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REPORT
OF THE CONFERENCE ON
SUPPLEMENTAL
IRRIGATION

COMMISSION VI
INTERNATIONAL SOCIETY OF SOIL SCIENCE

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FOREWORD

After the last world war there has been a strong and growing interest in supplemental irrigation. Both practical application and scientific knowledge have increased considerably during the last decade. This has been the motive of Commission VI of the International Society of Soil Science to organize a special conference devoted to the subject. The meetings of the conference were held from June 30–July 4, 1958 at the Royal Veterinary and Agricultural College in Copenhagen. The successful organization of the conference has been made possible through the aid given by several governmental services, private companies and individual officials in Denmark.

In this respect we want to express our gratitude for the help given by:

Det danske Landbrugsministerium
Det danske Gødnings – Kompagni A/S
Dansk Andels Gødningforretning
E. Lunding A/S, Import af Kalisalte
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Det danske Hedeselskab
Statens Forsøgsstationer, Lundgaard and St. Jyndevad

and

Mr. Fr. Heick, Director of Statens Forsøgsstation, St. Jyndevad
Mr. A. Krøigaard, Adviser of Det danske Hedeselskab
Mr. Jons. Olesen, Adviser of Foreningen af jydske Landboforeninger

This report contains the papers read and the main points of the discussions held during the sessions. May the report contribute to a better understanding of supplemental irrigation, which is becoming more and more important for all countries in semihumid and humid regions.

H. C. Aslyng
h.t. Secretary, Conference on Supplemental Irrigation

C. Van Den Berg
President, Commission VI of the I.S.S.S.
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INTRODUCTION TO THE CONFERENCE

C. van den Berg

(President, Commission VI, I.S.S.S.)

From the earlier proceedings of the VIth Commission of the I.S.S.S. it is evident that in these sessions attention was given to many subjects, but the relation between soil and water has always been a major aspect. In the special sessions of the VIth Commission these subjects came up for discussion in particular. They were mostly related to the amelioration of soils, drainage must be specially mentioned in this regard. As is shown by the proceedings of the third conference of the Commission, held in Zürich in 1937, supplemental irrigation was, however, already extensively discussed before the last war.

After the war no special meetings of this Commission have been held and on the congresses of the I.S.S.S. little has been done concerning supplemental irrigation. The reasons for this are perhaps that many distinguished scientists, who were experts in the field of supplemental irrigation, are not with us any more, and that the subjects of irrigation and drainage have received special attention in the sessions of some other international organizations. The „International Commission on Drainage and Irrigation“ in particular, is very active in this field.

In earlier proceedings of Commission VI attention was mostly given to the sprinkling with waste water and it is evident that in this context the influence on soil fertility, organic matter content, microbiology of the soil, etc., was studied.

Since that time a large increase in the use of sprinkling irrigation has taken place. The expansion of supplemental irrigation in the temperate zones of the world was caused by the need of enlarging the agricultural production after the war. The need of water was accentuated by a number of dry years occurring at that time. The nature of the problems involved has changed therefore; the use of river- and groundwater has become a normal procedure in supplemental irrigation too.

The problems regarding water supply are at this moment:
1. the limits of climate and soil, within which additional water supply is needed;
2. the amounts necessary and the moments when to give artificial rain in accordance with climate, soil and crop;
3. the technical installations;
4. the economy and the labour problem in agriculture.

The communications presented at this conference reflect these problems, with the exception of the technical installations used in sprinkling irrigation, which is anyway of less importance in a gathering of soil scientists. At the end of this conference it will be possible to draw up the balance sheet on our
knowledge of the field of supplemental irrigation, but already now it can be seen from the content of the contributions, that many aspects of water management are intensively studied everywhere.

The fundamental research has been expanding to a great extent during the past ten years:

a. Due to the work of Thornthwaite, Penman and many others much has become known on the relation between climatological factors and evaporation of water by crops.

b. New attention has been given to the research on soil moisture; a starting point for this research appears to be the measurement of the water tension in the soil. It is perhaps regrettable that no contribution was submitted on the measurement of moisture content of the soil by means of tensiometers, gypsum blocks or nylon elements.

c. Biological research has given a greater insight into the water management of the plants and has pointed out where the limiting factors in the moisture regulation by plants lie.

It will be profitable for agronomists and soil scientists to follow closely the development of this type of biological research.

In the practical application of supplemental irrigation the questions of time of supply and amount of water to be given have the full interest. The answers are often based on the moisture content of the soil. It is not clear, however, which soil moisture conditions must be seen as optimal for the various crops. Others therefore consider biological characteristics as a guide to ascertain the right dosage of water. The submitted contributions on this subject are therefore also of great interest.

Besides the physical-biological questions, agricultural-economic problems are asking attention in the field of supplemental irrigation. The supplying of water to the crop presents in the temperate zones of the world, a problem less easy to solve for the farmer than for example fertilizing does. Sprinkling irrigation has a great influence on the economy of farming, on account of the frequently changing weather conditions, the investment of capital goods, the relatively high yearly costs and the labour supply. Often the application is only remunerative if particular crops are grown.

While the need of supplemental water on various soil types can be more or less predicted by physicists and soil scientists, the application of sprinkling irrigation demands an insight in the character of each individual farm.

When seen against this economic background all the problems regarding sprinkling are made much more intricate than is the case with so many other problems in agricultural research. There are therefore good reasons to make this subject the theme of an international conference.
CLIMATIC ASPECTS OF SUPPLEMENTAL IRRIGATION

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INTRODUCTION

It is a great honour to be given the privilege of presenting the first lecture. At a conference like this we should discuss the present topics and problems. Much attention cannot be given to minor details and history.

In humid regions where the evapotranspiration part of the year exceeds the rainfall considerably supplemental irrigation is needed (ASLYNG, 1954) and applied more and more, fig. 1. The evaporation from a wet surface and the maximum evapotranspiration from a crop is primarily determined by weather or climatic conditions. The irrigation requirements are then determined by climate and by the capacity of available water in the soil. The influence of the crop is almost limited to characteristics regarding period of growth and root development.

During the last ten years much thought has been given to equations for estimating evaporation on basis of meteorological data. At this conference we have a paper dealing with some of the equations.

In our work at the climate and water balance station under The Hydro-technical Laboratory we have used the theory and the formula given by PENMAN (1948, 1956). Only in few cases we have applied also the THORNTHWAITE (1948) formula for comparison, fig. 2. It is my opinion that equations based

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**Fig. 1.**
Average water balance for Denmark with a humid climate.
The yearly rainfall is 640 mm. and the potential evapotranspiration approximately 500 mm. The deficit in summer months is ca. 150 for a sandy and ca. 50 mm. for a good clay-loam soil.
Evapotranspiration 1957

Fig. 2. In relatively wet months the direct determination gives higher results than the reduced Penman equation. The Thornthwaite formula often yields relatively high results late in the summer and in the fall. See also VAN WIJK et al. (1953 and 1954)

on temperature or on vapour pressure deficit can be of local and practical importance but not of universal interest. PENMAN has combined the energy and the aerodynamic balance in a theoretical sound and useful form.

**Energy balance**

\[ E_o = \frac{H_n - H_a - H_s}{59}, \]

where in unit time:

- \( E_o \) = evaporation, mm.
- \( H_n \) = net gain of radiation energy at the surface, cal/cm\(^2\)
- \( H_a \) = heat flux into the air, cal/cm\(^2\)
- \( H_s \) = heat flux into the soil or water, cal/cm\(^2\)
- \( 59 \) = cal/cm\(^2\) for evaporation of one mm. water, cal/cm\(^2\) mm. H\(_2\)O

Application of the energy balance method depends on the possibility of measuring the different quantities. The surface temperature for a crop is especially difficult to obtain.

**Aerodynamic balance**

\[ E_o = f(u) (e_0 - e_a), \]

where

- \( f(u) \) = function of the wind velocity profile, mm. H\(_2\)O/mm. Hg
- \( e_0 \) = vapour pressure at the surface, mm. Hg
- \( e_a \) = vapour pressure in the air (2 m. height), mm. Hg

The difficulties in applying the vapour pressure difference term lies in the empirical function \( f(u) \) and also in recording the surface temperature.

Due to the difficulties, equations like \( E_o = f(e_s - e_a) \), in which \( e_s - e_a \) is the saturation deficit at standard height and \( f \) a local empirical factor, are often used.
FIG. 3. Part of the climate and water balance station. In front instruments for radiation recording and in the background a 12 m.² free water surface. To the right a screened evaporimeter and besides that an anemometer and evapotranspirometers (the dark plot). Other instruments are also seen

**COMBINED ENERGY AND AERODYNAMIC BALANCE**

\[
E_o = \frac{H_n \times d + 0.5 f(u_2) (e_s - e_a)}{59 (0.5 + d) + 0.5 + d}, \text{ where}
\]

- \(d\) = slope of the saturation vapour pressure curve, mm. Hg/°C
- \(u_2\) = wind velocity at 2 m. height, m/sec
- 0.5 = psychrometer constant, mm. Hg/°C
- \(f(u_2) = 0.0146(0.5 + 0.54 u_2)\), mm. H₂O/mm. Hg

The minimum meteorological observations are: hours of sunshine, wind speed, temperature and dewpoint temperature at standard heights. MAKKINK (1957) found, however, that there can be a considerable difference between net gain of energy estimated on basis of hours of sunshine and recorded incoming radiation. Energy for photosynthesis and heat flux into the soil is neglected if it is not known.

We have recorded incoming radiation at the climate and water balance station (20 km. west of Copenhagen) and reflection (since 1953) with KIPP & ZONEN solarimeters, \(G_2\) (fig. 3). The heat flux into the soil is determined by use of thermistors to seven m. depth, (KRISTENSEN, 1958). Back radiation has been estimated by use of the formula (PENMAN, 1956):

\[
\sigma T^4 (0.56 - 0.09 \sqrt{e_a}) (0.1 + 0.9 n/N), \text{ where}
\]

- \(\sigma T^4\) = black-body radiation at mean (air) temperature, cal/cm²
- \(n/N\) = ratio of actual/possible hours of sunshine

For the last two years we have also used thermopiles or radiometers for direct recording of net gain of radiation energy. There are, however, still some problems concerning calibration so the results have not yet been applied.

The „energy part” of the combined equation yields in summer months a
much larger quantity than the "aerodynamic part". It is therefore not too serious that the wind factor is semi-empirical.

**Potential Evapotranspiration, \( E_p \)**

Potential evapotranspiration (\( E_p \)) can be defined as the amount of water evaporated in unit time from a short uniform green crop, actively growing, covering an extended surface and never short of water.

\( E_p \) is generally smaller than \( E_0 \) which mainly is due to closure of the stomata at night, but also to diffusion resistance in the stomata. Penman (1948) suggested a reduction factor (\( f \)) varying from 0.6 to 0.8 according to season or day-length. Instead of \( f \) he later (1953) gave a stomatal (\( S \)) and day-length (\( D \)) factor. In our work we have not found significant differences between \( f \) and \( SD \). Makkink (1957) found a factor of 0.73.

When the surface or the crop is wet, which in Denmark often occurs late in the summer and in the fall, \( E_p \) approaches \( E_0 \). We have found it satisfactory to use a constant factor of 0.8 throughout the year. Still \( E_p \) seems to be underestimated in periods or months with frequent rainfall. In relatively dry periods when it is most important to estimate the potential evapotranspiration for guidance regarding irrigation the results obtained are satisfactory.

In the combined equation

\[
E_p = \left[ \frac{H \times d}{59 (0.5 + d)} + \frac{0.5 f(u_d) (e_s - e_a)}{0.5 + d} \right] 0.8
\]

the energy part amounts to less for a green surface as for a water surface due to about 20 per cent reflection of incoming energy compared to only about 5 per cent for the water surface. On the contrary the aerodynamic quantity differs in the opposite direction due to larger vapour pressure deficit above a crop than above a large water surface at the same climatic conditions.

**Actual/Potential Evapotranspiration, \( E_a/E_p \)**

The actual evapotranspiration (\( E_a \)) falls below the potential evapotranspiration (\( E_p \)) when the transpiration is checked by lack of water. Generally it is assumed that about half of the available water in the root zone can be utilized before \( E_a \) is appreciably lower than \( E_p \). Makkink and Van Heemst (1956) state that it also depends upon the transpiration intensity when \( E_a < E_p \). It is also known that it is influenced by the root intensity.

When plants are grown in closed containers (pots or lysimeters) and the roots have completely penetrated into all parts of the soil and the transpiration intensity at the same time is low it may be possible to utilize almost all the available water before the transpiration and growth are checked like Veihmeyer et al. (1927, 1955) have found.

Our results from lysimeter investigations (Aslyng and Kristensen, 1953 and 1958) where the transpiration intensity most of the time was rather high, show a gradual reduction of \( E_a \) as the soil moisture content was reduced below field capacity. Results from our field experiments 1953 to '57 indicate, however, that \( E_a \) and \( E_p \) (calculated by use of the equation given above) for the total summer were of almost the same order of magnitude provided the soil moisture deficit did not exceed 75 to 100 mm., fig. 4 and 5. The maximum root depth was 100 to 150 cm. and for that depth the soil capacity for available water was 150 to
FIG. 4. Rainfall and soil moisture tension (measured with tensiometers) 1952 in plots (a to c) with oats yielding resp. 38, 51 and 57 hkg. grain per ha. Rainfall from spring to the middle of November, when field capacity is reached, equals the evaporation in that period. The water consumption is the same, independent of yield (ASYNG and KRISTENSEN; 1953)
Rainfall and potential evapotranspiration $E_p$ (Penman). The vertical difference indicates soil moisture deficit. When the curves cross at the same time when the tensiometers, at all depths to 150 cm., indicate field capacity, $E_a$ equals the estimated $E_p$ for the past period. It is natural that run-off commences somewhat later. In 1953 and 1954 e.g., the maximum deficit was 110 mm. In 1953 $E_a$ has been the same as $E_p$, whereas in 1954 $E_p > E_a$, because the deficit occurs early and before the roots penetrated deep enough.

200 mm. That also means that roughly half of the available water was utilized before limitation occurred.

The potential evapotranspiration concept seems to work well also for extended areas with uniform tall green and dense crops. For small areas with a tall crop extremely exposed to weather conditions, $E_a$ may be considerably larger than $E_p$, e.g. a crop in lysimeters not having sufficient buffer area and crop around them.

For determining time and quantity of water for irrigation it is important to have knowledge of rainfall, soil capacity for available water, depth of rooting, potential evapotranspiration and the soil moisture deficit which can be tolerated before $E_a$ is appreciably less than $E_p$ and growth is checked. Runoff and capillary rise of water can often be neglected for periods and areas where surface supplemental irrigation is needed. The soil moisture deficit then equals the evapotranspiration minus rainfall.

**Direct determinations of $E_a$ and $E_p$ at the climate and water balance station**

We are recording the evaporation from a 12 m.² free water surface 8 cm below the rim of a one metre deep circular concrete tank in the ground.
Evaporation from evaporimeters similar to the YOUNG (1954) screened tank is also measured, fig. 6. The water surface is one third square metre. The tank of metal is circular and one metre deep. The water surface is here also 8 cm. below the rim and level with the surrounding grass-covered ground. The screen is made of galvanized wire netting with 0.6 cm. mesh (or 15 meshes per 10 cm.) and suspended horizontally in the tank midway between the rim and the normal water surface. The water level is regulated three times weekly. A hook in the outside connected pipe indicates the normal position.

We have found that the evaporation in mm. water from a screened evaporimeter tank is about 80 per cent of the evaporation from the 12 m. free water surface or of the same order of magnitude as the potential evapotranspiration. Results are given in fig. 7. On each of eighteen State Experimental Stations in Denmark are now installed two screened evaporimeters. The two differ in degree of shelter as they are placed at different distances from shelter hedges. The amounts of wind and rainfall are recorded also.

We determine the potential evapotranspiration by use of six evapotranspirometers each having a grass-covered area of 4 square metres (2 × 2), (MATHER, 1954). They are constructed of concrete and are complete under the soil surface, fig. 3. The depth of soil is about 60 cm. and the ground water level is maintained at a depth of 45 cm. Supply and run-off are recorded. Until now three of them have got only the ground water supply whereas three are also surface-irrigated once every week with the same water depth as the net evaporation from the screened tanks described above. The surface-irrigation could not quite cover
the evapotranspiration in dry periods. This could be due to evaporation during the application of the water.

As shown in fig. 2 and 7 reasonable good agreement is found between the evapotranspiration determined by use of Penman's theory, screened evaporimeters and evaporotranspirometers. The relation to evaporation from the free water surface is most firm for the results from screened evaporimeters, fig. 7.

Further investigations are desired, but on basis of the results obtained we recommend to use the screened evaporimeters for experimental and practical irrigation purposes. The screen prevents interference from large animals. Placed in a field with grass which should be irrigated, one could in theory in a dry period apply the same quantity of water in mm. to the field as to the tank to maintain the water level. It is not even necessary to measure rainfall as it can be taken to be the same for the evaporimeter and for the field.

The evaporimeter is much cheaper and much less work is required to use it than to use e.g. tensiometers, gypsum blocks or meteorological estimations of potential evapotranspiration. It is important also that a balance easily can be made with short intervals.

A fairly large area can be served by one single evaporimeter, but then it is necessary to know the local rainfall. The variation in rainfall is far much greater than in potential evapotranspiration.

In practical irrigation it is difficult to distribute the water even and there may be a considerable evaporation during the spraying, therefore we recommend to use a quantity 25 per cent higher than required for the evaporimeter.
Often it is enough to regulate the water height in the evaporimeter once a week. Maximum evaporation we have had in one week is 30 mm. In case of rainfall above 30 mm. in a short period it is desirable to regulate immediately. Rainfall in excess of the soil moisture deficit must be considered as a loss like run-off in general.

