.
285	Kursk	560	574	239	225	,
286	Moskva	612	479	124	257	,
287	Leningrad	522	457	136	201	,

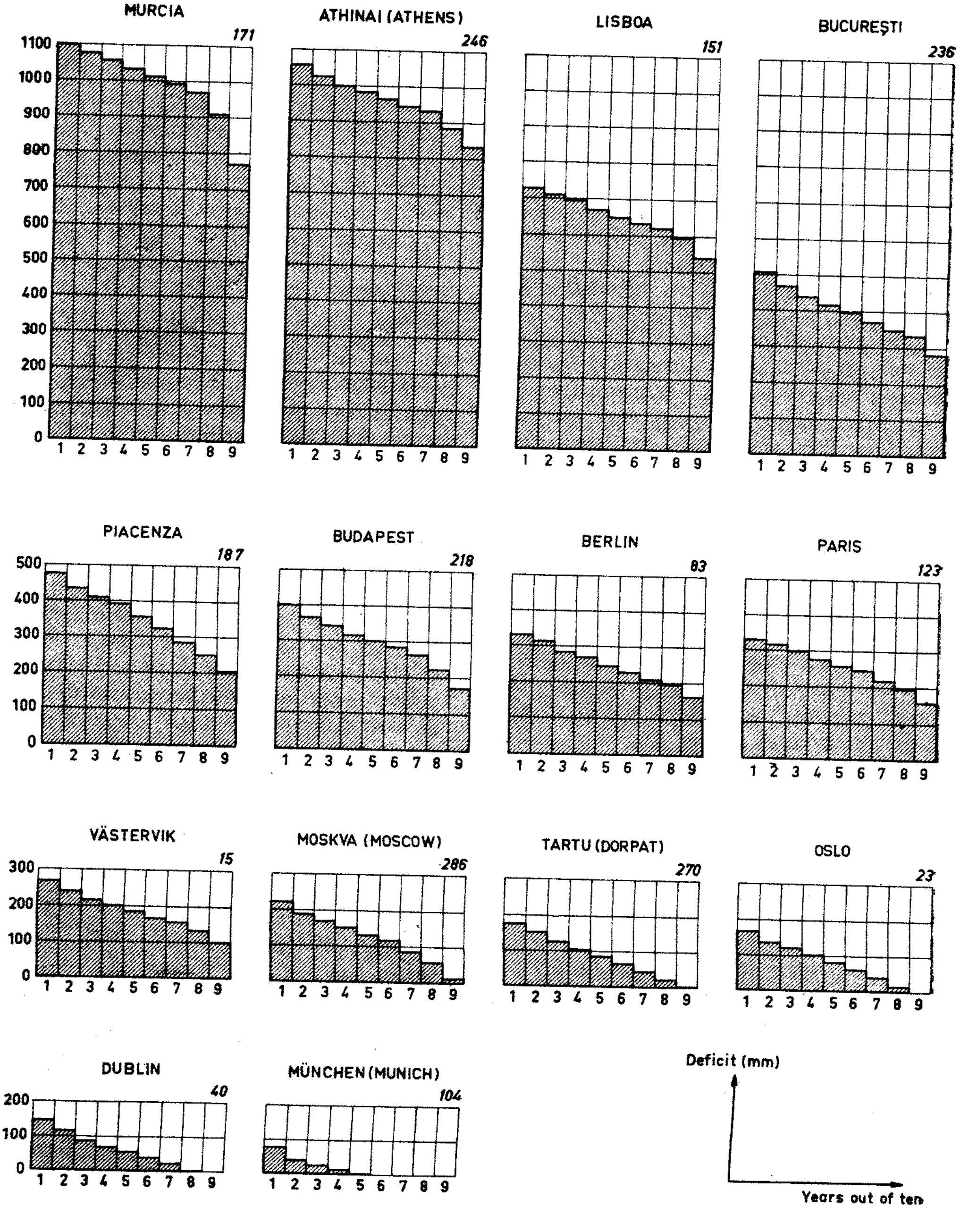
APPENDIX III

AVERAGE MONTHLY VALUES OF THE WATERBALANCE: $E_{pot} - P$, FOR A SELECTION OF PLACES IN EUROPE



APPENDIX IV

FREQUENCY OF THE PRECIPITATION DEFICITS FOR A SELECTION OF PLACES IN EUROPE



SUMMARY

On the basis of an analysis of the climate in Europe an investigation was carried out concerning the extent to which precipitation is capable of supplying crops with sufficient moisture. This investigation has been stimulated by the increasing value which is at present attached to the water supply of crops, the latter resulting from the growing agricultural productivity by such means as the cultivation of highly productive varieties and the use of constantly increasing amounts of fertilizer.
In the analysis made in this investigation the calculations are made for a crop which has a luxuriant growth throughout the year. One might imagine, for example, a plot of well-kept grassland, or alfalfa.