**Possibilities of Limiting Irrigation Requirements**

A little may be gained by growing deep rooted crops and crops having the main period of growth at a time when the evapotranspiration intensity is relatively low. In Denmark e.g. the conditions are much more suitable for growing root crops than grass.

It is also important to aim at soil conditions which stimulate deep rooting: drainage, subsoiling, mixing of stratified soil profiles, etc. A deep rooted lucerne crop may "open" the subsoil for roots of subsequent crops.

Another possibility is reduction of potential evapotranspiration by change of climatic conditions. By shelter investigations (Aslyng, 1958) it was found that decrease in wind speed in general increased day and decreased night temperature, which increased day and decreased night saturation deficit, fig. 8 and 9.

The decrease in wind speed or amount reduced evapotranspiration more than it was increased due to change in vapour pressure deficit.

Evaporation from screened evaporimeters was measured and the climatic factors were recorded so potential evapotranspiration could be estimated by use of the Penman formula. The two methods agreed very well. For the two
summers 1955 and 1956 the potential evapotranspiration was reduced by one third to one half as much per cent as the wind speed was reduced.

Western wind is prevailing (fig. 8) and a 2.5 m. high shelter screen North-South with 45 per cent openings could in average reduce the amount of wind by 40 per cent at a distance of 4 h to the East, when h is the height of the screen. That reduced potential evapotranspiration to 20 per cent or about 20 mm. per month in the most critical period, fig. 1.

The reduction in evapotranspiration by shelter was relatively larger in 1956 with a lower temperature than 1955.

The results also indicate that it is important that attention is given not only to energy supply, but also to the wind and saturation deficit factor in a formula for calculating potential evapotranspiration.

SUMMARY

Since 1953 the potential evapotranspiration has been estimated on basis of Penman's theory; recorded incoming and reflected energy; estimated back radiation and recorded wind speed, temperature and dewpoint temperature. Heat flux into the soil was determined.

Evaporation from a 12 m.² free water surface in a circular one metre deep ground tank, from screened evaporimeters and from potential evapotranspirometers with a four square metre grass covered surface has been determined 1956 and '57.

Meteorological estimation, evaporimeters and evapotranspirometers gave results of the same order of magnitude and about 80 per cent of the evaporation from the large free water surface.

The one metre deep screened evaporimeter with the rim 8 cm. high, the water surface level with the ground and the screen of wire netting suspended midway between rim and water surface is recommended for obtaining information on potential evapotranspiration for experimental and practical supplemental surface irrigation.

REFERENCES


MATHER, J. R. (editor). 1954. The measurement of potential evapotranspiration. Publications in Climatology (John Hopkins Laboratory of Climatology) 7


DISCUSSION

VISSEER:

What might be the influence of laterally incoming air in areas where the irrigated plot is situated in a dry area? What might be the necessary size of a homogeneous area to get rid of this lateral influence? Is there any chance that the HAUDE formula, which stresses the humidity deficit more than the PENMAN formula does, is dealing more with situations where the moisture relations over larger areas are even less homogeneous than in Denmark, England or Holland?

KORTE:

Die Verdunstung errechnet nach HAUDE stimmt mit Wasserverbrauch in der Tiefe 0-60 cm gut überein.

SMITH:

How much effort still is required to collect the meteorological data required to solve the PENMAN equation for estimating potential evapotranspiration? How does this compare with the installation and measurement of evaporation from an open water surface in an evaporimeter? I ask this question with the idea of obtaining advice on the best method of obtaining data on evapotranspiration in undeveloped countries.

MOHRMANN:

At many agricultural research stations simple evapotranspirometers are installed. The measurements are fairly simple and satisfactory.

What is the reason, that the PENMAN method is successfully applied in many coastal countries with a marine climate and that in countries with a continental climate preference is given to other methods (HAUDE, BLANEY-CRIDDLE, THORNTHWAITE)? It seems also that under arid conditions, PENMAN's calculations are yielding too low values. Could this be due to the influence of the saturation deficit?

The reduction factor (0.8 in the lecture) may vary much for different crops. For rice growing in lysimeters with groundwater level at 40 cm. in Belgian Congo it has been found that this factor was even much higher than 1.0.

Is not the wind effect in large areas less important than the speaker stressed? It seems that various methods for determining evapotranspiration in which the variations of the wind speed are not taken in account, correlate well with the PENMAN calculation and lysimeters observations.
MOLENAAR:

In the arid states of the United States, the BLANEY-CRIDDLE formula, \( U = KF \), is successfully used. When, about 10 years ago, I collaborated with Mr. CRIDDLE in writing a State Bulletin on the subject for the State of Washington, it became necessary to apply somewhat arbitrary corrections to \( K \), the crop factor, for areas of the state lying to the west of the Cascade Mountain Range where the climate is definitely influenced by the nearness of the Pacific Ocean. Though the corrections were applied to the \( K \)-factor, they probably should be applied to the \( F \)-factor in the formula.

Answer:

It is not too well known how large a homogeneous area is needed but for climatic conditions and soils as in Denmark a fairly small area will do reasonably well.

I have never used the HAUDE formula and am not able to comment upon the value of that equation.

On farms and experimental stations it is normally not possible to carry out the meteorological observations necessary for satisfactory use of PENMAN's formula. Furthermore it is important to get information on the evapotranspiration frequently, say every week, and without too many calculations.

The use of evaporimeters is much easier and cheaper, and the results obtained justify further investigations and comparisons of the methods discussed in the lecture.

The reduction factor may be 1.0 when the surface is wet -- as mentioned in the lecture -- and might even be higher for a tall crop on a small area due to extreme exposure to climatic factors.

The energy supply is the most important factor for evapotranspiration, but when the climate is like ours it seems important to use a formula where considerations to wind and saturation deficit also are given. Some energy may even be brought by the wind, and thereby affect the saturation deficit and the evapotranspiration.
CALCULATION METHODS
OF POTENTIAL EVAPOTRANSPERSION

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INTRODUCTION

A number of methods have been evolved to calculate the potential evapotranspiration. Some of these methods are based on an empirical correlation with monthly air temperature [Thornthwaite (1948), Blaney (1951)]. Makkink (1955) shows that the curve of the monthly values calculated according to Thornthwaite agrees with the observed potential evapotranspiration only after application of a correction for a time lag and for the wind velocity. No method based on monthly temperature alone can be expected to give reliable results for different regions [Van Wijk and De Vries (1954)].

Penman (1948) has evolved a formula on a basis of sound physical reasoning. Recently Makkink (1957b) published a correlation formula with incoming radiation and air temperature. Turc (1954b, 1955) has constructed a correlation formula for evapotranspiration in which he uses rainfall, temperature and radiation. Haude (1952, 1954) makes use of an empirical formula principally based on the saturation deficit at 14.00 p.m.

In this study six different methods will be used to calculate the potential evapotranspiration.

SOME GENERAL REMARKS CONCERNING THE DIFFERENT METHODS

a. The water balance method: Experiments based on this principle are performed at Wageningen with weighable monolith lysimeters covered with grass. Six of them were filled with a sandy soil and they had a constant ground water table at 50 cm. below the surface. This is a depth which on sand might be presumed to ensure that the evapotranspiration is not limited. The evapotranspiration can be calculated with the following hydrologic equation:

\[ E = P + I - D \pm \Delta W \]

where \( E \) = evapotranspiration, \( P \) = precipitation, \( I \) = infiltration, \( D \) = drainage and \( \Delta W \) = change in water content of the soil-block being considered.

The calculated data of the potential evapotranspiration have been corrected to a grass-length of two centimeters (Makkink 1957a).

b. Evapotranspiration from a water surface: The evaporation of water was measured with two evaporation pans (diameter 50 cm., depth 23 cm.). The water surface was kept 3.5 cm. below the rim. The rim of the pans was at the same level as the surface of the soil. They were surrounded by grass cut short. The data have been multiplied by Penman's reduction factor [Penman (1948)] to get a value comparable with potential evapotranspiration.
c. Penman's formula: For a full discussion of Penman's method of obtaining the potential evapotranspiration from meteorological observations, reference should be made to Penman's original papers (1948, 1956). He evolved the following equation to calculate the evaporation of free water$^1$):

$$E_o = \frac{\Delta H_o + \gamma E_d}{\Delta + \gamma}$$

Multiplying $E_o$ by an empirical reduction factor gives the potential evapotranspiration ($E_p$) for a soil covered with a crop. The values of this reduction factor were deduced from experiments at Rothamsted, [Penman (1948)].

The ratio $\frac{E_p}{E_o}$ has the following values:

- 0.6 from November to February
- 0.7 March, April, September, October
- 0.8 from May to August

Makkink (1957b) found that for some years the calculated incoming radiation (Appendix I) was smaller than the measured incoming radiation. In fig. 1, a comparison has been made between calculated and measured values of incoming radiation during 1957 at Wageningen. From this figure follows also that the calculated value is too small. De Vries (1955) suggests that on days with a partly clouded sky, an extra amount of radiation can reach the earth surface round the rim of the clouds. To get an idea of the influence of the discrepancy between the measured relative sunshine and the calculated "effective" relative sunshine a comparison was made between the calculated values of evapotranspiration and the measured evaporation from a pan. The figures 2 and 3 show the results of this. It is clear that the evapotranspiration calculated, with the measured incoming radiation and the calculated relative sunshine, gives the best agreement with the results of the evaporation pan.

$^1$ For the symbols see Appendix I.
MAKKINK's formula: Recently MAKKINK (1957b) published a new formula for calculating the potential evapotranspiration. He based his formula on the measured incoming radiation and temperature. He evolved the equation 1):

$$E_p = 0.61 \frac{R_n}{\Delta + \gamma} - 0.12$$

MAKKINK evolved his formula for average monthly potential evapotranspiration values at Wageningen. In this study the formula was used over periods of 10 days.

e. TURC's formula: TURC (1954b, 1955) has evolved a correlation formula based on rainfall, temperature and radiation. He gives the following equation 2):

$$E (\text{mm/10 days}) = \frac{P + a + V}{\sqrt{1 + \left(\frac{P + a}{L} + \frac{V}{2L}\right)^2}}$$

The small area of the lysimeters, presents difficulties in determining TURC's crop factor V. He gives for a luxurious growing crop, without shortage of water at any time, a crop factor $V = 70$, (1954a). This value has been used here. It must be expected that the calculated values with TURC's formula are somewhat higher than the results of the lysimeters, since these last values were corrected to a grass length of two centimeters.

f. HAUDE's formula: This method is principally based on the saturation deficit at 14.00 p.m. This value is multiplied by a reduction factor. HAUDE (1952) and UHlig (1954) give the following values for the reduction factor:

1) For the symbols see Appendix II.

2) See also Appendix III.
UHLIG (1954) gives the relation between the calculated evapotranspiration after PENMAN and after HAUDE in the equation: \( E_{(PENMAN)} = 0.44 E_{(HAUDE)} + 1.2 \). This relation holds true at Bad Kissingen (Germany). At Wageningen, the calculation of the evapotranspiration for 10-day periods gives other results. The figures 4 and 5 represent the relation between both methods, respectively at Wageningen and Bad Kissingen. Obviously a great discrepancy exists between the results in both places. A comparison between the calculated values with HAUDE's formula and the results of the lysimeters gives the same discrepancy. Later, HAUDE (1955) corrected his reduction factor for wind-velocity, measured from 11.00 a.m. till 15.00 p.m. at 10 meters height.

A new reduction factor was calculated at Wageningen, consisting of a day-length factor and a wind-velocity factor. The reduction factor can be calculated at Wageningen with the formula:

\[
f = \left(1.12 \frac{D}{24} - 0.26\right) (0.32 u_2 + 0.19)
\]

where \( D \) = day-length in hours
\( u_2 \) = average wind-velocity in m/sec at 2 m. height

This equation has been tested for the neighbourhood of Wageningen only, so one should be careful in using it for other regions.
DISCUSSION AND CONCLUSION

Potential evapotranspiration has been calculated with the six methods mentioned above. The evapotranspiration was calculated from meteorological data measured at Wageningen during 1957 for the mean values of 10-day periods expressed in mm/day. To get an idea of the similarity of the results each method has been plotted against the average of the six methods (fig. 6 to 11). Table 1 gives the correlation coefficients between the methods.

<table>
<thead>
<tr>
<th>Method</th>
<th>Pan x red. fact.</th>
<th>Penman</th>
<th>Makkink</th>
<th>Turc</th>
<th>Haude</th>
<th>Average of the six methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lysimeter</td>
<td>0.96</td>
<td>0.97</td>
<td>0.94</td>
<td>0.86</td>
<td>0.98</td>
<td></td>
</tr>
<tr>
<td>Pan x red. factor</td>
<td>-</td>
<td>0.99</td>
<td>0.97</td>
<td>0.96</td>
<td>0.96</td>
<td>0.99</td>
</tr>
<tr>
<td>Penman</td>
<td>-</td>
<td>-</td>
<td>0.98</td>
<td>0.98</td>
<td>0.95</td>
<td>0.99</td>
</tr>
<tr>
<td>Makkink</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.96</td>
<td>0.94</td>
<td>0.99</td>
</tr>
<tr>
<td>Turc</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.93</td>
<td>0.98</td>
</tr>
<tr>
<td>Haude</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.94</td>
</tr>
</tbody>
</table>

One may expect to get a fair impression of the error of each method by comparing the results with the average of all six, since the results of the six methods do not differ very much from each other. One must assume in this case that, though the results of the different methods have been correlated, there does not exist any correlation between the errors of the methods. It may therefore be expected that the average of the methods has a very small error relative to those of each method alone. Assuming that this average is without error, makes it possible to calculate the variance of each method (viz. table 2, column 2).

Fig. 6.
Relation between the average potential evapotranspiration of six methods and the evapotranspiration of the lysimeter. Average values of 10-day periods

Fig. 7.
Relation between the average potential evapotranspiration of six methods and the measured pan evaporation multiplied by a reduction factor. Average values of 10-day periods
The data of the direct measurements of the lysimeters and the evaporation pan are independent of the data from the indirect methods. The data calculated with these formulae almost certainly will not show a mutual independence of the errors, since the same meteorological data such as radiation, temperature and relative humidity were used. It is possible therefore to combine three methods that have mutually independent errors by comparing the results of the
lysimeters, the pan and one of the indirect methods. A combination of three independent methods offers a possibility to calculate the error without the help of repeats. Visser (1958) gives a formula to calculate the error of results from a comparison of three methods (x, y and z) having errors with a zero mutual correlation. He evolved the equation

$$\sigma_x^2 = \bar{u} \left( 1 - \frac{r_{uv} r_{uw}}{r_{vw}} \right)$$

where $\sigma_x$ = error in method x
$u = x - \bar{x}; \ v = y - \bar{y}; \ w = z - \bar{z}$
$r_{uv} = \text{correlation coefficient between x and y}$
$r_{uw} = \text{correlation coefficient between x and z}$
$r_{vw} = \text{correlation coefficient between y and z}$

The error of each method calculated with this formula is shown in table 2, column 3.

<table>
<thead>
<tr>
<th>Method</th>
<th>Error calculated with the average of the six methods in mm/10 days</th>
<th>Error calculated with the formula $\sigma_x^2 = \bar{u} \left( 1 - \frac{r_{uv} r_{uw}}{r_{vw}} \right)$ in mm/10 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lysimeter</td>
<td>2.7</td>
<td>2.8</td>
</tr>
<tr>
<td>Pan x red. fact.</td>
<td>1.5</td>
<td>1.9</td>
</tr>
<tr>
<td>Penman</td>
<td>2.5</td>
<td>2.7</td>
</tr>
<tr>
<td>Makkink</td>
<td>2.0</td>
<td>2.1</td>
</tr>
<tr>
<td>Turc</td>
<td>2.2</td>
<td>3.2</td>
</tr>
<tr>
<td>Haude</td>
<td>2.9</td>
<td>4.2</td>
</tr>
</tbody>
</table>

It appears that the methods have about the same degree of accuracy. The error in the results of the calculations after Hauude seems to be somewhat higher. A careful handling of Hauude's formula is necessary, since the given formula of the reduction factor only holds true at Wageningen. In other regions a new reduction factor will have to be determined. But where the method of Hauude is properly controlled, it will give a fair estimate of the evapotranspiration and it can be a valuable aid to hydraulic calculations.

It is possible to calculate the potential evapotranspiration from meteorological data after Penman, Makkink and Turc with the same accuracy as is obtainable with lysimeters and evaporation pans. The reduction factor of Penman holds true only for the potential evapotranspiration of a short crop. Turc's formula is the only one which gives some possibilities to calculate also the actual evapotranspiration.

Regarding the lack of knowledge concerning the reduction factor, the accuracy of the results for the potential evapotranspiration will be no restricting factor in this field of science. One may therefore assume, that further progress will not result from an increased accuracy of these modern evapotranspiration formulae but from a further study of the influence of environmental conditions on the reduction factor.
SUMMARY

Values of potential evapotranspiration, calculated with the formulae of Penman, Makkink, Turc and Haude, have been compared with measured values from a pan and from lysimeters covered with grass.

In the calculations with Penman’s formula, calculated values of the relative sunshine have been used. There is a good agreement for 10-day periods between $E_0$ calculated after Penman and the evaporation of the pan.

Haude and Uhlig give coefficients, with which Haude’s formula must be multiplied to get values of the potential evapotranspiration. These coefficients do not give correct results at Wageningen. A new reduction factor was calculated, consisting of a day-length factor and a wind-velocity factor. It is possible to calculate the potential evapotranspiration with the formulae of Penman, Makkink and Turc with the same degree of accuracy as is obtainable with lysimeters or evaporation pans. Haude’s formula gives results that seem to be somewhat less accurate.

RÉSUMÉ

Méthodes pour calculer l’évapotranspiration potentielle

On a comparé entre eux l’évapotranspiration potentielle calculée au moyen des formules de Penman, Makkink, Turc et de Haude et des valeurs mesurées d’une cuve évaporimétrique et de lysimètres herbus. Pour le calcul effectué au moyen de la formule de Penman on s’est servi de valeurs calculées pour l’insolation relative.

Pour les moyennes de décades il existe un rapport assez étroit entre le $E_0$ calculé selon Penman et les valeurs mesurées de la cuve évaporimétrique.

Le facteur de réduction donné par Haude et Uhlig pour l’application de la formule de Haude donne pour Wageningen de fausses valeurs d’évapotranspiration. A Wageningen on a calculé un nouveau facteur de réduction se composant d’un facteur de longueur de journée et d’un facteur de la vitesse du vent.

Il est possible de calculer avec autant d’exactitude l’évapotranspiration en se servant des formules de Penman, Makkink et Turc, qu’au moyen de cuves évaporimétriques et de lysimètres. Il se peut que la formule de Haude ait des résultats quelque peu moins précis. Pour cette dernière méthode il y a en outre la difficulté que le facteur de réduction doit être fixé dans chaque région.

ZUSAMMENFASSUNG

Berechnungsmethoden der potentiellen Evapotranspiration

Die potentielle Evapotranspiration wie diese berechnet wird mit den Formeln von Penman, Makkink, Turc und Haude wurde mit den Werte gemessen an einer Wasserschale und an Lysimetern mit Gras verglichen.

Bei der Berechnung mit der Penmanschen Formel sind berechnete Werte für den Sonnenscheinverlauf gebraucht. Es gibt eine gute Zusammenhang für Dekaden zwischen dem berechneten $E_0$ nach Penman und den gemessenen Werte an einer Wasserschale.


REFERENCES


22
——— 1957b. Ekzameno de la formulo de Penman. Neth. J. Agric. Sci. 5: 290
——— 1954b. Le bilan d'eau des sols. Relations entre les précipitations, l'évaporation et l'écoulement. Annales Agronomiques 5: 491

APPENDIX I: PENMAN'S formula

\[ E_o = \frac{\Delta H_o + \gamma E_a}{\Delta + \gamma} \]

where:
- \( E_o \) = evaporation from a water surface in mm/day
- \( H_o \) = net gain in radiation-energy per unit of surface
- \( \Delta \) = slope of temperature - vapor-pressure curve
- \( \gamma \) = psychrometer constant = 0.49 mm. Hg degree centigrade
- \( E_a = 0.35 \left( 0.5 + 0.54 u_2 \right) (e_a - e_d) \)
- \( u_2 \) = wind-velocity at 2 m. height in m/sec
- \( e_a \) = saturation vapor-pressure at air temperature
- \( e_d \) = saturation vapor-pressure at dew point

The incoming radiation can be calculated with the formula

\[ R_i = \left( 0.29 + 0.71 \frac{n}{D} \right) Q \]

where:
- \( R_i \) = incoming radiation per unit of surface
- \( n \) = relative sunshine
- \( D \) = incoming radiation on totally clear days

De Vries (1955) gives day-values of \( Q \) at Wageningen.

APPENDIX II: MAKKINK'S formula

\[ E_p = 0.61 R_m \frac{\Delta}{\Delta + \gamma} - 0.12 \]

where:
- \( E_p \) = potential evapotranspiration
- \( R_m \) = measured evapotranspiration in mm day
- \( \Delta \) = slope of temperature - vapor-pressure curve
- \( \gamma \) = psychrometer constant = 0.49 mm. Hg degree centigrade
APPENDIX III: Turc's formula

\[ E \text{ (mm/10 days)} = \frac{P + a + V}{\sqrt{1 + \left(\frac{P + a + V}{L + \left(\frac{V}{2L}\right)^2}\right)^2}} \]

where:
- \( P \) = precipitation in mm/10 days
- \( a \) = soil factor. This factor can be calculated as follows: \( a = 35 - \Delta \) with a maximum value \( a = 10 \) and a minimum value \( a = 1 \)
- \( \Delta \) = deficit of soil moisture at the beginning of the ten-day period that must be calculated
- \( L = \frac{1}{16} (t + 2) \sqrt{R} \)
- \( t \) = average air temperature during the period
- \( R \) = average incoming radiation in cal/cm² per day

Turc states that if \( L < 10 \) the crop factor \( V = 0 \)

The crop factor \( V \) can be calculated as follows:

\[ V = 25 \sqrt{\frac{M_c}{Z}} \text{ or} \]

\[ V = \left( \Delta_o + 30 + 1.5 \frac{M_c Z}{Z} \right) - \Delta \]

where:
- \( M \) = production of dry matter in 100 kg/ha
- \( Z \) = length of growing season in periods of 10 days
- \( z \) = number of the period considered
- \( c \) = crop constant with the following values:
  - \( \frac{1}{3} \) corn and beets
  - \( \frac{1}{4} \) potatoes
  - \( \frac{1}{5} \) cereals, carrots, flax
  - \( \frac{1}{6} \) beans, clover, other leguminous plants
  - \( \frac{1}{8} \) lucerne and grass
- \( \Delta_o \) = deficit of soil moisture at the beginning of the period.

The smallest of the two calculated \( V \)-values should be used.

The growing season begins twenty days after the sowing date.

DISCUSSION

J. M. Lyshede:

It is quite certain that the formula of Penman is too simple, but I feel sure that a universal formula must be found by physical and climatological considerations sooner than by means of statistics.

Answer: (W. C. Visser)

Physics has to present new functions, statistics will have to prove and eventually reject them and will be able to hint to better approaches. The cooperation between the two fields of science will not be difficult. I quite agree that the qualitative accuracy – taking into account all factors concerned – will be of more importance than an increase in the quantitative accuracy. As regards statistics, we will have to select with preference those methods that are free of a presumed functional relation.
A TENTATIVE SURVEY OF
THE WATER DEFICIENCIES IN EUROPE AND
THE NEED OF (SUPPLEMENTAL) IRRIGATION

J. C. J. MOHRMANN
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INTRODUCTION
This paper will deal with the question as to where, and in what degree and frequency, a shortage of water may occur in European agriculture, and what amounts would have to be supplied in order to be able to maintain or reach an optimum level of production. Emphasis will be laid on the hydrological aspect of the question. 1)

PRINCIPLES UNDERLYING THE PROBLEM
In the first place it is necessary to investigate the climatic and hydrological sequence of events during periods of drought. It is characteristic of climatically dry periods that the total amount of moisture withdrawn from the soil by evapotranspiration (E) is greater than the total amount of moisture supplied by precipitation (P). As soon as evapotranspiration begins to exceed precipitation a precipitation deficit is created which steadily increases in the course of the climatic dry period.

At the moment this period commences an amount of soil moisture is available for plant growth which decreases as the precipitation deficit increases. This supply continues to be drawn on until all moisture that can be reached and absorbed by plants has been exhausted.

By moisture available is here meant the soil moisture which is retained within the root zone and can be absorbed and evaporated by the plants. Only a part, however, of the amount of soil moisture defined in this way is readily available for vegetation without checking transpiration. Irrespective as to whether this percentage is high or low the absorption then is practically equal to the potential evapotranspiration (E_p). 2) Following Penman, we term this part of the available moisture the root-constant (R). This is chiefly determined by root zone depth and root distribution, but also depends on the moisture-holding capacity of the soil.

Generally speaking, the root-constant may vary from 10–50 mm. in the case of shallow-rooted market garden crops or seedlings, up to 200–250 mm. in the

1) In the preparation of this paper a great deal of assistance was given by Mr. J. KESSLER.

2) For the practical purposes of this study it was considered inevitable to assume that in a certain moisture range in the soil the actual evapotranspiration corresponds more or less with the potential one, although it is known from recent investigations that already with low moisture tensions the actual evapotranspiration deviates from the potential one, particularly with a high light intensity and highly drying atmospheric conditions (Bierhuizen, Makkink and Wind).
case of deep-rooted crops, including trees. In the case of grassland and a number of moderately deep-rooted crops, the value taken is often in the region of 75–125 mm. These values should, of course, be modified in the case of soils having a very high or very low content of absorbable moisture.

If we now take as our starting point a situation in which the soil is at field capacity when the precipitation deficit occurs, the absorption of moisture by the plants and the drying-out of the soil will be able to proceed almost without restraining as long as the reduction in the supply of moisture continues to be less than the root-constant. But as soon as the reduction in the moisture supply exceeds the root-constant the plants have less opportunities to absorb moisture; actual evapotranspiration is much less than potential evapotranspiration and the need is felt of an artificial supply of water. If, however, this need is met by irrigation, actual evapotranspiration will continue to be substantially the same as potential evapotranspiration.

**THE AMOUNTS OF WATER REQUIRED FOR AN OPTIMUM SUPPLY OF WATER**

In the first place one should determine the maximum precipitation deficit \((E_p - P)\) for the climatically dry periods. Moreover the root-constant \((R)\) must be ascertained with reference to plant and soil type. The difference between precipitation deficit and root-constant represents the amount of water which should be supplied to allow potential evapotranspiration: \((E_p - P) - R = I\).  

The magnitude and frequency of the precipitation deficit and the need of irrigation can be determined for a particular location, taking into account the required data of a great number of years.

The International Institute for Land Reclamation and Improvement has made an initial attempt at constructing the pattern of precipitation deficit and irrigation needs throughout the whole of Europe. The maximum precipitation deficit yearly occurring on an average is equal to the maximum difference between the summed mean evapotranspiration and the summed mean precipitation calculated from the moment at which evapotranspiration begins to exceed precipitation. In the case of 287 meteorological stations this was calculated from the figures for the mean monthly precipitation and potential evapotranspiration. Potential evapotranspiration was calculated by Turc's method (see Appendix). Some further explanation is required as to why this hitherto little-known method was preferred.

It is usually advisable to employ a method which includes the most important variable factors determining the phenomenon of evaporation (temperature, solar radiation, relative humidity and wind velocity). The method, evolved by Penman in the south-east of England and in which the natural evaporation is derived from the energy balance, would therefore be most obvious, but despite its accurate physical basis it is not entirely free from empirically determined constants and hypotheses of which the universal validity still has to be proved.

1) It is assumed that the upward capillary rise from the phreatic level does not extend to the lower limit of the root zone.

2) The express reservation is made that potential evapotranspiration need not always correspond with maximum yield.
As long as this method has not been subjected to further tests the specific scientific advantages cannot be accredited with their full value.

Moreover, in order to obtain a geographical survey, it is essential that the data from a great number of meteorological stations should be included in the survey. In the case of the majority of stations of which the precipitation deficit had to be calculated, it was found that the data required for the energy balance method were either unknown or not known with sufficient accuracy.

Hence the use of this method for the present survey was faced with drawbacks which were mainly of a practical kind.

Various other methods, in most cases solely based on the variation in the temperature, proved very valuable in the areas where they had been evolved and where the constants had been determined empirically, but no universal validity should be attached to these formulae either. A general application is particularly hazardous when climatic conditions are variable. Moreover the great drawback of these methods is the phase shifting between temperature and solar radiation (Van Wijk and De Vries).

The method evolved by Turc at the Centre National de Recherche Agronomique, in Paris, has the following advantages:
- it can be used without difficulty for calculating a large number of cases;
- the most important variable factors, viz. temperature and solar radiation, are taken into account;
- it is based on the water balances of a very large number of catchment areas throughout the world and on many scattered lysimeter observations.

The method has also been tested for the present survey by comparison with the observations and calculations which were found to be reliable in specific areas, with which generally very good results were obtained.

The main disadvantages are:
- it is not based on a physical principle but is essentially empirical;
- it takes no account of the variability of wind velocity and atmospheric humidity; in most cases, however, their relative effect is slight (Penman; Van Wijk and De Vries; Makkink).

The solar radiation could be derived with sufficient accuracy from the maps of Black; the precipitation and temperature data were derived from meteorological yearbooks of the various countries.

It will be obvious that transpiration is not identical for all plants. Nevertheless it is more or less generally accepted now that for most crops the differences in potential evapotranspiration are less important than was previously assumed and that there is relatively little difference in the order of magnitude of these figures. Hence what is meant in the present discussion by potential evapotranspiration applies to a great variety of crops provided they cover the soil well, reach their optimum development and are cultivated on extensive surfaces. Deviations may be expected in very high and open cultivations, such as orchards, and in ripening crops.

The results of this part of the survey are shown in maps I and IV.1) Map I

1) The maps are inserted at the end of this Report.
gives an overall picture of the distribution of the maximum precipitation deficit occurring annually, mainly during the summer months 1), and map IV gives the mean annual potential evapotranspiration.

If it is needed to deduce from map I the maximum amount of irrigation water required in the mean annual situation during the summer months, the root-constant should be subtracted from the precipitation deficit. This interpretation is – of course – only valid where, during the period in which the precipitation deficit occurs, the soil is continuously covered by a vegetation which actually absorbs and evaporates the maximum amount of water. However, particularly in southern Europe it is important to know also how the situation develops during the summer months since a great many crops do not remain in the field during the whole of this period. Hence it is also planned to compile maps showing the mean summed precipitation deficit to the end of June, and the increase of the deficit during July, August and September (Mohrmann and Kessler).

**Frequency of the need of irrigation**

Hitherto only the mean situation over a great number of years has been taken into account, but for supplemental irrigation it is certainly not only this mean situation that is important. The frequency of the need of irrigation, viz. the percentage of a given number of years in which there is a need of supplemental irrigation, should also be included in the survey.

The frequency of the need of irrigation can be calculated from all monthly or ten-day figures of the precipitation and the potential evapotranspiration over a great number of years; a root-constant of a specific magnitude should be included in the calculation as a credit item.

It is clear that a calculation of this kind applied to a great number of stations would be extremely time-consuming. Since – however – the degree of accuracy is mainly determined by geographical irregularities and the corresponding density of the number of observation stations, we are justified in simplifying the above mentioned detailed process without lowering the possible standard of accuracy.

It is known that precipitation may vary extensively from one year to another. Hence in order to acquire a good knowledge of the frequency of the need of irrigation it is quite obvious that the variations in precipitation should be included in the investigation. Thus, for the time being, use was only made of the variability of the total annual precipitation over a great number of years of 86 meteorological stations, from which was deducted the spread in the precipitation totals over the part of the year in which the deficit occurred.2)

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1) It should be noted that the picture for the mountainous areas can only be a rough one, considering that in these areas precipitation may vary considerably over comparatively short distances. Consequently local exceptions will occur particularly in these areas; they have been indicated with a special symbol on the map.

2) When deducting the variability of the precipitation total over the deficit period, account was taken of the fact that this variability, which only occurs during a part of the year, is usually greater than the variability throughout the year, viz. of the order of \( \sqrt{P \text{ year P season}} \). No account was taken of any local deviations from this inferred variability during the deficit period – a possible seasonal effect. It is believed – however – that for the object in view the element of introduced reduced accuracy is not large. For stations where this method was tested the deviation was – in fact – found to be very small.
Although it is obvious that the variability of the precipitation is very important for the frequency of the need of irrigation, it is a question whether this also applies to potential evapotranspiration. Calculations have shown that the variability of the potential evapotranspiration is very slight as compared with the variability of the precipitation 1), and that the mean monthly figures for potential evapotranspiration may be conveniently used in calculating the chances of drought and irrigation frequencies.

Maps II and III show the results of the tentative survey, viz.:
Map II for a root-constant of 100 mm.,
Map III for a root-constant of 200 mm.

It should be emphasized that these maps do not pretend to give more than an extremely approximate and tentative survey of the irrigation needs in Europe. It would certainly be impossible to use this material in order to read accurately the situation in a particular location; it does, however, afford an idea of the irrigation needs in extensive areas.

CONTINUATION OF THE HYDROLOGICAL IRRIGATION INVESTIGATIONS

The International Institute intends to continue and extend the survey on these lines. As in the case of the precipitation deficit maps, the first object will be to include the observations of the greatest possible number of stations in compiling the frequency maps. The accuracy of the maps will have to be subjected to a critical examination and tested from regional measurements and calculations of evapotranspiration, precipitation deficit and water consumption where these have already been undertaken in the various countries. It may be worth-while considering the setting-up of a record department for evaporation data.

Afterwards an attempt can be made at compiling a geographical survey of the root-constant of the most frequent types of agricultural crops on the characteristic soil types of European agricultural districts. This survey will do a great deal towards simplifying the interpretation of deficit maps and frequency maps.

SUMMARY

The International Institute for Land Reclamation and Improvement has made an initial attempt at constructing the pattern of precipitation deficit and irrigation needs throughout the whole of Europe.

The mean monthly precipitation figures of 287 meteorological stations were subtracted from the mean monthly potential evapotranspiration figures. From this the maximum precipitation deficit was calculated for each station, according to the annual average. The potential evapotranspiration was calculated by TLIRC's method.

Map I is an overall picture of the distribution of the maximum precipitation deficit. From this map it is possible to infer the maximum amount of irrigation water required in the mean annual situation by subtracting the root-constant from the precipitation deficit.

The root-constant is that part of the soil moisture supply which can be reached and absorbed by plants almost without checking the potential evapotranspiration.

The frequency of the need of irrigation was calculated from the variability of the annual maximum precipitation deficit figures over a great number of years.

1) In the Netherlands, for example, the precipitation variability is 5 to 7 times greater than the potential evapotranspiration variability.
For this purpose the variability of the precipitation over that part of the year in which the
deficit occurred was calculated from the variability in the total annual precipitation. These
figures were compared with the mean evapotranspiration figures. Root-constants of 100 and
200 mm, respectively were included in the calculation. The results are shown in maps II and III.
The annual evapotranspiration lines are shown in map IV.
The survey will be continued and extended.