Chapter 2 deals with the effect on crop yields of the soil moisture conditions. Various opinions on this problem are to be found in the literature. Without expressing an opinion regarding the correctness of any one of these views, it is assumed in this investigation that a crop is capable of optimum growth so long as less than 50 % of the theoretically available soil moisture – within the root zone and between field capacity and wilting point – has been consumed by the plant. In the present investigation this amount is termed the soil-root value. When the soil has a moisture deficit which is greater than the soil-root value the crop will no longer be able to absorb the moisture in amounts corresponding to the potential evapotranspiration, so that in many cases growth will be inhibited.
On good soils the soil-root value varies from 10–50 mm for seedlings or shallow-rooted market garden crops to 200 mm for deep-rooted crops including trees. In the case of grassland and moderately deep-rooted crops the value generally assumed ranges from 50–100 mm.

The calculations made are discussed in chapter 3. The water shortages are calculated from the water balance.

$E_{pot} - (P + R) =$ water shortage

$E_{pot} =$ potential evapotranspiration
$P =$ precipitation
$R =$ soil-root value.

In this equation, however, the soil-root value is a factor which is greatly dependent on local conditions. It was therefore found desirable to draw up a purely climatological water balance viz.:

$E_{pot} - P =$ climatological precipitation deficit.

With the help of averaged monthly figures this water balance was calculated for 287 meteorological stations scattered over the whole of Europe (see map IV and Appendix II).

The potential evapotranspiration was calculated by means of TURC's formula (see Appendix I). This method has the following advantages over other well-known formulae such as those of PENMAN, BLANEY-CRIDDLE, THORNTHWAITE and HAUDE:

- the meteorological data needed for the calculation are known of practically all meteorological stations;
- the starting points are temperature and incoming radiant energy; moreover atmospheric humidity is taken into account by including precipitation in the formula;
- the empirical constants are determined from numerous data relating to the water balance of river basins throughout the world.

The results of the calculations are mapped in various ways (see maps I, Ia, Ib, Ic, II, III and IV). These maps show the situation for a normal year.

It is, however, also important to know with what frequency a particular climatological precipitation deficit is liable to occur. The frequency distribution of the precipitation deficit was calculated from the frequency distribution of the precipitation. The variability in the potential evapotranspiration was assumed to be negligible, compared to the variability in the precipitation; the errors thus introduced were found to be very small. The results of these calculations are incorporated in maps Va, Vb and Vc.

The results are considered in chapter 4. Maps I, Ia, Ib and Ic show respectively the climatological precipitation deficit as a total over the entire deficit period (map I), up to and including the month of June (map Ia), over the months of July, August and September (map Ib), and over the period of growth of winter wheat (map Ic).

These four maps illustrate clearly the difference between north and south, as well as the influence of mountainous regions which catch rainfall, generally resulting in a rain-deficient region behind the mountains.

Viewed approximately, it is found from map I that much more than half of Europe has a deficit exceeding 100 mm. In these areas shortages of water for agriculture may be expected. Where the deficit exceeds 200 mm (approximately 1/3 of Europe) even deep-rooted crops on good soils will have difficulties in obtaining their water supply.

Map Ia shows that the position is more favourable with regard to early crops, but in this case the water supply on the Iberian peninsula is still very poor even where there is a high soil-root value. Map Ib shows practically the same picture as map Ia. Map Ic enables us to compare together the various wheat districts of Europe with respect to the natural water supply. It is noticeable that most highly productive wheat-growing districts are found to lie within the zone with a precipitation deficit of 100–150 mm.

Map II illustrates the amount of the climatological precipitation surplus. Instead of the marked difference between north and south to be observed in the first maps, the difference between west and east is found to predominate in this case. The winter rains are closely related to the proximity of the sea. A 100 to 200 mm surplus, such as occurs in eastern Europe in particular, is in most cases sufficient to ensure that the storage of moisture in the soil will be properly supplemented; it is only in the case of good soils with high soil-root values that this rain surplus is rather on the low side. A supplement of 50 to 100 mm, however, is insufficient for most soils, while a supplement of less than 50 mm is entirely inadequate. Here again it can be seen that the most unfavourable situation occurs in Spain, particularly on the south-east coast.

Map III shows the duration of the deficit period. For the entire central area of Europe the deficit period is found to last from about the beginning of April to the beginning of

October. The length of the period increases further to the south, while in the extreme south-eastern part of Spain a precipitation deficit is even found for every month of the year.

Map IV illustrates the total annual potential evapotranspiration. This map illustrates most clearly the difference between north and south caused by the difference in incoming radiant energy and temperature.

Maps Va, Vb and Vc show in how many years out of a period of ten years one may expect a climatological precipitation deficit of 50, 100 and 200 mm respectively, or in other words in how many years out of a period of ten years the crops will have a shortage of water at an assumed soil-root value of 50, 100 and 200 mm respectively. It is noticeable that at a soil-root value of only 50 mm the greater part of Europe suffers from a shortage of water in more than nine years out of ten. Appendix IV, in which the frequency of the precipitation deficit for a number of places is plotted in the form of a graph, shows that there are no great differences as between frequency patterns. It was therefore possible to draw an average frequency pattern which is representative of most places in Europe. This frequency pattern (fig. 2) may be very conveniently used for estimating the frequency of the precipitation deficit of a place of which only the mean precipitation deficit is known.

In the concluding remarks it is pointed out that the maps should not be employed for examining the exact situation at a specific place. It is, however, possible to compare large areas with respect to the need of supplemental irrigation. In this connection a more detailed investigation of the cost/benefit ratio ensuing from the use of supplemental irrigation would be of great importance.

RÉSUMÉ

D'après une analyse effectuée sur le climat de l'Europe, on a contrôlé à quel point les précipitations peuvent pourvoir suffisamment les cultures en humidité. Cette expertise est importante par le fait que de plus en plus on attache du prix à l'approvisionnement en eau des cultures; ce développement est en rapport avec l'augmentation de la productivité dans l'agriculture, obtenu par l'introduction de variétés très productives et par l'application de quantités d'engrais chimiques toujours plus grandes.
Dans les analyses, effectuées pour ces recherches, des calculs ont été faits pour une culture montrant une croissance luxuriante pendant l'année entière. Pensons p.ex. à une parcelle d'herbe bien entretenue ou à la luzerne.

Dans le chapitre 2 on a insisté sur l'influence qu'a le régime d'eau dans le sol sur la production des cultures. La littérature nous offre différentes conceptions sur ce problème. Sans vouloir nous prononcer sur l'exactitude d'aucune de ces interprétations on a admis dans cette expertise qu'une culture peut atteindre une optimum croissance tant que 50% de l'eau accessible et absorbable (se trouvant dans la zone radiculaire entre la capacité de rétention au champ et le point de flétrissement) n'a pas été consommé par la plante. Dans cette expertise cette quantité est appelée 'soil-root value' (valeur du sol et de l'enracinement). Quand le sol a un déficit en eau supérieur au 'soil-root value' les cultures ne peuvent plus absorber l'eau en quantités correspondant à l'évapo-transpiration potentielle ce qui amène en la plupart des cas un ralentissement de la croissance.
Sur les bonnes terres 'soil-root value' varie entre 10–50 mm pour les plantes très jeunes ou à enracinement peu profond, et 200 mm pour les cultures à enracinement profond, arbres y compris. Dans la plupart des cas on se tient à une valeur de 50–100 mm pour les herbages et pour les plantes à enracinement médiocre.

Dans le chapitre 3 ont été traités les calculs effectués. Le déficit d'humidité fut calculé au moyen de données du bilan d'eau.

$E_{pot} - (P+R)$ = déficit d'humidité
E_{pot} = évapotranspiration potentielle
P = précipitation
R = 'soil-root value'.

Dans cette équation le 'soil-root value' est un facteur qui dépend beaucoup des circonstances locales. Il importait donc de dresser un bilan d'eau purement climatologique, savoir:

$E_{pot} - P$ = déficit climatologique de précipitations.

Au moyen de chiffres indiquant la moyenne mensuelle, ce bilan d'eau a été calculé pour 287 stations météorologiques dispersées sur toute l'Europe (voir carte IV et appendice II).

L'évapo-transpiration potentielle fut calculée en se servant de la formule de TURC (voir appendice I). Outre ceux des formules connues de PENMAN, BLANEY-CRIDDLE, THORNTHWAITE et de HAUDE, cette méthode a les avantages suivants:

- de presque toutes les stations météorologiques les données nécessaires au calcul sont connues.
- on part des données de la température et de la radiation globale, en outre on tient compte de l'humidité de l'air en impliquant les précipitations dans la formule;
- les constantes empiriques sont fixées d'après nombreuses données sur les bilans d'eau des bassins versants dispersés dans le monde entier.

Les résultats des calculs effectués ont été mis sur carte de différentes façons: voir les cartes I, Ia, Ib, Ic, II, III, et IV. Ces cartes montrent la situation pour une année moyenne.