RéSUMÉ
L'INSTITUT INTERNATIONAL POUR L'AMÉLIORATION ET LA MISE EN VALEUR DES TERRES a
entrepris une première tentative pour composer un relevé des déficits de précipitations et du
besoin d'irrigation dans toute l'Europe. Pour 287 stations météorologiques, on a fait la
soustraction des chiffres moyens d'évapotranspiration mensuelle potentielle des moyennes
mensuelles des précipitations. A partir de ces données, on calcula pour chaque station la
moyenne annuelle du déficit maximum de précipitations.
L'évapotranspiration potentielle fut calculée suivant la méthode de Turc.
La carte I donne un aperçu de la distribution du déficit maximum de précipitations. Cette
carte permet la déduction de la quantité maximale d'eau d'irrigation que nécessite la situation
moyenne annuelle en faisant la soustraction de la constante radiculaire du déficit de précipita­tions.
La constante radiculaire représente la partie de l'eau emmagasinée dans le sol qui est acces­sible et absorbable par les plantes, et dont l'évapotranspiration permet l'absorption presque libre.
La fréquence du besoin d'irrigation fut calculée à partir de la variabilité des déficits maxi­maux annuels de précipitations dans un grand nombre d'années.
A cet effet, la variabilité des précipitations dans la partie de l'année où se produisent les
deficits fut calculée à partir de la variabilité du total des précipitations annuelles. Ces chiffres
furent comparés à ceux de l'évapotranspiration moyenne. On fit entrer dans les calculs des
constantes radiculaires de 100 et de 200 mm. Les résultats sont indiqués dans les cartes II et III.
La carte IV montre les tracés de l'évapotranspiration annuelle.
Cette étude sera poursuivie et étendue.

ZUSAMMENFASSUNG
Vom INTERNATIONALEN INSTITUT FÜR LANDGEWINNUNG UND KULTURTECHNIK ist ein erster
Versuch unternommen worden, um ein Bild aufzubauen des Niederschlagsdefizits und des
Irrigationsbedarfs in ganz Europa. Von 287 Wetterwarten wurden die mittleren monatlichen
Niederschlagszahlen von den monatlichen Mittelzahlen der potentiellen Evapotranspiration
abgezogen. Hieraus würde für jede Station das maximale Niederschlagsdefizit berechnet, wie es
durchschnittlich jährlich auftritt.
Die potentielle Evapotranspiration wurde nach der Methode von Turc berechnet.
Karte I gibt eine Übersicht der Verteilung des maximalen Niederschlagsdefizits. Aus dieser
Karte kann die maximale Menge Irrigationswasser abgeleitet werden für die in der mittleren
jährlichen Situation Bedarf vorliegt, indem man die Wurzelkonstante vom Niederschlags­
defizit abzieht.
Die Wurzelkonstante ist ein Teil des für Pflanzen erreichbaren und aufnehmbaren Wasservorrats im Boden, dessen Aufnahme fast ungehindert stattfindet entsprechend der potentiellen Evapotranspiration.
Die Frequenz des Irrigationsbedarfs wurde aus der Variabilität der jährlichen gesamten
Niederschlagsdefizitzenahlen über eine grosse Anzahl von Jahren berechnet.
Dazu wurde die Variabilität der Niederschläge über denjenigen Teil des Jahres, in dem das
Defizit auftritt, aus der Variabilität im gesamten jährlichen Niederschlag berechnet. Diese
Zahlen wurden mit den mittleren Evapotranspirationszahlen verglichen.
Wurzelkonstanten von 100 bzw. 200 mm wurden in die Berechnung einbezogen. Die
Ergebnisse sind auf den Karten II und III angegeben.
Die Linien des mittleren jährlichen Evapotranspiration sind auf Karte IV zu sehen.
Die Untersuchungen werden fortgesetzt und weiter ausgedehnt.
BIBLIOGRAPHY

ANNUAL REPORTS of Meteorological Observations of the different European Countries.
BLANEY, H. F. and W. D. CRIDDLE. 1950. Determining water requirements in irrigated areas from climatological and irrigation data. Soil Cons. Serv. TP 96


MOHRMANN, J. C. J. and J. KESSLER. 1959. Water deficiencies in European agriculture (a climatological survey). International Institute for Land Reclamation and Improvement, Publ. 5, Wageningen, Netherlands


APPENDIX

Turc's general formula for the evapotranspiration of a vegetation-covered soil:

\[ E = \frac{P + a + V}{\sqrt{1 + \left(\frac{P + a}{L + 2L}\right)^4}} \]

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:
  \[ L = \frac{1}{16} (t + 2) \sqrt{i} \]
  in which
  - \( t \) = mean temperature of the air in a sheltered location during the 10-day period, in degrees centigrade
  - \( i \) = solar radiation in cal/sq cms per day
- \( a \) = amount of water evaporated from a bare soil, disregarding precipitation, at the expense of the reserves contained in the soil, in mm. per 10-day period
- \( V \) = effect of the vegetation cover on natural evaporation, viz. further decrease of the water reserves in the soil.

In the case of evapotranspiration of a luxuriant stand of vegetation which is never lacking in water, the formula becomes:

\[ E_p = \frac{P + 80}{\sqrt{1 + \left(\frac{P + 10}{L + 2L}\right)^4}} \]
\[ \text{for } L > 10 \]

and

\[ E_p = \frac{P + 10}{\sqrt{1 + \left(\frac{P + 10}{L}\right)^4}} \]
\[ \text{for } L \leq 10 \]

in which

- \( E_p \) = potential evapotranspiration in mm. of water per 10-day period
- \( a = 10 \), maximum value of \( a \), for humid soils
- \( V = 25 \sqrt{\frac{M}{Z}} \) (where evapotranspiration is not limited by lack of water), 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
  - \( c \) = coefficient indicating the relation of the transpiration coefficient of such a crop to that established for wheat.

\[ V = 70 \], in cases of potential evapotranspiration of a luxuriant vegetation, e.g. \( c = 1 \);
\[ M \cdot Z = 8 \] for a production of „harvestable“ dry matter equivalent to 800 kg. per 10-day period per ha., or \( c = 4.3 \) (maximum value); \( M \cdot Z = 6 \).

DISCUSSION

SCHONNOPP.

Definition des Begriffs „Wurzelkonstante“.

Answer:

By root-constant is meant the amount of soil moisture that can be reached and absorbed by the root system without plant growth being retarded.

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Ostromcki:

Der Wasserbedarf auf die Karten sind kalkuliert mit Formeln. Ist es nicht nötig regionale Koeffiziente versuchsweise einzuführen in den einzelnen Ländern laut der verschiedenen lokalen Bedingungen?

Answer:

The formula of TURC, which has been used for the calculation, is primarily an empirical formula. The usefulness of empirical formulae is largely determined by the climatic conditions of the region for which the formula is drawn up. Although TURC's formula is based on numerous water balance observations throughout the world, it is indeed advisable to check the results as good as possible and if necessary to improve the formula by changing the empirical coefficients.
THE WATER BALANCE AS A BASIS FOR IRRIGATION RESEARCH

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Provided one has at ones disposal data on ground- and ditch water depths and if also data are available on rainfall and computed evaporation, an insight may be obtained into storage and evaporation variations occurring in the soil. This is made possible by the fact that ditch- and ground water levels constitute a measure for subsoil drainage, the pertinent data rendering it possible to convert pressure head losses into discharge in mm. per time unit.

To secure an impression of the relation between these variables, one may subtract the rainfall (r) and the estimated evaporation from an open water surface (E_o) from each other as a first step. Furthermore, for small sections of the rise or fall of the water level (ΔH) as occur in the unit of time over which rainfall and evaporation data have been obtained, data may be gathered on the pressure head loss between the water level (H) and the ditch water level (d) and also on the discharge (r-E_o). If, for the cases with approximately identical ΔH-values, the values found for r-E_o are plotted, for each month separately, against those for H-d, scatter diagrams as shown on fig. 1, are obtained. Comparison of the scatter diagram for January with that for June reveals a relationship which is depicted by a curve identical in shape but shifted to a lower level for r-E_o. This is due to the fact that the E_o has been taken too high. The actual evaporation is smaller by a factor x. When the vertical shift of the curve for June is measured with respect to the curve for January, an approximation is obtained for the difference x_{Jan.}-x_{June}, the actual evaporation E_w being equal

Fig. 1. The H-d value, being a measure of the prevailing pressure head and the r-E_o, being a measure of subsoil drainage, together give rise to the drainage curve, which from month to month shows different levels. The vertical difference x is a measure of the reduction factor for evaporation
The reduction factor is derived from an analysis of the water balance, but is subject to marked variation due to easily evaporating, recently fallen rain. In this way the actual evaporation could be determined if a month with no evaporation at all should happen to be available. As the evaporation is however, only very small in winter the error introduced with respect to $x$ is only very small if, through extrapolation from the available data for autumn and spring, the reduction factor $f = E_w/E_o$ is estimated and from this the factor $x$ for the winter season is deduced. Fig. 2 gives an impression of this.

A good approximation of the reduction factor is then available for the remaining months. This factor appears to be highly variable, however, due to a large number of deranging factors, so a further study of these additional factors is called for. One should also guard against accidental errors.

The accuracy of the curve, which is obtained as a mean for the discharge $r - E_o$ against $H - d$, may be checked with the existing drainage formulas. The drainage formula

$$q = \frac{8k_o D (H-d)}{L^2} + \frac{4k_b (H-d)^2}{L^2}$$

may be rendered

$$\frac{q}{(H-d)} = \frac{8k_o D}{L^2} + \frac{4k_b (H-d)}{L^2}$$

$$\frac{q}{(H-d)} = A + B (H-d)$$

$q =$ drainage in mm. per time unit $= r - E_w - b \Delta H$

$k_o =$ permeability factor subsoil

$k_b =$ permeability factor surface soil

$D =$ thickness of aquifer

$b =$ storage factor

$L =$ half the distance between drainage ditches

In plotting the value found for $r - f E_o - b \Delta H$ divided by $H - d$, against $H - d$, a straight line must result which should hold good for all months of the year. This check on the accuracy of the mean drainage function provides at the same time a reliable check on the value found for $f$, see fig. 3.

When in this manner a clear insight has been obtained into the function by means of which the groundwater depths may be converted into drainage rates, it is possible to go deeper into the problem, since actually the process used is of the approximative type. For instance, the variations in moisture content are adequately accounted for in $\Delta H$, in as far as groundwater is concerned.
The drainage curve, as is apparent from a drop of the variables recorded along both axes through $H - d$, accurately follows the drainage formula

$$r - E_o = bH$$

but the drainage term has not yet been corrected with the variations in soil moisture ($\Delta V$) above the groundwater level.

The reduction factor $f$ is furthermore a highly variable quantity. Soils wetted with rain will show a higher rate of evaporation than soils containing an equal amount of moisture, but evenly distributed over the entire profile. Also the amount of evaporation will be affected by such factors as moisture discharge or depth of groundwater, type of crop grown and other conditions.

One may now go on by determining the rate of discharge for all periods from $(H-d)$. In addition, the periods with approximately identical values for $r$ and $\Delta H$ may be combined into groups. By plotting drainage discharge $(A)$ against the evaporation of the open water $(E_o)$ for the various groups of values in the different $r$, $\Delta H$ groups individually, a picture will be obtained as represented in fig. 4. This figure gives a somewhat different representation of the water balance than does fig. 1, use having been made of the circumstance that any water that evaporates cannot flow off via a subterranean route. If the $E_o$ should actually provide a picture of the true evaporation, the line showing the relation between $E$ and $A$ ought to run at an inclination of 45°. However, since the $E_o$ deviates from the $E_w$, this becomes apparent as a deviation from this 45° angle of inclination, the tangent of inclination of this line indicating the value of the reduction factor $f$.

The reduction factors $f$ may now be arranged according the values found for $r$ and $\Delta W$, resulting in a graph as given in fig. 5. This figure illustrates the extent to which evaporation in a soil recently wetted by rain increases, provided

**Fig. 3.**

**Fig. 4.** The magnitude of the reduction factor, but also the value of the seepage can be more accurately determined by plotting $E_o$ against the drainage for periods with approximately identical precipitation and storage values.
FIG. 5.
Recently fallen rain appears to cause increasing evaporation, the increase being dependent on the amount of rain fallen and the amount of water draining away towards the groundwater.

the precipitation has saturated the soil profile concerned, as is shown by the rising of the water level $A_0$. If, notwithstanding the fallen rain, the groundwater level should register a drop, it is apparent that the loss of water from the soil profile will be larger than the amount of water received from the rainfall. The total result will be an increased loss of water from the soil and an insignificant increase in the reduction factor. If the precipitation should be insufficient to make the soil thoroughly wet, evaporation losses will be a little more than those from a soil which has not been exposed to rain.

This type of elaboration of the water balance data may, however, also suggest a number of other conclusions. The depletion of moisture from the soil profile, or the increase in storage in the upper layers, may be determined by diminishing the amount of rain actually fallen with the relevant drainage, evaporation and groundwater storage values. Total moisture losses may be found by summation. This value may be used to correct the evaporation with respect to the degree of moisture depletion from the soil profile involved. By incorporating the water level data for various areas and soil profiles in these figures and by comparing the results, it is possible to estimate the influence of groundwater depth and water holding capacity of the soil profile on evaporation and over-all moisture losses. Indeed, there are many aspects and details of the water balance which are open to study in this manner. Gradually a better grasp on evaporation might thus be acquired. In those cases where the groundwater depth may be utilized as a measure of subsoil drainage, statistical analysis of the water balance should be considered to provide a versatile and universal method in hydrologic research.

RÉSUMÉ

Étude d'équilibre hydrologique comme base de recherches d'irrigation

L'équilibre hydrologique peut être étudié en plein champ, pourvu qu'il y ait moyen de mesurer la décharge. Or, cette mesure est possible à partir de la diminution de pression dans la direction du courant, que l'on peut mesurer à l'aide de sondes de niveau souterrain. En marquant dans un diagramme pour une même augmentation ou diminution du niveau des eaux souterraines dans la période de mesure la différence entre les mm de pluie et les mm
d’évaporation en eau ouverte en fonction de la diminution de pressions, et cela séparément pour les différents mois de l’année, on obtient une collection de points environnant des lignes courbes, de forme égale mais situées à des hauteurs différentes pour chaque mois (voir fig. 1). La différence de hauteur (x) indique de combien l’évaporation en eau ouverte (E_u) dépasse l’évaporation réelle (E_r). En évaluant E_r pour le mois à évaporation minimum, on peut calculer pour toute l’année les valeurs E_r à partir de E_u – x ou bien déterminer le facteur de réduction f = E_r/E_u. La figure 2 montre le résultat. La courbe de la décharge, qui en forme le résultat graphique, se trouve en très bonne concordance avec la formule de drainage (voir fig. 3).

Le facteur de réduction est très variable, les conditions d’évaporation étant très différentes. Or, en groupant les résultats de chaque période de mesure en classes d’augmentation égale du niveau des eaux souterraines et d’intensité de précipitations égales, le diagramme de la décharge, calculée selon l’opération décrite ci-dessus, par rapport à l’évaporation E_u fait voir un rapport linéaire (voir fig. 4), qui indique que ce qui ne s’évapore pas doit être déchargé. Mais puisque E_u ne représente pas l’évaporation réelle E_r, mais bien E_u/f, l’inclinaison des droites trouvées selon la fig. 4 se trouve représenter la valeur f.

Or, il apparaît que l’évaporation dépend fortement de la quantité de pluie tombée, tandis qu’en ce cas, la hausse ou la baisse du niveau des eaux souterraines font fonction de mesure du dessèchement ou de l’excès d’eau et influencent également considérablement l’évaporation. La figure 5 en montre un exemple.

ZUSAMMENFASSUNG

Die Wasserbilanz als Grundlage für Bewässerungsuntersuchungen

Die Wasserbilanz kann im Felde studiert werden, wenn nur die Möglichkeit gegeben ist, die Abfluss zu messen. Dies ist nun möglich aus dem Druckgefälle in der Richtung der Strömung, die man mit Grundwasserstandsröhren messen kann. Wenn man für ein gleiches Steigen oder Sinken des Grundwassers während der Messperiode die Millimeter Regen abzüglich der Millimeter Verdunstung von offenem Wasser auf das Druckgefälle für die einzelnen Monate des Jahres einträgt, so erzielt man einen Punktevorrang um gebogenen Linien, die von gleicher Form sind, aber für jeden Monat eine eigene Höhenlage haben (siehe Figur 1). Der Höhenunterschied x zeigt an, um wieviel die Verdunstung von offenem Wasser E_u grösser ist als die wirkliche Verdunstung E_w. Nimmt man für den Monat mit der kleinsten Verdunstung eine geschätzte E_w an, so kann man für das ganze Jahr die E_w-Werte berechnen aus E_u – x oder den Reduktionsfaktor f = E_w/E_u bestimmen. Figur 2 zeigt das Ergebnis dieser Berechnungen. Die Abflusskurve, die das Resultat einer graphischen Bearbeitung ist, stimmt sehr gut mit der Dränierungsformel überein, wie aus Figur 3 ersichtlich ist.

Der Reduktionsfaktor ist sehr variabel, weil die Voraussetzungen für die Verdunstung sehr ungleich sind. Wenn man nun die Resultate für die Zeiteinheiten der Messung in Klassen gleicher Zunahme des Grundwasserniveaus und gleicher Regenintensitäten einteilt, so ergibt die Eintragung der laut obenerwählter Bearbeitung berechneten Abfluss auf die Verdunstung E_u einen gradlinigen Zusammenhang (siehe Figur 4), der anzeigt, dass das, was nicht verdunstet, abgeführt werden muss. Weil jedoch E_u nicht die wirkliche Verdunstung E_w darstellt, sondern E_u/f, geht aus der Neigung der nach Figur 4 gefundenen Linien den Wert von f hervor.