Cependant il importe aussi de savoir avec quelle fréquence un certain déficit climatologique de précipitations peut surgir. La répartition de la fréquence du déficit des précipitations a été calculée d'après la répartition de la fréquence des précipitations. On a considéré la variabilité de l'évapo-transpiration potentielle comme un chiffre négligeable en comparaison de la variabilité des précipitations; l'inexactitude qu'introduit cette omission se trouve être très faible. Les cartes Va, Vb et Vc montrent les résultats de ces calculs.

Dans le chapitre 4 ces résultats ont été détaillés. Les cartes I, Ia, Ib et Ic indiquent le déficit climatologique de précipitations noté respectivement comme total de toute la période de déficit (carte I), sur une période jusqu'au mois de juin y compris (carte Ia), sur les mois de juillet-août-septembre (carte Ib) et sur la période de croissance du froment d'hiver (carte Ic).

Ces quatre cartes accusent très clairement la différence entre le nord et le sud, ainsi que l'influence des régions montagneuses qui provoquent la pluie et d'où résulte en même temps une région sèche derrière les montagnes.

Globalement pris, bien plus de la moitié de l'Europe se trouve avoir un déficit de plus de 100 mm. Dans ces régions on peut s'attendre à des déficits d'eau pour l'agriculture. Là où le déficit est supérieur à 200 mm (1/3 de l'Europe à peu près) même les cultures à enracinement profond auront sur les bonnes terres des difficultés quant à l'approvisionnement en eau.

La carte Ia nous montre que pour les cultures prématurées la situation est plus favorable. En ce cas cependant l'approvisionnement en eau sur la péninsule ibérique est très mauvaise même avec un 'soil-root value' très élevé. L'aspect de la carte Ib est presque identique à celui de la carte Ia. D'après la carte Ic on peut comparer entr'eux les différentes régions de froment en Europe, au point de vue approvisionnement naturel. Il est remarquable que la plupart des régions de froment à haute productivité se trouvent sur les sols profonds dans la zone ayant un déficit de précipitations de 100–150 mm.

La carte II nous montre l'importance de l'excédent de précipitations. Au lieu de la différence entre nord et sud qui se manifestait clairement dans la première carte, c'est ici la différence entre ouest et est qui prédomine. Les pluies d'hiver sont étroitement liées à la proximité de la mer. Un excédent de 100–200 mm, ce qui se présente surtout en Europe orientale est suffisant dans la plupart des cas pour garantir un bon approvisionnement de la réserve du sol; ce n'est que pour les bonnes terres ayant une grande 'soil-root value' que cet excédent est plutôt bas. Un supplément de 50–100 mm cependant est insuffisant pour la plupart des terres, alorsqu'un supplément de moins de 50 mm est absolument insuffisant. Encore une fois on constate que la situation la plus défavorable se présente en Espagne et surtout le long de la côte du sud-est.

La carte no. III donne la durée de la période de déficit. Pour toute la région centrale de l'Europe la période de déficit se trouve être du début d'avril jusqu'au début d'octobre. Plus on descend vers le sud, plus cette période est longue, alors que dans le sud-est de l'Espagne il y a même un déficit de précipitations chaque mois de l'année.

L'évapotranspiration potentielle annuelle et totale a été fixée sur la carte IV. C'est cette carte qui montre le plus clairement la différence nord-sud provoquée par les différences entre les radiations globales et températures.

Les cartes Va, Vb et Vc montrent pour combien d'années dans une période de dix ans on peut s'attendre à un déficit climatologique des précipitations de respectivement 50, 100 et 200 mm. Ou en d'autres termes pour combien d'années dans une période de 10 ans les cultures auront un déficit d'humidité tout en ayant un 'soil-root value' de respectivement 50, 100 et 200 mm. Il est remarquable qu'avec un 'soil-root value' de 50 mm, la majeure partie de l'Europe souffre d'un déficit d'eau pendant plus de neuf ans sur dix.

L'appendice IV dans lequel on a représenté le graphique de la fréquence du déficit des précipitations de quelques localités, nous montre que le caractère de fréquence ne diffère pas beaucoup entr'eux. Ceci nous permit de faire un modèle de la fréquence moyenne qui est réprésentatif pour la plupart des endroits en Europe. Ce modèle de fréquence (fig. 2) est fort bien utilisable pour évaluer la fréquence du déficit de précipitations d'une localité, dont on ne connaît que le déficit de précipitations moyen.

Dans la conclusion on insiste sur le fait que les cartes ne peuvent pas servir de moyens pour vérifier la situation exacte d'une certaine région. De grandes régions cependant peuvent être comparées entr'elles en ce qui concerne la nécessité de l'irrigation complémentaire.

Comme suite à ceci il importerait d'élaborer la relation entre les frais et le revenu obtenu en appliquant l'irrigation complémentaire.

ZUSAMMENFASSUNG

An Hand einer Analyse des Klimas in Europa ist untersucht worden, inwieweit die Niederschläge wohl oder nicht imstande sind, die Kulturen ausreichend mit Wasser zu versehen. Diese Untersuchung ist von Bedeutung, da heute auf die Wasserversorgung der Gewächse mehr und mehr Wert gelegt wird. Diese Entwicklung hängt mit der Steigerung der Produktivität in der Landwirtschaft zusammen, n.a. durch den Anbau von hochproduktiven Sorten und durch die Anwendung von stets grösser werdenden Mengen Kunstdünger. Hierdurch wird die Wasserversorgung immermehr ein einschränkender Faktor in der Produktion der landwirtschaftlichen Erzeugnisse. Bei den in diesen Untersuchungen ausgeführten Analysen sind die Berechnungen für eine Kultur gemacht worden, welche das ganze Jahr hindurch ein üppiges Wachstum zeigt. Man würde z.B. an eine Parzelle gut gepflegtes Grünland oder an einen Schlag Luzerne denken können.

In Abschnitt 2 wird auf den Einfluss des Wasserhaushalts im Boden auf den Ertrag der Kulturen eingegangen. Im Schrifttum sind verschiedene Auffassungen in Bezug auf dieses Problem zu finden. Ohne ein Urteil aussprechen zu wollen über die Richtigkeit einer dieser Auffassungen, ist bei diesen Untersuchungen angenommen worden, dass der optimale Wuchs einer Kulturpflanze möglich ist, solange noch nicht 50 % des erreichbaren und aufnehmbaren Wassers (innerhalb der Wurzelzone und zwischen Feldkapazität und Verwelkungspunkt) von ihr verbraucht ist. Diese Menge wird in der vorliegenden Untersuchung '*Boden-Wurzel-Wert*' (soil-root value) genannt. Hat der Erdboden einen Wassermangel, der grösser als dieser Boden-Wurzel-Wert ist, dann werden die Gewächse das Wasser nicht mehr aufnehmen können in Mengen, die der potentiellen Evapotranspiration entsprechen, was zur Folge hat, dass in vielen Fällen, das Wachstum gehemmt wird. Auf den guten Böden schwankt der Boden-Wurzel-Wert zwischen 10 und 50 mm für Sämlingen oder flachwurzelnden Gemüsearten, bis zu 200 mm für tiefwurzelnde Gewächse einschl. Baüme. Für Grünland und für mässig tief gehende Gewächse wird meistens ein Wert von 50 bis 100 mm angenommen.

In Abschnitt 3 werden die ausgeführten Berechnungen behandelt. Das Wasserdefizit wurde aus der Wasserbilanz berechnet:

$$E_{pot} - (P+R) = \text{Wasserdefizit}$$

E_{pot} = potentielle Evapotranspiration
P = Niederschlag
R = Boden-Wurzel-Wert.

In dieser Gleichung bildet der Boden-Wurzel-Wert jedoch einen Faktor, der stark von den örtlichen Umständen abhängig ist. Es war deshalb erwünscht, ein rein-klimatologischer Wasserbilanz aufzustellen, nämlich

$E_{pot} - N$ = klimatologisches Niederschlagdefizit.

Mit Hilfe der mittleren Monatszahlen wurde diese Wasserbilanz für 287 Wetterwarten berechnet, über ganz Europa verteilt (siehe Karte IV und Anhang 2).
Die potentiellen Evapotranspiration wurde mit der Formel von TURC berechnet (siehe Anhang 1). Diese Methode bietet die nachfolgenden Vorteile, gegenüber andere bekannte Formelen wie die von PENMAN, BLANEY-CRIDDLE, THORNTHWAITE und HAUDE:

- die für die Berechnung notwendigen meteorologischen Angaben sind von nahezu allen Wetterwarten bekannt;
- es wird von der Temperatur und der globale Einstrahlung ausgegangen; ausserdem wird der Luftfeuchtigkeit Rechnung getragen, indem man der Niederschlag mit in die Formel einbezieht;
- die empirischen Konstanten wurden bestimmt an Hand zahlreicher Unterlagen in Betreff Wasserbilanzen von Stromgebieten in der ganzen Welt.