Es zeigt sich nun, dass die Verdunstung in hohem Grade abhängig ist von der gefallenen Regenmenge, während in diesem Falle das Steigen oder Sinken des Grundwassers als Massstab dient für das Mass der Vertrocknung oder den Wasserüberschuss und ebenfalls einen starken Einfluss auf das Mass der Verdunstung hat. Davon gibt Figur 5 einen Beispiel.

DISCUSSION

LYSHEDE:

Ich möchte fragen nach Art und Grösse der besprochenen Abflussgebiete.

Answer:

The size of the areas is limited by the location of the ditches if a test-well was object of study. The area is then somewhere between 0.5 and 1 ha. Where a whole polder is taken, the size of the catchment area may differ. We studied a polder of 200 ha. and one of 1200 ha. They are in most cases larger, but the larger areas are often less interesting due to heterogeneities.
A STATISTICAL ANALYSIS OF THE DIFFERENCES BETWEEN PRECIPITATION AND EVAPORATION IN THE NETHERLANDS

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INTRODUCTION

In elaborating problems in water management, data on the frequency distribution of precipitation are often used. In that case only a part of the climatic factors, affecting problems in hydraulic engineering are taken into account however.

A more complete description of the climate in a water balance is obtained by evaluating the evaporation as well. In the same way as up to now has been done for the rainfall alone, the difference between rainfall and evaporation can be integrated in a frequency research. It will then be possible to determine with greater precision the frequency of the precipitation (respectively evaporation) surplus.

In the Netherlands such an inquiry has been set up for one of the southern provinces, in which use was made of the 10-days total of the measured precipitation \( R \) and the evaporation \( E_0 \), which was determined with PENMAN's formula as a starting-point. The difference between precipitation and evaporation was calculated according the formula \( R - xE_0 \), in which \( x \) is the reduction factor for \( E_0 \).

As variable factors, the following were included in this inquiry:

1. the months of the year;
2. periods of 10, 20, 30, 60, 90, 120 and 180 consecutive days respectively, calculated from the first of each month;
3. the quantity \( R - xE_0 \) in mm. from the years 1933 to 1953 inclusive, for the periods mentioned sub 2 with a value of \( x \) of 0.25, 0.40, 0.55, 0.70, 0.85 and 1.00 respectively;
4. the cumulated relative frequencies of occurrence of the quantities sub 3.

ANALYSIS OF ELABORATION POSSIBILITIES

The factors which were included in the inquiry gave rise to the making and compilation of a great number of diagrams, each of which elucidates a definite facet of the relation between the data. On the axes of a system of coordinates only two variables can be plotted, but in the plane of the coordinates different curves can be drawn for a third variable. The diagram obtained in this way is valid for a specific value of a fourth variable.

Working in this manner, the number of potential permutations for every reduction factor is \( 4! = 24 \). Since there will always be a preference for the factors on the ordinate or on the abscissa and since changing the axes yields...
The monthly totals of $R - 0.7\, E$ for the month April over the years 1933 to 1953 are given as summated relative frequencies. For $R - 0.7\, E > 0$ there is a precipitation surplus, for $R - 0.7\, E < 0$ the absolute value gives the evaporation surplus.

In the elaboration the elementary frequency-polygon of which an example is given in figure 1 has been taken as a starting-point. On a normal probability scale the number of mm. evaporation surplus ($R - 0.7\, E$) has been plotted for a period of 30 days from April 1st.

For the month of February it is shown in figure 2, how the curves for the different periods may be integrated into one figure.

A certain facet of the four-dimensional relation may be inferred from this stereogram for example by application of horizontal sectioning. This has in figure 2 as a result that contour lines (polygons) arise for a probability with a constant level. These polygons may be projected in a graph, which then gives the relation between the number of mm. evaporation surplus and the period length.

It is possible to make vertical sections through the stereogram in the same way (figure 3), which gives polygons for a constant $R - 0.7\, E$. In that case the variables on the axes are the probability and the length of the period.

Instead of the absolute magnitude of the evaporation surplus, the values expressed in mm. in 24 hours can be used in many cases as well. Even though by doing so no new factors are introduced in this investigation, this way of representation may be illuminating in some cases.

**APPLICATIONS OF THE FREQUENCY CURVES**

The broken lines of the frequency polygons (see figure 1) were straightened out by means of flowing curves for which the technique of the intersection-check was adopted. In the procedure followed, it was taken as being essential that local corrections on the original polygon would not result in irregularities in one of the sections. The complete four dimensional model is included in the intersection-check by means of this operation.

The graphs obtained with this method may serve to solve certain problems on the frequency of occurrence of an evaporation- and precipitation surplus. Before applying the graphs the magnitude of the reduction factor to be used in each special case has to be chosen. Furthermore the order of magnitude should
Fig. 2. Three horizontal cross-sections for a 5, 50 and 95% surplus probability respectively, through a collection of frequency polygons on several periods from February 1st onward (Fig. 2 and fig. 3 are both models for February)

Fig. 3. Three vertical cross-sections for a 0, 20 and 50 mm. rainfall surplus respectively, through the same collection of frequency polygons as shown in fig. 2
be known of the maximum moisture deficit which is admissible for the profile and the same applies for the moisture capacity. Besides this, it will be of importance to know what underground drainage- and supply possibilities can occur. The graphs now make it possible to establish a connection between these quantities with the frequencies of the climatic factors e.g., the precipitation and the evaporation. When making improvement plans on land and water management, an appreciation can be obtained about the combination of possibilities which from a technical point of view as well as from an economic one are best to be realized and which at the same time will approach the agricultural desiderata the closest.

In the following only examples of the treatment with the reduction factor $x = 0.7$ will be given.

**APPLICATION ON THE PROBLEM OF THE WATER SUPPLY**

By introducing the moisture capacity of a soil profile, when for the latter is asked what probability there exists of desiccation after a certain amount of time, that series diagrams can be selected in which the probability and the period length are taken as coordinates and each curve in the graphs represents a constant amount of moisture.

Figure 4 gives an example of this manner of representation. When it is assumed that in a profile a quantity of moisture, which the crop is allowed to use, of 120 mm. is available as a supply on April 1st, the profile can compensate an evaporation surplus of the same size without water supply from sprinkling or infiltration. Now, in figure 4 the 120 mm.-curve can be followed and it appears that in 5 out of a hundred years, or once in 20 years, an evaporation surplus of more than these 120 mm. will occur in approximately 70 consecutive days. The longer a period chosen, the larger the probability of the appearance of an evaporation surplus greater than in the case mentioned. The critical position lies at 140 days or almost 5 months, namely the period of April 1st up to and including July with 20 days in August. So in somewhat more than 32 years out of a 100 years or once in 3 years, the profile will be uncapable of supplying the required volume of moisture. In that case more than 1 mm. per day will have evaporated.

Calculated from July 1st, the probabilities of desiccation of the profiles
FIG. 5.
As fig. 4, but now calculated from July 1st

mentioned are much larger. If it is checked how the condition is from July 1st, the quantity already evaporated should be deducted in the first place. There is no saying how large this quantity is, but it may be inferred from figure 4 that from April up to and including June, a median evaporation surplus of 65 mm. will appear. In the above mentioned case the profile chosen as an example will have still available 120-65 = 55 mm. moisture on July 1st. In figure 5 the probability of an evaporation surplus larger than the latter volume of moisture is shown, the probability being largest after well over 50 days and then amounting to 30 %.

This example shows how the course of the evaporation can be followed with the aid of the required diagrams for the specific months.

In the above, the attention has been drawn to the probabilities with which moisture deficits occur. The question of the possibility to cope with these deficits now presents itself.

Without going into the technical aspect of this problem, the frequencies in which the occurring evaporation will be in excess of the volume of water supplied, will be given attention.

An easy way of rendering this problem is a diagram in which on the ordinate R = 0.7 Eo is projected and on the abscissa the period-length. It is now possible to draw lines in such a diagram that represent a constant mean supply in mm. per 24 hours and to establish a relation between them and the frequencies of the evaporation surplus.

A similar representation is given in figure 6. It can be concluded from this graph that with a probability of 25 %, or once in 4 years, an evaporation surplus may be expected of more than 25 mm. for a period of 30 days, starting on April 1st; for 60 days this is more than 55 mm. and for 90 days approximately 100 mm.

The advantage of working on water supply problems with a graph as given in figure 6 can be seen from the following example. If there exists a possibility of supplying from April 1st an amount of water with a maximum of 1 mm. per 24 hours then, over 2 months such an amount of water will be provided, that merely once in 4 years (25 % probability) an evaporation will appear that will
A relation is given for various surplus probabilities (the figures with each curve) between evaporation surpluses and lengths of periods. The dotted line agrees with a supply of 1 mm. per 24 hours.

exceed this quantity. After 90 days however, a moisture deficit will be of more frequent occurrence. Once in 4 years this deficit will be at least 12 mm., that can be determined by measuring in figure 6 the vertical distance between the dotted line and the 25% curve at 90 days.

The interpolating of the value of the probabilities between the lines in figure 6 can not always be done with adequate accuracy. Also, when taking into consideration the effects of irrigation, corresponding with for instance $\frac{1}{2}$, 1, 1$\frac{1}{2}$, 2, etc., mm. per 24 hours, two families of curves have to be compared with each other. This becomes easier if one, starting with figure 4, constructs a new diagram which will show curves of equal quantities, expressed in mm. per 24 hours. This new diagram (figure 7) gives an other kind of representation of the same information that can be obtained from figure 6.

If it is determined how the situation is when calculated from July 1st, one obtains figure 8.
An evaporation surplus with an average of 1 mm. per 24 hours for the month of July is exceeded in approximately 45% of the number of cases, but calculated for 2 months it is less than 30%. In this diagram is expressed the fact, that in the Netherlands the months of August and September are among those which are richest in precipitation while the evaporation is already decreasing in this period. Calculated from July 1st, precipitation surplus occurs after 90 days with a probability of already 50%.

**Applications on Drainage Problems**

Following the diagram on July, the series of diagrams can be continued with the corresponding one of the month of October (figure 9). This graph, concerning the winter months, indicates that now mainly the problem of the precipitation surplus appears. For the month of October there is a probability of 35% of such a surplus of more than 1 mm. per 24 hours, but this probability will reach a maximum of 80% after somewhat more than 90 days. After this period the surplus lessens because now months with a stronger evaporation are involved in the summation, months in which at the same time the volume of precipitation is decreasing.

**Curves for Equal Quantities, Gemert R-0.7, Oct. mm per 24 Hours**
From the diagrams it can be determined how large the amounts of precipitation surplus to be expected are going to be and have to be discharged by artificial means in low lying polder districts. In order to be able to drain away in October, in 10 days time the precipitation surplus occurring in this period with a probability of 20% (consequently once in 5 years), a drainage discharge of 2 mm. per 24 hours would be necessary. That, as a rule, this rate of discharge is taken much higher (viz.: well over 11 mm. per 24 hours) ensues from three facts.

In the first place the surplus probability is frequently taken much smaller than 20%; the occurrence of a condition that a drainage system is unable to cope with the quantities of precipitation surplus is, as a rule, considered permissible only with a much smaller frequency than once in 5 years. According the agricultural investment in a certain area, this may vary from once in 10 or 20 or even more years.

In the second place the demand to be able to discharge the precipitation surplus of 10 days during that period is not put strong enough. Very often there will be the desire of removing the precipitation surplus within already 2 or 3 days. The circumstance that one has to work with at least 10-days periods when calculating the evaporation to obtain the required accuracy, is the cause that extreme cases of precipitation surplus over a very short period of time do not show to a sufficient advantage in the given diagrams.

In the third case it should be pointed out that in the months November and December, with an equal probability and for the same - short - periods, a larger surplus may occur.

**Summary**

The differences between precipitation and evaporation determined per 10-day period over 20 years provided the basis for a statistical analysis of the occurrence of precipitation and evaporation surplus.

In the inquiry, the months of the year, different lengths of periods, the quantity \((R - xE_n)\) and the cumulated relative frequencies were taken as variables.

It is possible to give the relation for each reduction factor \(x\) between this number of variables in 12 different ways. In the diagrams obtained by means of this procedure each time light is cast on another aspect of this relation. It is possible to make suitable selection from the diagrams available both for problems relating to the water supply in periods with an evaporation surplus as well as for problems in which the precipitation surplus is studied. The problems presented can be elucidated and studied now in the most appropriate manner.

**Résumé**

*Une analyse statistique de la différence entre les précipitations et l'évaporation aux Pays-Bas*

Les différences entre les précipitations et l'évaporation, déterminées par dècée sur une période de vingt années, ont fourni les bases d'une analyse statistique de la fréquence d'excès de précipitations et d'évaporation. L'analyse porte sur les variables suivantes: mois de l'année, périodes de différente longueur, la quantité \((R - xE_n)\) en mm et les fréquences relatives additionnées.

Il s'est trouvé possible de reproduire le rapport entre ce nombre de variables de 12 manières différentes pour chaque facteur de réduction. Les figures obtenues de cette façon illustrent chacune un aspect différent de ce rapport. Il est possible de faire un choix approprié parmi ces figures tant pour les problèmes relatifs à l'amenée d'eau dans les périodes à excès d'évaporation que pour les problèmes relatifs aux excès de précipitations, de sorte que les problèmes à résoudre peuvent être exposés et étudiés le plus simplement possible.
ZUSAMMENFASSUNG

Eine Statistische Analyse von Niederschlags- und Verdunstungsüberschüssen in den Niederlanden


Die variabelen Einheiten bei der Untersuchung waren die Monate des Jahres, die Längen verschiedener Perioden, die Menge \((R - \dot{x}E_0)\) in Millimetern und die summierten relativen Frequenzen.

Es hat sich als möglich herausgestellt den Zusammenhang zwischen diesen variabelen Einheiten für jeden Reduktionsfaktor auf 12 verschiedene Weisen darzustellen. In den dabei erzielten Figuren wird immer ein anderer Aspekt dieses Zusammenhanges beleuchtet. Es ist möglich, sowohl für Probleme, die die Zufuhr von Wasser in Perioden mit einem Verdunstungsüberschuss betreffen als für Probleme, in denen der Niederschlagsüberschuss studiert wird, eine geeignete Wahl aus den vorhandenen Figuren zu treffen, wodurch das fragliche Problem auf möglichst einfache Weise erklärt und studiert werden kann.
If it should be asked to what extent the practice of overhead irrigation may benefit from applied soil science, the answer must be either fully positive or mildly negative, depending on the education and training of the person in charge of such operations.

The simplest soil test i.e., the taking of soil samples with the aid of a soil borer to establish the moisture content visually with in mind the alternatives: irrigation at once called for, or irrigation not necessary at all, may after some practice be performed with success by any duly instructed person with a thorough knowledge of the field concerned.

A more intricate type of analysis is based on a judicious use of the pF-curve and a knowledge of the relevant instructions concerning the way to prepare soil samples with a moisture content of known pF by mixing dry soil with water. Here too, estimation of the moisture content of the samples drawn is, either visually or by touch, comparing the artificially obtained moisture conditions in the various samples with the moistness of the natural soil, but in this case the conclusion may be expressed in both moisture content and pF. If the pF is known the possibility exists of estimating the rate of evaporation of the crop with reference to this pF, so the time that will expire before a degree of dampness will have been reached below one does not wish the soil to drop, or before a pF will have been reached one does not want to exceed, may be tentatively predicted. This method is already in a lesser degree confined to a single type of soil profile, but it requires the availability of pF-curves for all strata of the profile under investigation.

Really large-scale advisory operations call for a comprehensive range of pF data for each profile and a soil map showing extent and limits of the various profiles.

A step further again may be achieved by those field officers who, for certain regions and on the basis of visual observations, are capable of drawing a pF-curve from the lithologic data supplied by examining the soil profiles. Regional surveys covering such data as influence of silt and humus content, relative coarseness of the sand and similar information on the shape of the pF-curve, may enable irrigation experts with an adequate training in soil engineering to set up a tentative pF-curve. If now the moisture content of the soil is determined by inspection, it is possible to establish at what level the moisture content may be expected to range between the wilting point and the field capacity.

A closer consideration of the methods to obtain an adequate advice on irrigation available to date reveals them to consist of three stages. The first of these covers an estimation of the moisture content, the second the additional estimation of the corresponding pF and the third the estimation of the relevant rate of evaporation.

The pF alone may provide indications on the desirability of instantaneous
irrigation. The relation between the established moisture content and the lowest admissible one divided by the evaporation rate – deduced from the pF – may indicate by how many days irrigation may eventually be safely delayed.

The first stage represents the development of a more accurate estimate of the moisture conditions with respect to moisture holding capacity and quantity of moisture. The second stage deals with a characterization of the milieu of the crop with respect to its requirements regarding the availability of moisture. The third stage investigates the length of time in which both the drop in moisture content per layer and the depth of the desiccated zone will have reached a limit that, from the agricultural point of view, must be considered as representing the limit of the admissible loss of moisture from the profile.

In considering the proper function of soil science in this vast field, taking into account the aspects which are still lagging behind and consequently deserving more attention, and the present-day trend of research, it will in the first place be necessary to provide a delineation of limits within which this knowledge is to be applied.

The experimental farm and the large estate, being both of them assured of adequate scientific assistance, may be safely left to themselves. Problems of quite a different nature in advisory work present themselves, however, in the case of large areas with the usual variation in soil profiles. These areas may comprise some thousands of irrigated fields belonging to a large number of small holdings. Any assistance, in as far as management of sprinkler installations is concerned, can in that case of necessity no longer be on an individual scale. In such a case more general methods must be resorted to, such as the use of pF-curves constructed on the basis of visual soil estimates, the estimation of moisture contents through comparison with standard samples, etc.

At this stage the question arises, which part of this chain of considerations and procedures may already today be made to yield tolerably accurate results and which part is sufficiently tried out and studied, requiring only a very restricted amount of scientific attention.