Die Ergebnisse der ausgeführten Berechnungen sind auf verschiedene Art kartiert worden: siehe die Karten I, Ia, Ib, Ic, II, III, und IV. Diese Karten stellen die Situation für ein Durchschnittsjahr dar.
Es ist jedoch auch von Bedeutung zu wissen, mit welcher Frequenz ein bestimmtes klimatologisches Niederschlagsdefizit auftreten kann. Die Frequenzverteilung des Niederschlagsdefizits wurde aus Frequenzverteilung der Niederschläge selbst errechnet. Die Variabilität in der potentiellen Evapotranspiration wurde als vernachlässigbar angenommen hinsichtlich der Variabilität im Niederschlag; die dadurch eingeschlichenen Fehler erwiesen sich als sehr klein.
Das Ergebnis der Berechnungen ist in den Karten Va, Vb, und Vc verarbeitet worden.

In Abschnitt 4 werden die erzielten Resultate einer Betrachtung unterworfen. Die Karten I, Ia, Ib, und Ic zeigen eine Wiedergabe des klimatologischen Niederschlagsdefizits und zwar als Total über die ganze Defizitperiode (Karte Ia), weitherhin bis einschl. Monat Juni (Karte Ia), ferner über die Monate Juli-August-September (Karte Ib) und schliesslich über die Wachstumszeit des Winterweizens (Karte Ic).
Sehr deutlich kommt in diesen vier Karten der Unterschied Nord-Süd zum Ausdruck, ebenso wie der Einfluss der gebirgigen Gebieten, die den Regen auffangen, was meistens zugleich ein regenarmes Gebiet hinter den Bergen zur Folge hat.
Global gesehen zeigt sich, dass mehr als die Hälfte von Europa ein Defizit hat von mehr als 100 mm. In diesen Gebieten kann man also Wassermangel für die Landwirtschaft erwarten. Wo das Defizit grösser als 200 mm ist (ungefähr ein Drittel Europas) werden sogar die tiefwurzelnden Gewächse auf den guten Böden Schwierigkeiten mit der Wasserversorgung haben.
Aus Karte Ia ist zu ersehen, dass die Sachlage für die Frühkulturen günstiger ist. Auch in diesem Falle ist jedoch, sogar bei einem grossen Boden-Wurzel-Wert, die Wasserversorgung auf der iberischen Halbinsel sehr schlecht. Karte Ib zeigt nahezu dasselbe Bild wie Karte Ia.
An Hand von Karte Ic können die verschiedenen Weizengebiete Europas miteinander verglichen werden in Bezug auf die Wasserversorgung. Auffallend ist, dass die meisten Weizengebieten mit hoher Produktivität innerhalb des Gebietes mit einem Niederschlagsdefizit von 100 bis 150 mm liegen.
Karte II veranschaulicht die Grösse des klimatologischen Niederschlagsüberschusses. An Stelle des deutlichen Nord-Sud-Unterschiedes

auf den ersten Karten überwiegt hier der Unterschied West-Ost. Die Winterregenfälle hängen eng mit der Nähe des Meeres zusammen. Ein Überschuss von 100 bis 200 mm, wie er vor allem in Ost Europa vorkommt, ist in den meisten Fällen ausreichend um eine gute Anfüllung des Wasserspeichers im Boden zu gewährleisten. Nur bei den besseren Böden mit hohem Boden-Wurzel-Wert ist dieser Regenüberschuss etwas knapp. Eine Anfüllung von 50 bis 100 mm ist jedoch für die meisten Böden ungenügend, während eine von weniger als 50 mm als durchaus ungenügend bezeichnet werden muss. Auch jetzt wieder ist die ungünstigste Situation in Spanien und zeigt sich vor allem an der Südostküste des Landes.
Karte III gibt die Dauer der Mangelperiode an. Für das ganze Mittelgebiet von Europa dauert diese Periode der Defizite von ungefähr Anfang April bis Anfang Oktober. Weiter nach dem Süden hin nimmt die Länge der Periode zu, während in Südostspanien sogar jeder Monat des Jahres ein Niederschlagsdefizit gibt.
Die gesamte jährliche potentielle Evapotranspiration ist in Karte IV dargestellt. Diese Karte zeigt am deutlichsten den Nord-Süd-Unterschied unter Einfluss des Unterschiedes in globale Einstrahlung und Temperatur.
In den Karten Va, Vb und Vc ist angegeben, in wieviel Jahren aus einer Periode von 10 Jahren man ein klimatologisches Niederschlagsdefizit erwarten kann von 50 bzw. 100 bzw. 200 mm. Oder mit anderen Worten gesagt: in wieviel Jahren aus einer Periode von 10 Jahren werden die Gewächse Wassermangel haben bei einem angenommenen Boden-Wurzel-Wert von bzw. 50, 100 und 200 mm. Auffallend ist, dass bei einem Boden-Wurzel-Wert von 50 mm schon der grösste Teil von Europa in mehr als 9 von den 10 Jahren unter Wassermangel leidet.
Aus Anhang IV in welcher für eine Anzahl Orte die Frequenz des Niederschlagsdefizits graphisch dargestellt ist, ist ersichtlich, dass die Frequenzbilder untereinander grosse Unterschiede zeigen. Es war dadurch möglich ein mittleres Frequenzbild zu machen, welches für die meisten Orte in Europa repräsentativ ist. Dieses Frequenzbild (Abb. 2) ist sehr gut brauchbar für die Einschätzung der Frequenz des Niederschlagsdefizits eines Ortes, von dem nur das mittlere Niederschlagsdefizit bekannt ist.