On the other hand it ought to be possible to point out the weakest link with the greatest error, as this would enable investigators to concentrate their joint efforts on its improvement or solution.

The requirements of the crop

Present-day research into the moisture requirements of the crop is done mainly along two lines. Partially, attempts are made to characterize the relative humidity of the soil on the basis of the pF. Their aim is, to determine the pF at which the largest yield is obtained, as well as the magnitude of possible declines in the yield ascribable to moisture conditions which deviate from the optimum value of the pF. This should be done for various crops and types of soil. Figure 1 provides an example of such a study. A striking feature in this diagram is the occurrence of the same relation between crop yield and pF for the different soil types and crops. The number of tests in this field of study the world-over, has probably been so far not very high. However, what research there has been should be enough to provide us with an idea of the nature of the result to be expected. The probability exists that at the optimum pF the soil moisture content falls below the field moisture content (see figure 2) so in the event of field irrigation tests, yields are usually found on that part of the curve where
The fresh yields of various crops react in an identical manner to the pF of the soil, quite independent of the soil profile. After Bierhuizen, the yield declines through desiccation, whereas, the field moisture content never reaches the level required for the optimum yield. The soil cannot hold that quantity of water against gravity.

A true optimum in production with respect to the factor water is in all probability not entirely attainable through the expedient of overhead irrigation alone, it being impossible to get beyond conditions which are just somewhat too dry.

In case of a prevailing water scarcity, watering will be started only at a high pF, whereas with the availability of cheap water this will already be done at a much lower pF. Watering of expensive crops, including horticultural crops, will, even on soils with a relatively large moisture holding capacity, start earlier than will be the case with the less expensive cereal crops. The point of lowest admissible moisture content will therefore have to be fixed separately for each individual case, the shape of the growth reaction curves must have been determined in advance however. This doubtless calls for further research, though it does not seem to represent the worst lacuna in our present knowledge.

Another direction of research operates with evaporation as a standard for...
growth. The simple relations found in this way are certainly very attractive (see the figures 3 and 4). This type of research, however, is preferably concentrated on evaporation as observed over longer periods of time and this, on account of the relatively short periods involved in sprinkling, tends to lay considerable difficulties in the way of investigations concerned with the nature of critical periods or preferential moments of application of water occurring during the growth process, where research has shown sudden changes in reaction of the crop. It may be presumed that research of this type – even though it is still in its initial stage – may soon yield practical results and that at the cost of a comparatively inconsiderable amount of work.

**DETERMINATION OF MOISTURE CONTENT**

The energy with which investigators have attempted to design a convenient method for determining the moisture content of the soil is truly amazing. The number of methods now available certainly runs into scores, varying from methods which are complicated and hard to perform to the extremes of simplicity. Nevertheless they all are apparently still too intricate to be useful in practice. As to the standards of accuracy to be achieved with them, these too, in view of the important variations in moisture content in the soil profile from place to place, are lower than is generally assumed.

Any study of this type must invariably make use of a large number of samples. For the purpose of soil analysis a wide use has so far been made of estimated soil data, whilst also the accuracy with which the soil moisture content can be estimated today is such, as to make it a matter of some surprise that no trouble
has been taken by scientists to develop any methods for estimation of the moisture content by eye or hand and also that the method of determining the moisture content by estimation has found so few adherents.

In attempting to deduce from these moisture content data how much water the plant is capable of extracting from a given soil profile or, for that matter, how much moisture is still to be added to such a profile, some recent results of study present themselves for consideration which are still rather less well-known. The rate of moisture extraction tends to decrease with depth. It is customary to assume a certain depth for the root zone of any crop and furthermore to suppose that of the total amount of moisture available for the plant in all layers, the part that is present in the surface layer is taken up in its entirety, whilst that present in the lowest layers is left untouched and that on the average from each layer a share proportionate with its depth is removed by the roots. In homogeneous soil profiles this would come to half the amount of moisture which should be available, if all the water above wilting point is computed from the pF-curve.

The possibility of supplementation of the moisture content is computed by subtracting the moisture content as observed in the field from the moisture contents obtained from the pF-curve, taking as a maximum the moisture content at field capacity. But here too, a large number of different influences makes itself felt, such as air inclusions, irregular moisture distribution – with the result of subsoil drainage in the presence of non-saturated sections – whilst finally more moisture may be temporarily retained by the soil, which will be available to the crop during the length of the period required for the water to sink beyond the reach of the roots. With a regular use of the field irrigation system, or in the event of casual natural showers, this extra amount of moisture may be not inconsiderable.

Laboratory tests by YOUNGS (figure 5) tend to show that a rate of infiltration equal to some 10% or 20% of what will be transmitted through the soil at a fall of 1:1, will fill up a major share of the available air volume and increase the moisture content, as prevailing during conditions of equilibrium, by a fair
Samples repeatedly taken show from which layers moisture is derived by the crop as well as the rate at which soil moisture is consumed in the process. After SCHUURMAN, a wide fund of material has been collected on this subject, from which a clear outline of the laws governing the rate of infiltration into the capillary zone, the elimination of moisture from the soil profile and the evaporation rate of crops may be obtained.

The aspects of the problem presented by the amount of moisture available for consumptive use, have for some time been the subject of thorough investigation by a large group of workers, who all aim at a deduction of the moisture distribution pattern from the non-stationary capillary flow, the pattern that will, under certain marginal conditions, arise through the influence of moisture extraction by the crop or supplementation of the moisture content through irrigation and sprinkling.

Since in the presence of unsteady conditions of capillary flow, amounts of moisture are concerned which may be far in excess of the quantities arrived at by computation from pF-curve and plant root depth, a field of investigation which will prove to be of decisive importance is undoubtedly opened up. It is, however, to be anticipated that the difficulties that will have to be overcome will be formidable. This would seem to point to the desirability of the use of a parallel statistical research, to be carried out in conjunction with the fundamental investigation, so the trend and the magnitude of the forces at play may be already known to some degree even before the final difficulties of the physical–mathematical stage will have been fully mastered.
FIG. 8. A relation appears to exist between pF-curve and humus and silt content, which may be deduced from the data for a number of samples analysed for the pF.

Moisture tension and soil moisture content

For advisory work it will be necessary to derive the pF from estimated moisture contents. As the, before mentioned, more refined type of research is making a large use of the moisture tension of the soil and for a simpler type of interpretation the pF-curve may be expected to become increasingly indispensable also, it will be impossible to avoid the complication of the conversion of moisture content into moisture stress. Henceforward one of the aims of future work will mainly consist in the determination of many hundreds of pF-curves. Both from a technical and a financial point of view this will not be a simple matter.

It seems therefore more probable that in future, scientific advice on irrigation problems will become based increasingly on some type of hydrological soil mapping. One may imagine that the individual statistical units involved will be defined by hydrological standards and will be delimited in the field with an accuracy that is compatible with the visual method of estimation. These hydrological units will have to be calibrated against the corresponding pF-curve and other physical constants that are possibly available.

Yet another, certainly also attractive, possibility is to set up the pF-curve as a function of the silt and humus content and further properties of the soil. For each field a curve may then be constructed with the aid of these properties. A relevant example for clay soil is provided in figure 8. A closer study of those soil constants that lend themselves best as a characteristic of the hydrologic properties might be of major importance. Such characteristics will enable one to obtain a better grasp on the nature of the relationship between these soil constants and the pF-curve. Little mention has so far been made of this type of investigations in international literature, yet this would be of the greatest value for irrigation engineering.

Evaporation

Research into the cause and effects of evaporation has been enormously stimulated by the investigations of Thornthwaite, Penman, Haude, Turc and others. To such an extent, that it has acquired a quite different character in
a comparatively short time. As far as sprinkler-type irrigation is concerned, it may be safely stated that future studies will be concerned chiefly with the influence of evaporation on soil moisture conditions and on the growth of the crop.

Investigations with the use of a lysimeter, by Makkink (see fig. 9) and field studies by Wind (see fig. 10), have demonstrated a distinctly decreased evaporation with an increase in pF. Actually, if one would like to establish the total amount of evaporation for any given day, pF-determinations or estimations might give a solution. But here too, the rule holds good that a solution for any given test-field is not necessarily a sound over-all solution for general practice. It seems probable that the summation of the daily evaporation values could preferably be achieved by calculation and not by moisture determination. To
An analysis of groundwater depth may provide an insight into many aspects of the water balance and the moisture content of the soil to exemplify this, the amount of discharge and the rate of moisture depletion from the profile are indicated.

In reviewing the various degrees of accuracy attainable in computing the rate of evaporation by the various methods now available, it would seem that Penman’s evaporation formula is more than sufficiently accurate, even though the error of the reduction factor is slightly on the high side. For the purpose of a single irrigation the latter inaccuracy is still well within admissible limits, but taken over the entire irrigation season, this error will tend to add up, so after several irrigations it would be beyond the capacity of any continuous moisture registration of this type to predict the time of the next irrigation with a reasonable measure of accuracy. In spite of this, the keeping of moisture records computed by adding up daily rainfall and evaporation data, will be of importance in many cases since a correct and regular evaluation of the current water balance, however simple, will always be hard to achieve if a large number of irrigated plots should be concerned.

Finally the attention should be drawn to the influence of natural rainfall, which will tend to provide complications if occurring immediately following a period of artificial rain. Part of this natural rain water will drain away into the subsoil, but the laws governing this type of drainage are at the moment not entirely clear. The simple notion of the soil first becoming filled to saturation and the excess amount draining down into the subsoil is, as pertinent investigations have demonstrated, not correct. Actually, water already starts seeping away into the lower strata when the maximum saturation point of the surface soil has not yet been reached by a far stretch (see fig. 11). To obtain a good insight into the moisture balance of soil profiles with a view to irrigation, it would therefore seem to be of the highest importance that the discharge of moisture into the deeper strata of the subsoil should equally be made the subject of exhaustive investigation. Soil science may provide a contribution in this respect by supplying a clearer picture of the maximum water-holding
capacity of a given soil profile, since the laws governing this factor are obviously more complicated than has been supposed so far.

**TRENDS IN SOIL PHYSICS WITH RESPECT TO IRRIGATION**

If one is to set oneself a purpose in the study of irrigation research, it would seem to be relevant to aim at a standardized method of computation, by means of which it would be possible to establish day-by-day alterations in the moisture balance for a given number of soil types and also in the amounts of artificial rain that would be required, whilst duly accounting for the naturally occurring precipitation. To this end a few test-fields should be available, for the purpose of regularly checking up with the results of these computations. In this manner it would be possible to give an irrigation advice which might serve as a guide for a large number of farms. This would appear to provide a firmer basis for a rational irrigation policy for each farm, than would be achieved if the performance of moisture studies or estimates were to be left to the farmer's own initiative.

With a view of putting this type of research on a firmer basis and, more particularly, to get a better insight into the various soil characteristics, water balance studies should preferably be carried out on a world-wide scale and with sufficient precision. This would certainly be invaluable since climatological variations, particularly in the smaller countries, would be too insignificant to warrant adequate over-all results, whilst the long periods of time spent in waiting for an extremely wet or an extremely dry year would tend to render research of this type too laborious and too expensive.

A nucleus of a similar type of international collaboration is already available in the form of the "Working Party on Supplemental Irrigation" of the FAO, which might issue the necessary directives with regard to this kind of studies. Equally important results might be expected to follow from combined investigations concerning root growth and the progressive depletion of moisture from the soil. Both the very large number of crops and the equally wide variation in soil types will tend to make such a study a major task, which might be advantageously tackled at various different places simultaneously and after that be integrated by suitable mutual consultation.

Much indeed is still to be done in the field of soil engineering that will give the so very necessary support to better moisture provisions for the crop.

May, therefore, full attention be given to international, collectively organized, irrigation research.

**RÉSUMÉ**

**Pédologie et Irrigation par Aspersion**

L'agrologie pourra apporter un appui considérable à la bonne gestion des systèmes d'irrigation par aspersion.

Il est de haute importance de développer les recherches concernant les exigences des cultures pour ce qui est de l'humidité et d'approfondir l'étude relative à la mesure dans laquelle la plante est capable d'épuiser l'eau retenue dans le profil. Cette étude porte sur les constantes d'humidité permettant de représenter le mieux ou le plus simplement possible les réactions de la culture. Sont étudiés le pF (voir fig. 1 et 2) et l'évaporation (voir fig. 3 et 4). L'une et l'autre méthode permettent d'obtenir de bons résultats. Les connaissances à ce sujet pourront être considérablement approfondies par une étude concernant la soustraction d'eau par rapport à la profondeur de la couche et à la période de l'année (voir fig. 7). Vu la grande variété de
types de profils, de climats et de culture, une étude de ce genre aurait grand avantage à être exécutée en coopération internationale. Les résultats d’une telle étude permettront d’obtenir une vue d’ensemble sur le rendement en fonction du climat et de l’humidité du profil et sur l’effet produit par l’irrigation par aspersion.

Afin de donner à ces connaissances une utilité pratique, il faudra pouvoir déterminer par une méthode simple et rapide la teneur en humidité du profil. De plus, il faudra pouvoir déterminer la tension d’eau, le tracé du pF et la quantité d’eau pouvant être absorbée par la plante pour une teneur d’eau déterminée. Enfin, il faudra pouvoir prédire l’évaporation par l’intermédiaire des plantes pour être à même de calculer combien de jours le stock d’eau pourra encore suffire à la culture. Dans les grandes exploitations et les stations d’essais à grandes ressources scientifiques, ces problèmes pourront être résolus. Il faudra chercher des voies particulières pour l’instruction en masse des nombreuses petites exploitations. Malgré l’existence d’un grand nombre de méthodes, la teneur en humidité ne peut encore être mesurée aisément. A ce sujet, les meilleurs résultats semblent pouvoir être obtenus par la comparaison à des échantillons d’humidité artificiels ou par une évaluation visuelle directe. Lorsqu’il s’agit de quelques lots de terre, la détermination du tracé du pF ne présente pas de grandes difficultés. Mais si l’on veut fournir à partir de ce tracé du pF des conseils se rapportant à de grandes étendues, la détermination de ces tracés devra être liée au lever agrologique. La teneur en limon et en humus, ainsi que d’autres propriétés du sol permettent de prédire le tracé du pF (voir fig. 8).

Il faudra encore bien quelque étude pour déterminer à base de ces données la quantité d’eau accessible aux cultures, puisque l’étude de courants d’eau capillaire non-stationnaires a permis de constater que le sol peut retenir momentanément une quantité d’eau supérieure à sa capacité de rétention et que, par cette quantité d’eau supplémentaire, la plante peut disposer pendant un nombre de jours non négligeable d’une plus grande quantité d’eau qu’en présence de la quantité d’eau emmagasinée à l’état stationnaire. Les figures 5 et 6 en donnent une idée.

L’étude de l’état d’humidité du sol et de l’évaporation conclut la série d’exposés. On sait déjà que l’évaporation d’eau diminue à mesure qu’augmente la tension d’eau. Les figures 9 en 10 forment l’illustration de ce fait. Il doit cependant y avoir encore d’autres facteurs influençant l’évaporation et sous ce rapport, il serait important de procéder à une étude de tout l’équilibre hydrologique. La figure 11 montre une partie des résultats d’une telle étude de l’équilibre hydrologique. Une étude pareille semble être plus importante pour l’obtention d’une vue d’ensemble des conditions hydrologiques et, vu la grande variété d’états du profil, de cultures, de climats et de systèmes hydrologiques, ne pourrait probablement donner des connaissances assez larges que si elle était entreprise en collaboration internationale. Comme centre de recherches, le „Working Party on Supplemental Irrigation“ de la FAO semble être l’organisation indiquée.

ZUSAMMENFASSUNG

Bodenkunde und künstliche Beregnung

Die Bodenkunde wird einer guten Verwaltung der künstlichen Beregnung in erheblichem Masse Vorschub leisten können.

Wenn man diese Kenntnisse praktisch verwerten will, so wird es notwendig sein den Feuchtigkeitsgehalt des Profils schnell und einfach zu bestimmen. Weiter wird es erforderlich sein die zu diesem Feuchtigkeitsgehalt gehörende Feuchtigkeitsspannung, die pF-Kurve und die für die Pflanze aufnehmbare Feuchtigkeitsmenge bestimmen zu können. Schliesslich sollte man die Verdunstung durch das Gewächs voraussagen können. Für grosse Betriebe und Versuchsfelder mit reichlicher wissenschaftlicher Unterstützung werden sich diese Probleme schon lösen lassen. Für die Aufklärung in grossem Umfange vieler kleinen Betriebe wird man besondere Wege suchen müssen.

Der Feuchtigkeitsgehalt kann trotz der vielen verschiedenen Methoden noch nicht auf einfache Weise bestimmt werden. Es scheint, dass durch Vergleichung mit künstlich zusammengesetzten Feuchtigkeitsmustern oder durch unmittelbare visuelle Schätzung vermutlich noch die besten Ergebnisse erzielt werden können.


**DISCUSSION**

CZERATZKI:

In Fig. 2 wird „field capacity“ für den Sand- und den Tonboden einheitlich bei pF 2,4 ange nommen. Eigene Untersuchungen haben gezeigt dass gewisse Unterschiede zwischen den Bodenarten zu bestehen scheinen und zwar tritt die „field capacity“ bei Sand bei niedrigeren Werten ein als bei Ton und schluffhaltigen Böden.

*Answer:*

We found in literature the differences in field capacity mentioned but I do not quite remember in which direction they pointed. I wanted to stress with fig. 2 that the optimum for plant growth is found at a lower pF than that concurring with field capacity and this remains also true, according to our experience, for light soils if we stick to the definition that field capacity is the water content that remains in a deeply drained soil after free drainage.