In der Schlussbetrachtung wird darauf hingewiesen, dass das Kartenmaterial nicht benutzt werden darf, um die exakte Situation an einer bestimmten Stelle festzustellen. Wohl können grosse Gebiete miteinander verglichen werden im Hinblick auf deren Bedarf an Ergänzungsbewässerung. Im Anschluss hieran würde eine nähere Untersuchung des Kosten-Nützen-Verhältnisses bei Anwendung von Ergänzungsbewässerung von grosser Wichtigkeit sein.

COMPENDIO

A base de un análisis del clima en Europa, se ha llevado a cabo una investigación con objeto de averiguar hasta que punto las precipitaciones pluviométricas son capaces de suministrar a las cosechas suficiente humedad. Esta investigación ha sido estimulada por el aumento de interés que en el momento actual se le concede al suministro de agua a las cosechas, el último como consecuencia también del incremento de la producción agrícola por medios tales como el cultivo de variedades altamente productivas y el uso de abonos en cantidades constantemente crecientes.

En el análisis realizado en esta investigación, los cálculos se han hecho para una cosecha que tenga un buén crecimiento a lo largo del año. Se puede pensar, por ejemplo, en una parcela de buèn pastizal o alfalfa.

El capítulo 2 se refiere a la influencia de la humedad del suelo sobre las cosechas. Se exponen diversas teorías sobre este asunto. Sin expresar opinión sobre la certeza de los distintos puntos de vista, se considera en esta investigación que un cultivo es capaz de crecer en condiciones óptimas siempre que la planta no haya consumido más del 50 % del agua absorbible contenida en la zona de raices (diferencia entre la capacidad del campo y el punto de marchitez). En la presente investigación esta cantidad es llamada valor suelo-raiz. Cuando el suelo tiene un déficit de humedad superior al valor suelo-raiz, la planta no será capaz de absorver la humedad en cantidades que correspondan a la evapotranspiración, de tal forma que en muchos casos se detendrá el crecimiento.

En buenos suelos el valor suelo-raiz varía de 10–50 mm. para cosechas de semillas o de raices superficiales de 200 mm. para cosechas de raiz profunda, incluyendo árboles. En el caso de pastos y de cosechas de profundidad media en las raices el valor considerado generalmente como término medio es de 50–100 mm.

Los cálculos hechos se analizan en el capítulo 3. El déficit de agua se calcula por la ecuación del agua:

$E_{pot} - (P+R)$ = déficit de agua

E_{pot} = evapotranspiración potencial

P = précipitación

R = valor suelo-raiz.

En esta ecuación, sin embargo, el valor suelo-raiz es un factor que depende grandemente de las condiciones locales. Por consiguiente se consideró deseable deducir una ecuación del agua puramente climatológica, tal como:

$E_{pot} - P$ = déficit climatológico de precipitación.

Con la ayuda de las cifras medias mensuales esta ecuación fué calculada para 287 estaciones meteorológicas repartidas por toda Europa (ver el mapa IV y Apéndice II).

La evapotranspiración potencial fué calculada por medio de la fórmula de TURC (ver Apéndice I). Este método tiene las siguientes ventajas sobre las otras bien conocidas fórmulas de PENMAN, BLANEY-CRIDDLE, THORNTHWAITE y HAUDE:

- los datos meteorológicos necesitados para el cálculo son conocidos en todas las estaciones meteorológicas practicamente;
- los puntos de partida son temperatura e irradiación solar; por otra parte la humedad atmós-férica es tenida en cuenta incluyendo la precipitación en la fórmula;
- las constantes empíricas se determinan por numerosos datos referente a la ecuación del agua de cuencas de rios de todo el mundo.