ASLYNG:

Concerning fig. 3, I believe an other limiting factor is keeping the yield down. Fig. 9 to 10: I am inclined to think that the actual evapotranspiration is reduced more rapidly for lysimeters than for field crops.
We need more information about root depth and intensity as a function of soil aeration. It is important to have deep rootings to reduce the requirements for irrigation.

**Answer:**

The curve in the scatter diagram of fig. 3 depicts the law of the limiting factor. The horizontal part is the limitation due to another factor.

The difference between evaporation in lysimeter tanks and the free soil depends on the water supply in both instances. In the lysimeters of MAKKINK the water was supplied to keep the groundwater constant. Here the reduction of the evaporation at higher soil water stresses, due to a higher soil watertable, might be less.

We see research of root depth and water relations, as given by Dr. SCHUURMANN, as a subject of utmost importance and should particularly appreciate international cooperation in this respect.

**LYSHEDE:**

Though the fig. 11 shows that discharge takes place before field capacity is reached it also shows that only a small part of the rain is drained-off when the soil moisture is below field capacity.

**Answer:**

The point I wanted to stress is, that we are simplifying the moisture relations in the soil too much, if we take that drainage only occurs if the moisture content in the profile agrees with the equilibrium content as given by the pF-curve. The errors, due to such simplification may amount to 50 to 100 mm. and must not be neglected.

**HALLGREN:**

The water capacity is no fixed value. It is greatly depending on the groundwater table. Especially on sandy soils there will be a great difference between the „field capacity” determined in the laboratory on short soil columns (10 to 20 cm.) and the field capacity determined in the field when the groundwater lies e.g. at 2 m. depth. In practical irrigation it is of course the conditions in field that are of primary interest.

**Answer:**

The point which I wanted to stress is that according to YOUNGS, even in deep profiles the field capacity is not a well defined quantity, due to hysteresis. The mentioned effect of the soil watertable is indeed an effect that is too often overlooked in practical application of the theory of the water in the soil.
In Finland there is usually a dry period in the late spring or early summer that limits the growth of plants. It is thus possible for irrigation to increase yields, even though in regular farming up to now it has not given economically profitable results. In the cultivation of fruit and vegetables, however, the results obtained have been more advantageous.

**IRRIGATION METHODS**

Of all irrigation methods the sprinkler system is the most used, but subsoil irrigation combined with subsoil fertilization is also gaining ground in practice. The following are the results of experiments where the latter method was used. The investigation was carried out in South-West Finland near Turku, where the amount of precipitation between May and September in the experimental year 1956 was 230 mm. The distribution of rain during these summer months is given in fig. 1. The experimental terrain used was a row of Melba apple trees growing in a heavy clay soil (>80% clay). The soil under the whole row of trees had been covered with straw during the previous winter. Irrigation was carried out by means of a so-called subsoil irrigation-fertilizing apparatus to a depth of approximately 50 cm. in 5 to 6 places for each tree. The water pressure was 2.5 to 4.0 atmospheres and the amount of water used at each irrigation time was approximated to correspond to 40 mm. of precipitation.

Soil moisture tension or the equivalent negative pressure to which matter must be subjected in order to be in hydraulic equilibrium, through a porous permeable wall, with the water in the soil is given in mm. Hg, i.e. as direct readings of the mercury vacuum-gauges of the tensiometers used. The porous cups of the tensiometers were placed at depths of 15, 35 and 75 cm. from the soil surface and the distances between the tensiometers were approximately 50 cm. The tensiometer readings were taken at 8 a.m. and 8 p.m. and the air accumulated in the tensiometers was removed after each reading.

**IRRIGATION IN A FALLOW SOIL**

Fig. 1 (the soil moisture tension curve in a non-irrigated fallow soil) shows the fluctuation of soil moisture curves affected only by natural factors.

After removing the straw cover in the beginning of June the soil moisture tension increased very rapidly in the topsoil (15 cm.) to over 700 mm. Hg, which is the upper limit of the measuring range of the tensiometer. The tension curves of the subsoil layers (35 and 75 cm.) reached the same level approximately three weeks later. In the beginning of July the whole soil profile was already so dry that two days rain (8 and 14 mm.) could not decrease the soil moisture tension below 700 mm. Hg. The influence of this rain, however, is to
Fig. 1.

Fig. 2.
be seen from the curves of all the other treatments in the experiment (figs. 2 to 4).

The rainy period which began at the end of July caused the first fluctuation in the soil moisture tension of the topsoil layer. It also had a slight influence on the tension at the 35 cm. depth but no measurable effect at the 75 cm. depth. After 20th August there was enough moisture in the soil to lower the tension to minimum in the topsoil layer and the upper subsoil layer. During the relatively dry September the tension in these layers, however, again exceeded 700 mm. Hg. In the deeper subsoil layer no measurable changes in soil moisture tension were caused by the rains in the later part of the summer.

The three subsoil-irrigations (of 40 mm.) in a fallow clay soil produced the changes in soil moisture tension shown in fig. 2. It should be noted that during the dry period (until the 24th of July) the soil moisture tension in the topsoil layer increased much more rapidly than below this layer and the increase was slowest in the deeper subsoil layers. During the late summer the situation reversed itself. Three irrigations during the early summer maintained the soil moisture tension, in general, within the measuring range of the tensiometers and kept the deeper subsoil layers so moist that the rains in the late summer clearly affected their soil moisture tension. It should also be noted that the soil moisture tensions in the irrigated and non-irrigated fallow soils were nearly equal at the end of September.

IRRIGATION THROUGH STRAW COVER

Subsoil-irrigation experiments were also carried out simultaneously in a soil covered with straw. The straw cover alone (fig. 3) decisively affected the moisture tension in the deeper subsoil, which in the early summer dried a little more slowly, became wet soon after the saturation of upper subsoil layers (August 20) and then remained wet until the end of September or until the autumn rains. The cover also prevented the drying of the uppermost layers during the relatively dry September.
Two irrigation times (fig. 4) kept the soil under the straw cover wet. It can be seen that the soil moisture tension in the topsoil layer no longer tended, to any noteworthy degree, to increase from its minimum after the rainy days in the beginning of July. In the case of the deeper subsoil the increase was slow and reached only a little over 300 mm. Hg tension before the decrease caused by the rains in the late summer. In the straw covered soil, the soil moisture tension only fluctuated markedly in the upper subsoil layers, which may be due to the consumption of water by plant roots.

Conclusions

The main results of the study are as follows. Under Finnish conditions soil drainage in early summer is often too effective and disturbs the growth rhythm of fruit trees, thus indirectly decreasing their winter resistance.

The drainage of a fallow soil goes to a relatively great depth and subsoil irrigation carried out in early summer has little or no influence on soil moisture tension at the end of September.

Straw mulching preserves the moisture of subsoil from evaporation and, especially in autumn keeps the whole soil profile in moist condition. Subsoil irrigation of a straw-mulched soil is very effective.

The effect of the even condition of moisture during the whole growing season and the influence of subsoil irrigation on the development, yields and winter resistance of fruit trees in Finland are very shortly to be investigated.

RÉSUMÉ

De la tension de l’humidité du sol dans les vergers irrigés en profondeur

Une enquête a été faite dans le Sud-Ouest de la Finlande au sujet de l’influence de l’irrigation en profondeur sur la tension de l’humidité dans un sol argileux dur. On a pu ainsi déterminer les variations dans l’humidité du sol et choisir les dates les plus favorables à l’irrigation. L’irrigation fut exécutée au moyen d’un appareil d’irrigation fertilisante souterraine et à une profondeur de 50 cm environ.

Les faits principaux suivants ressortent de cette enquête.
Dans les conditions existant en Finlande l’assèchement est souvent trop fort au début de l’été, ce qui est nocif au rythme de croissance et particulièrement à celui des arbres fruitiers. Indirectement cela diminue leur résistance au froid pendant l’hiver.

Les terres restées en friche sèchent à une profondeur relativement grande sans que l’irrigation en profondeur exécutée au début de l’été ait influencé la tension d’humidité du sol en septembre.

Le "mulching" avec de la paille empêche l’évaporation de l’humidité en profondeur et conserve, en particulier en automne, l’humidité dans toutes les couches du sol. L’irrigation en profondeur est particulièrement efficace dans un sol recouvert d’un paillis.

L’incidence d’une humidité égale pendant toute la période de végétation et d’autre part celle de l’humidité du sol en automne sur le développement des arbres fruitiers, leur rendement et, ce qui est particulièrement important pour la Finlande, sur leur résistance au froid, est en voie d’investigation en Finlande.

ZUSAMMENFASSUNG

**Feuchtigkeitsspannung in einem tiefbewässerten Obstgarten**


Die wichtigsten Ergebnisse sind:

Unter Finnländischen Verhältnissen ist die Dränung des Bodens im frühen Sommer oft zu stark und demzufolge wird der Wachstumsrhythmus der Obstbäume gestört und die Frostresistenz im Winter verringert.

Die Dränung einer Brache geht bis in den großen Tiefe hervor und Untergrundbewässerung im frühen Sommer hat am Ende September keinen einzigen Einfluss mehr auf die Bodenfeuchtigkeitsspannung.

Eine Strohdecke verringert die Verdunstung des Bodenwassers und hält, speziell im Herbst, das ganze Bodenprofil im feuchten Zustand. Untergrundbewässerung eines derartigen be deckten Boden ist sehr wirksam.

Die Wirkung einer konstanten Bodenfeuchtigkeit während der ganzen Wachstumsperiode und der Einfluss der Untergrundbewässerung auf Entwicklung, Ertrag und Frostresistenz von Obstbäumen werden in der nahen Zukunft in Finnland untersucht werden.

**DISCUSSION**

**Kalisvaart:**

a. Why do people not use sprinkling irrigation instead of your method of subsoil irrigation?
b. Can there be found different names for the different kinds of subsoil irrigation?

*Answer:*

a. Deep irrigation of this type is in Finland very new, it has been tested less than 10 years.
The purpose is 1) to protect water against evaporation, 2) to keep the temperature from decreasing, 3) to fertilize with irrigation to the middle of the root system at the right time, 4) keep the soil surface dry, 5) not to give water the grasses do not like and 6) get higher grade apples.
b. Irrigation by groundwater control and subsurface irrigation.
Although it is well known that a crop takes up water from the soil, it is probably less known from which layers this water is withdrawn. CONRAD and VEIHMEYER (1929) found a relation between the amount of roots of Sorghum and the water content of the soil at a distinct moment. The present author has made an attempt to study the root development of two crops in two different profiles, and the desiccation of several soil layers during the whole growth-period of these crops.

For this purpose, in 1956 an experiment has been performed with spring wheat and perennial ray grass upon profiles consisting of a top soil of light marine clay of 25, 50 or 75 cm. and a sandy subsoil of 75, 50 or 25 cm. respectively. A number of uncropped profiles were included (fig. 1). These profiles were built up artificially by careful filling in concrete tubes with a height of 100 cm. and an inner diameter of 30 cm.

The density of the subsoil was about 1.45. This is much lower than VEIHMEYER and HENDRICKSON (1948) found to impede root penetration. The subsoil sand was mixed with 0.8 g. lime per kg. moist soil. The pH-KCl was made approximately 5.0 in this way.

In order to vary the amount of roots in the soil without changing the physical

![Diagram](image-url)
conditions, half of the profiles were given a fertilized subsoil, by mixing it with 0.07 g. N, 0.1 g. P₂O₅ and 0.15 g. K₂O per kg. moist soil (Goedewaagen, 1932). The fertilizers used were ammonium nitrate, superphosphate and potassium sulphate. The subsoil in the other profiles was not fertilized.

The water table was fixed at 90 cm. below soil level. This was verified regularly. In case the water level was too high due to rainfall, the superfluous water was pumped out. In the reverse case water was supplied. These amounts of water were measured (fig. 6).

For the determination of the amounts of roots in the soil layers at distinct moments, a periodical sampling was carried out. Simultaneously the water content of these samples was determined by drying and weighing. Afterwards the pH-curve of both soils was determined, showing that the water content in the clay at pH 2 was about 26 %, at pH 4.2: 8 %; in the sand at pH 2: 8 %, at pH 4.2: 1 % (percentages of dry weight of the soil). Moreover the oven dry weights of the tops of the plants were determined.

Each profile obtained a top soil dressing of ammonium nitrate, superphosphate and potassium sulphate in amounts that depended upon the height of the clay layer. These amounts were calculated in kg/ha:

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>P₂O₅</th>
<th>K₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 cm. loam upon sand</td>
<td>60</td>
<td>80</td>
<td>120</td>
</tr>
<tr>
<td>50 &quot; &quot; &quot; &quot; &quot; &quot; &quot; &quot; &quot; &quot; &quot; &quot; &quot; 50</td>
<td>50</td>
<td>70</td>
<td>100</td>
</tr>
<tr>
<td>75 &quot; &quot; &quot; &quot; &quot; &quot; &quot; &quot; &quot; &quot; &quot; &quot; &quot; 45</td>
<td>45</td>
<td>60</td>
<td>80</td>
</tr>
</tbody>
</table>

**Results**

a. Growth of the crop

The seeds were sown on April 4 and had germinated in the end of April. The first ears of the spring wheat appeared on June 22; on July 2 the whole crop had formed ears. Flowering occurred some days later. The ripening of the wheat started July 27; on August 20 the whole crop was mature. The growth was therefore very regular, as was the case with the perennial ray grass (fig. 2).

The first differences between the profiles with fertilized and unfertilized subsoil could be observed on June 12 in the wheat and on July 3 in the ray grass. Later these differences became even more significant.

Only small mutual differences were present in the oven dry weights of the tops of the profiles with unfertilized subsoil. These may be attributed to the different amounts of topsoil dressing. Much greater differences were found between the profiles with fertilized subsoil, where the highest yield was obtained from the profile with 25 cm. loam. This was evidently due to the subsoil fertilization. Large differences were found between the corresponding profiles with and without subsoil fertilization, in favour of the first.

b. Root development

The root weights were determined in soil cores with a height of 10 cm., taken with an auger having a diameter of 7 cm. (Goedewaagen, 1948). The samples consisting half of sand and half of loam were divided in these two
Dry weights of the tops

Perennial ray-grass 1956

Spring wheat 1956

FIG. 2.

parts. Later the results of several layers were added up. These data are given in the figs. 3, 4 and 5.

From fig. 3 it appears that the total amount of roots of spring wheat in the profiles with unfertilized subsoil had already reached its maximum at about the 12th of June. This was shortly before the ears became visible. Similar results were already found with cereals by SCHULZE (1906), KÖNEKAMP (1953) and GOEDEWAAGEN (unpublished data). The maximum was not influenced by the profile. After the 12th of June the amount of roots decreased, especially in the subsoil, although there were some irregularities.

On June 12 the roots already deeply penetrated into the sandy subsoil. The relatively highest amount of roots was, however, developed in the clayey subsoil of the profile with 75 cm. loam. Further it was clear that by far the greatest amount of roots was formed in the toplayer of 0 to 10 cm.

The maximum amount of roots in the profiles with fertilized subsoil was reached on July 3. At that moment the ears had already been formed. After July 3 the amount of roots rapidly decreased. There were only slight differences between the maxima in the different profiles, although the smallest amount was found in the profile with 75 cm. clay. The maxima were considerably higher than those found in the unfertilized profiles.

FIG. 3.
In these profiles the roots penetrated deeply into the subsoil sand too. The amount of roots in the top soil and in the sand of the fertilized profiles with 25 and 50 cm. loam exceeded that of the unfertilized ones.

The total amount of roots of the perennial ray grass in the profiles without subsoil fertilization increased until the end of the experiment in November. There were again only small differences between the profiles (fig. 4). At the time of the first sampling, when the length of the leaves was about 15 cm. the roots penetrated already to a depth of 70 cm. The amounts of roots in the subsoil were at that date, however, exceedingly small but they increased rapidly so that finally rather important quantities of roots had been developed in the subsoil.

The root development in the fertilized profiles resembled that of the unfertilized ones (fig. 5). Again the total amount of roots increased to the end of the experiment. Ultimately, only the amount of roots in the profiles with 25 and 50 cm. clay exceeded that of the corresponding unfertilized profiles. The profiles with 75 cm. loam showed the reverse. These differences were principally found in the subsoil. The root development in the subsoil took place in the later period of growth, similar to that in the unfertilized profiles.

A comparison of spring wheat and perennial ray grass did show that there were important differences in root growth of these crops:

1. Root growth of spring wheat attained an early maximum, the root growth of perennial ray grass continued until November.
2. The ultimate quantity of roots of perennial ray grass exceeded that of spring wheat.
3. The speed of the root formation of spring wheat exceeded that of ray grass.
4. In both crops the greater majority of roots was formed in the top soil. This was the most pronounced in ray grass.

c. The moisture content of the soil

The large differences in growth between the crops on the profiles with unfertilized and fertilized subsoil suggest that there may have been considerable differences in water absorption by these crops. The data in fig. 6 show that indeed the greater amount of water has been absorbed from the profiles with fertilized subsoil. The total quantities of water supplied were:

<table>
<thead>
<tr>
<th>Crop</th>
<th>Subsoil</th>
<th>Total Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>perennial ray grass</td>
<td>unfertilized subsoil</td>
<td>66 litres</td>
</tr>
<tr>
<td></td>
<td>fertilized subsoil</td>
<td>143 litres</td>
</tr>
<tr>
<td>spring wheat</td>
<td>unfertilized subsoil</td>
<td>110 litres</td>
</tr>
<tr>
<td></td>
<td>fertilized subsoil</td>
<td>462 litres</td>
</tr>
</tbody>
</table>

From these data it may also be concluded that water consumption of the wheat exceeded that of ray grass.

The question arises from which soil layers this water has been absorbed. The moisture tensions in the various layers of the profiles of all samples are summarized in the figs. 7, 8, 9, 10.