Los resultados de los cálculos se han llevado a mapas de diferentes formas (ver los mapas I, Ia, Ib, Ic, II, III y IV). Estos mapas muestran la situación para un año medio. Sin embargo, es también importante conocer con qué frecuencia un déficit en la précipitación puede presentarse. La distribución de la frecuencia del déficit de précipitación se calculó a partir de la distribución de frecuencia de la precipitación. La variabilidad en la evapotranspiración potencial se ha considerado despreciable, comparada con la variabilidad en la precipitación; los errores introducidos se vió que eran muy pequeños.

Estos resultados de los cálculos están incorporados en los mapas Va, Vb y Vc.

Los resultados se consideran en el capítulo 4. Los mapas I, Ia, Ib, y Ic muestran respectivamente el déficit climatológico de precipitación como un total sobre el total periodo de déficit (mapa I), hasta incluir el mes de Junio (mapa Ia) incluyendo Julio, Agosto y Septiembre (mapa Ib), y sobre el total periodo de crecimiento de trigo de invierno (mapa Ic).

Estos cuatro mapas ilustran claramente la diferencia entre el Norte y el Sur así como la influencia de las regiones montañosas con las lluvias retenidas, resultando generalmente un déficit en la région tras las montañas.

Aproximadamente se encuentra que mas de la mitad de Europa tiene un déficit superior a los 100 mm. En estas áreas se puede esperar un déficit de agua para la agricultura. Donde el déficit supere los 200 mm. (aproximadamente un tercio de Europa), incluso los cultivos de raíz profunda en buenos suelos tendrá dificultades en abastecer sus necesidades de agua.

El mapa Ia muestra que la situación es mas favorable para cosechas tempranas, pero aún en este caso el suministro de agua en la Península Iberíca es muy pobre, incluso allí donde el valor suelo-raíz es mas elevado. El mapa Ib, muestra prácticamente el mismo contorno que el mapa Ia. El mapa Ic nos permite comparar juntos los varios distritos de trigo de Europa en lo que se refiere al suministro natural de agua. Es notable que los distritos de más alta producción triguera se encuentran en la zona con un déficit de precipitación de 100–150 mm.

El mapa II ilustra la cantidad de exceso climatológico de precipitación. La marcada diferencia entre Norte y Sur que se observó en los primeros mapas, en este caso se encuentra entre el Oeste y el Este. Las lluvias de invierno están estrechamente relacionadas a la proximidad del mar. Un exceso de 100 a 200 mm, tal como ocurre en particular en el Este de Europa, es, en la mayoría de los casos, suficiente para asegurar que la reserva de humedad en el suelo será debidamente suplementada; solamante en el caso de suelos con un alto valor suelo-raíz este exceso de lluvia es mas bién bajo. Un suplemento de 50 a 100 mm, sin embargo, es insuficiente para la mayor parte de los suelos, mientras que un suplemento de menos de 50 mm es completamente inadecuado. Aquí de nuevo, puede verse que la situación más desfavorable ocurre en España, especialmente en la costa Sur-este.

El mapa III muestra la duración del periodo de déficit. Para el total del área central de Europa se encuentra que el periodo de déficit dura aproximadamente desde el comienzo de Abril hasta el comienzo de Octubre. La longitud del periodo aumenta hacia el Sur, y en el caso de la España Sur-Este puede encontrarse déficit de precipitación en todos los meses del año.

El mapa IV ilustra la total evapotranspiración potencial anual. Este mapa ilustra más claramente la diferencia entre Norte y Sur causada por la diferencia en irradiación solar y temperatura.

Los mapas Va, Vb y Vc muestran en cuántos años de cada diez se puede contar con un déficit climatológico de precipitación de 50, 100 y 200 mm. respectivamente, ó, en otras palabras, cuántos años, en un periodo de diez, los cultivos tendrán un déficit de agua, para un supuesto valor suelo-raíz, de 50, 100 y 200 mm respectivamente. Es notable que con un valor suelo-raíz de 50 mm. la mayor parte de Europa sufre falta de agua en mas de nueve años de cada diez.

El Apéndice IV, en el cual figura la frecuencia del déficit de precipitación para varios sitios en forma de gráfica, muestra que no hay grandes diferencias entre los esquemas de frecuencia. Por consiguiente fué posible deducir un esquema medio de frecuencia que es representativo de la mayor parte de los lugares en Europa. Este esquema de frecuencia (figura 2) puede usarse convenientemente para estimar la frecuencia del déficit de precipitación de un lugar del cual solamante se conoce el déficit medio de precipitación.

En las conclusiones se observa, que el material del mapa no debe emplearse para examinar la situación exacta de un determinado lugar. Es, sin embargo, posible comparar grandes extensiones respecto a la necesidad de riego complementario. En relación con esto seriá de gran importancia una investigación mas detallada sobre la relación coste/beneficio que se sigue del uso del riego complementario.

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