It appears from these graphs that the moisture contents of the soil layers were not constant during the experiment. Theoretically this can be caused by several factors. In the first place the evaporation, especially in the top soil, will have given some losses. We cannot determine this amount, since there are only data from uncropped profiles at the beginning and at the end of the experiment. It may be assumed, however, that the heavy losses of moisture have not been principally caused by evaporation from the soil, nor have they been caused by drainage of the water. The major cause of the decrease of moisture in the soil must have been the absorption by the plants.
We first may pay attention to the results of the spring wheat on the profiles with unfertilized subsoil. The graphs in fig. 7 show that the pF in the clay of the uncropped profiles on April 27 reached a value of about 3. The pF in the subsoil was about 2. At this time the young wheat plants had developed the first leaf. It may be assumed that the water conditions in the cropped soil were conform with those in the uncropped ones. After this date the moisture content in the top soil of the cropped profiles decreased rapidly.

This was followed by an increase on June 12, probably due to heavy rainfall in the preceding period. After this date the moisture content decreased again and remained low for the greater part of July. After July 20 the soil moisture content did show a definite increase to the value of April 27.

The deeper layers followed this course more or less. The increase of moisture on June 12 reached only to a depth of about 20 cm. The increase of moisture in July started earlier moreover.

The maximum depth, where decrease of moisture could be determined was dependent on the thickness of the clay layer. With a clay layer of 25 cm. loss of moisture was determined with certainty in the layer of 25 to 30 cm., in the upper 5 cm. of the sandy subsoil, and on July 3 probably also in the layer of 30 to 40 cm. In the profiles with 50 and 75 cm. clay, the moisture decrease reached a depth of 50 cm.

From this it is clear that the period of major moisture absorption by the spring wheat lasted from about May 24 to July 3.

The absorption of water by spring wheat from profiles with fertilized subsoil resembled that of the unfertilized ones (fig. 8). The main difference was that the uptake in the profiles with 25 and 75 cm. clay reached a depth of 40
and 60 cm. respectively, instead of 30 and 50 cm. Moreover the rate of absorption in the top soil of the fertilized profiles was higher, especially in the profile with 25 cm. clay.

The water absorption by the perennial ray grass on the profiles with unfertilized subsoil started also after April 27. This was most pronounced in the upper 10 cm. (fig. 9). The maximum decrease of moisture was found in the period from May 24 to July 3. The increase of moisture after this date may have been caused by heavy rainfall. It must be assumed that water absorption had not stopped at that date since there was a substantial decrease of moisture thereafter. Only after September 21 the moisture content of the top layer increased towards the value of April 27.

This trend was followed more or less by the lower layers. The maximum depth was again dependent to a certain degree on the thickness of the clay layer, reaching 30, 50 and 40 cm. in the profiles with 25, 50 and 75 cm. clay respectively. It is clear that the desiccation in the lower layers started less vigorously or later and stopped earlier.

The course of the water contents in the profiles with fertilized and unfertilized subsoil did show a large conformity (fig. 10). It appears, however, that the desiccation in the fertilized profiles, especially in the profile with 25 cm. loam was more vigorous than in the unfertilized ones. Moreover the rate of desiccation in the fertilized profiles was higher and there was hardly an increase in moisture in the period of July 3 to August 10, showing an uninterrupted period of absorption from May 5 to September 21. The maximum depth where pF
changes in the fertilized profiles with 25 and 75 cm. clay occur, exceeds that of the unfertilized ones with 10 cm.

Some general remarks may be made here about the figures 7 to 9. There exists always a striking difference in pF between the bottom layer of the clay and the top layer of the sand. This indicates that the vertical upward transport of water through the soil is hampered considerably near the boundary of sand and clay.

The fact that the pF of the top soil of clay was continually above 2.7 to 3 means that water transport in these layers was merely possible by diffusion and in consequence unimportant.

d. The relation between the root development and the moisture content of the soil

There exist two possibilities of relation between soil moisture content and roots, i.e. 1. with the quantity of roots and 2. with the velocity of uptake by the roots due to transpiration. We now will see which were the relations with the root quantities of spring wheat in the various soil layers.

This crop germinated in the end of April. At that moment water absorption was small and must have been restricted to the top layer. During the sampling on May 24 the crop had a height of 20 to 25 cm. There are no data available of the root development on that date. It may, however, be assumed that the plants had already a well-developed root system on that date. In accordance herewith a strong decrease of moisture was found to a depth of 30 or 50 cm. in the unfertilized as well as in the fertilized profiles.

The root mass in the unfertilized profiles increased probably up to June 12 when the crop had a height of about 50 cm. On this date the roots had attained a depth of 70 cm. This corresponds with a desiccation of the deeper soil layers, especially in the profiles with 50 and 75 cm. clay. After June 12 the total root mass decreased slightly, especially in the deeper layers. This, however, did not affect the absorption since the desiccation increased in several of these layers until July 3. On that day the ears of the wheat had appeared. The increase in moisture in the soil, the top layer excepted, in the following period shows no distinct relation with the root quantity. Probably this increase is mainly a consequence of the heavy rainfall in the period from 5 to 16 July. Moreover, decreasing transpiration rather than a decreasing root quantity may have influenced the moisture content especially after July 20, when the crop started ripening. It is evident from the figures that the absorption of water had already ceased before August 29. VAN DER PAAUW (1949) also found a decrease of transpiration of oats after the appearance of the panicles.

Contrary to the unfertilized profiles, the root mass in the fertilized ones still increased after June 12, mainly in the top layer but also deeper in the soil. This may explain why the rate of desiccation in many layers on July 3 exceeded that of May 24. After July 3 there was a decrease of root mass that corresponded with an increase of water in the soil, this again may be caused by the rainfall between 3 and 16 July together with decreasing transpiration especially after July 20.

Comparing the crops on the profiles with fertilized and unfertilized subsoil it may be stated that the first difference in growth of the tops was visible first on June 12. This was most pronounced on the profile with 25 cm. loam. Parallel with this, the root mass in the fertilized profiles exceeded that in the unfertilized
ones and this resulted in an increased water absorption that could be ascertained by the different amounts of water supplied.

The perennial ray grass was sown on April 4. It germinated at the end of April. During the sampling on May 24 the plants had a height of about 10 cm. Root data on that date are not available, but water absorption had already reached a considerable height since the moisture content in the soil had decreased materially in the top layer and to a lesser extent in the lower layers. There was a more distinct difference in the rate of desiccation between the top layer and the other ones than with spring wheat. However, in the later stages of growth this difference diminished.

The growth of the plants on the unfertilized subsoil continued up to August 10. After that date no more increase of dry matter was found. The root development, on the other hand, continued after this date, although slowing down and probably becoming unimportant in the deeper soil layers. The maximum of desiccation of the soil was already reached at July 3. This was followed by an increase of moisture in the period up to August 10, this may be attributed to a very heavy rainfall in the period up to August 8. It must be assumed that the absorption of water had not yet stopped on that date since there followed a desiccation in the period up to September 21 that cannot be ascribed to evaporation of the soil. The absorption must, however, have decreased. This was certainly the case in the period after September 21, when the soil moisture content rapidly increased to the point of April 27.

The growth of the plants on the fertilized profiles with 25 and 50 cm. loam continued until the end of the experiment, the root development showed a similar picture. Up to July 3 the moisture decrease followed the same trend, after that date the increase in roots did not enhance the water absorption. After September 21 the absorption by the roots apparently ceased.

Comparison of the crops on the fertilized and the unfertilized profiles shows that the growth on the first was much better, although the root development did not show important differences. Nevertheless the desiccation of the soil was considerably stronger in the fertilized than in the unfertilized profiles, showing that the absorption per weight-unit of the roots must have been higher. This is in accordance with the fact that the quantity of supplied water also was much higher.

There is still one question that is worth mentioning. The fact that the soil layers below 50 cm. did not show any desiccation, although there were many roots present in these layers, might suggest that these roots did not contribute to the absorption. This, however, may be explained as follows, although the moisture decrease in a soil layer is certainly related to the root activity, this, however, does not imply that a diminution of moisture in a distinct layer must be attributed only to the roots present in this layer. Moisture that is absorbed from a soil layer may be replenished by capillary flow from the underlying layer, if replenishment of that layer is possible in the same manner. In an extreme case, moisture may be replenished from the soil water with such a velocity that there is only a very short-lasting decrease of the water content. It may be assumed that this was the case in the layers below 50 cm. The quantity absorbed below 50 cm. cannot be calculated from the available data. The uptake of water by roots in the deeper soil layers is now studied in an experiment with profiles without a groundwater table.
SUMMARY

Root growth and top growth of perennial ray grass and spring wheat on three profiles were studied. Simultaneously, data were collected on the uptake of water from various soil layers.

The results found were:

1. Root growth of spring wheat reached a maximum early in the spring. Subsoil fertilizing resulted in a considerable increase of roots, mainly in the top layer of the soil.
2. Root growth of perennial ray grass continued up to November, although the rate of increase was slowing down. Subsoil fertilization did not materially influence the total amount of roots.
3. The dry matter in the tops increased in both crops up to the end of the growth period.
4. Subsoil fertilization caused a strong increase of the growth.
5. In consequence of the stronger growth the total water uptake by the plants on the profiles with fertilized subsoil exceeded that of those on the unfertilized ones.
6. The water absorption by spring wheat remained high from May 24 up to July 20. The maximum depth was dependent to a certain degree on the profile, but water absorption could not be demonstrated below a depth of 50 cm., although there were roots present in these layers.
7. The water absorption by perennial ray grass remained high from approximately May 24 to September 9. There was again a certain relation between the maximum depth of absorption and the composition of the profile. With this crop also, water absorption could not be demonstrated with certainty below a depth of 50 cm., notwithstanding the presence of roots in these layers.
8. It is assumed that moisture has been absorbed from depths below 50 cm. but that this water was replenished with a high velocity by capillary flow.

RÉSUMÉ

La croissance des racines et des parties aériennes du ray-grass anglais et du froment de printemps a été étudiée sur trois profiles. Simultanément des données furent recueillies sur le prélèvement d'eau dans les différentes couches du sol.

Voici les résultats trouvés:

1. La croissance des racines du froment de printemps atteignit un maximum au début du printemps. La fumure du soussol stimulait fortement le développement des racines, spécialement dans la couche arable du sol.
2. La croissance des racines du ray-grass anglais continuait jusqu'en novembre, quoique le degré de croissance allait en diminuant. La fumure du soussol n'a pas influencé de façon importante la quantité totale des racines.
3. La matière sèche dans les parties aériennes des deux végétaux allait croissant jusqu'à la fin de la période de croissance.
4. Les fumures du soussol occasionnèrent une forte augmentation des parties aériennes.
5. A la suite de cette augmentation de croissance le prélèvement d'eau par les végétaux sur les profiles avec un soussol fertilisé dépassa celui des profiles avec soussol non fertilisé.
6. L'absorption d'eau par le froment de printemps resta élevée du 24 mai au 20 juillet. La profondeur maximum dépendait jusqu'à un certain degré du profil, mais l'absorption d'eau ne put être démontrée à une profondeur de plus de 50 cm, quoiqu'il s'y trouvèrent quand même des racines.
7. L'absorption d'eau par le ray-grass anglais resta élevée du 24 mai au 9 septembre. Ici également il y avait une certaine relation entre la profondeur maximum d'absorption et la composition du profil. Avec ce végétal il ne fut également pas possible de démontrer qu'il y eut une absorption d'eau dans les couches plus profondes que 50 cm, malgré la présence de racines dans ces couches.
8. Il fut présumé qu'il y eut peut être une absorption d'humidité des couches plus profondes que 50 cm mais que cette eau a été rapidement remplacée par voie capillaire.
ZUSAMMENFASSUNG


Die wichtigsten Ergebnisse dieser Forschung waren:


3. Die Trockensubstanz der oberirdischen Teile nahm bei beiden Pflanzen bis zum Ende der Vegetationsperiode zu.

4. Die Untergrunddüngung begünstigte in hohem Masse das Wachstum der oberirdischen Teile.

5. In Übereinstimmung mit dem üppigeren Wachstum entzogen die auf Profilen mit Untergrunddüngung erwachsenen Pflanzen dem Boden im gesamten mehr Wasser als die auf ungedüngten Profilen erzogenen.


8. Man könnte daher annehmen, dass die Pflanzen auch unter dem 50 cm-Niveau dem Boden Wasser entzogen haben, das aber sehr schnell aus den tieferen Bodenschichten durch kapillaren Aufstieg ersetzt wurde.

Bibliography


———. 1948. De methoden, die aan het Landbouwproefstation en Bodemkundig Instituut T.N.O. te Groningen bij het wortelonderzoek op bouw- en grasland in gebruik zijn. 11 pp


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THE EFFECT OF SOIL MOISTURE ON THE GROWTH AND YIELD OF VEGETABLE CROPS

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1. INTRODUCTION

Although the total precipitation in humid climates of the temperate zone is sufficient for the growing of vegetable crops, it is known that considerable damage can be caused by short spells of drought. Therefore, Dutch vegetable growers often use sprinkler irrigation to supply additional water. Generally speaking the expenditure necessary in that case is rather low in comparison with overhead production costs.

Fundamental research on the relation between plant growth and soil moisture content is necessary as a basis for advice on sprinkler irrigation. Previous moisture regime experiments do not correspond, however, since the results obtained by various investigators largely depend on the procedure followed, the climatic conditions, the soil type and the crop with which the experiment was carried out, cf. STANHILL, 1957.

In the next paragraphs some results are given concerning the relations between soil moisture and various aspects of plant growth. The influence of some external factors on this relation will also be discussed.

At our Institute investigations concerning the effect of soil moisture on plant growth were performed with vegetable crops, in containers placed in a glass house or on field plots, that could be sheltered against natural precipitation by movable glass covers. In the experiments the moisture content of the soil varied between field capacity and fixed tension limits. As soon as the latter were reached the soil was again irrigated to field capacity. The irrigation frequency and the amount of water supplied depended on the tension limits, the transpiration conditions during the experiment and the plant development. In the containers the whole root-zone (20 to 60 cm.) was brought to field capacity, in the field only a depth of 30 to 40 cm. In the latter case, the majority of the roots was found in this layer. The different treatments started some time after planting or sowing, to obtain a favourable initial development.

For the characterization of the soil moisture content, pF curves were used. In fig. 1 they are given for the soils used in the experiments: a coarse sand (A), a clay loam (B) and a loess loam soil (C), respectively. The moisture content was determined at certain intervals, either by oven drying of samples or by resistance measurements with nylon blocks. The mean tension was calculated from the moisture content data. Field capacity corresponded with a pF 2.0 or pF 2.1.

2. THE RELATION BETWEEN SOIL MOISTURE AND PLANT GROWTH

The conclusions drawn from experiments on soil moisture and plant growth,
depend for a great deal on the properties studied. Differentiation ought to be made according to a.o. vegetative growth, production of fresh material or dry matter, yield of reproductive organs, root development, quality, etc.

In the following paragraph various aspects of growth will be discussed.

2.1. Influence on stem elongation and leaf area

Generally, soil moisture depletion had a large effect on the development of vegetative parts of the plant, in a great number of crops.

In broad beans the stem elongation, for example, was measured under various moisture treatments starting three weeks after planting from the 15th of June till the 6th of July. This period represents nearly one irrigation cycle of the dryest plot (tension limit: pF 3.4). The results are shown in fig. 2, in which the increase in height of the main stem is plotted against the mean moisture tension in the top 40 cm. of the soil. It can be seen that the maximum stem elongation of 40 cm. occurred with a mean tension between pF 2.1 and 2.4. At the highest tension (pF 2.9), the length of the stem increased only 25 cm.

In other crops a maximum in stem elongation between pF 2.1 and pF 2.4 was observed as well. A similar effect was found for the increase in leaf size,
while the number of leaves and the number of internodes was nearly the same for all treatments. No marked differences were found in the number of cells. The reduction in leaf size under clay soil moisture conditions can be mainly attributed to a corresponding reduction in cell size. This may imply, that the development of primordia is not very drought-sensitive.

2.2. Influence on fresh weight and dry matter production

In the glass house experiments with various vegetables, large containers were used. The latter were filled with 5 cm. gravel, 5 cm. coarse and 50 to 60 cm. of a sandy or clay loam soil (fig. 1, curves A and B). The total weight of the containers varied between 180 and 230 kg. depending on soil type and moisture content. The surface area was 0.2 sq.m. The experiments were carried out for four moisture levels with four replicates, unless indicated otherwise.

All the crops investigated showed a large decrease in fresh weight yield of the vegetative parts, with an increase of the mean moisture tension. The yield varied according to the crop used: those with the highest fresh weight production displayed the largest decrease. It is obvious that this decrease is nearly the same for various crops, such as lettuce, spinach and radish (fig. 3), when represented as a percentage. The yield decreases regularly from 100% to 20-30% in spring, with an increase in mean pF from 2.3 to 3.4. In autumn this decrease is less pronounced, however, than in spring and amounts to only 50 to 60% under comparable soil moisture conditions. On clay loam and on sandy soil nearly the same trend was found in our experiments. The seasonal influence and the effect of the soil type on the yield of vegetable crops will be discussed in paragraph 3.

The experimental procedure may give rise to deviations in the decrease of the observed yield. It is possible, for example, that on soils irrigated to field capacity immediately before harvest, higher yields in fresh weight will be observed than on plots treated in the same manner and harvested at the end of a drying cycle. The higher yield may be due to a rapid passive water absorption, through which the water content of the plant in gms. of water per gm. dry matter increases. On the other hand, the mean moisture tension may show a small change whether or not water is supplied immediately before harvest. These assumptions have been verified in an experiment with lettuce, in which some low (L) and some high (H) tension replicates were irrigated immediately before harvest time (table 1).

![Fig. 3.](image)

The effect of mean moisture tension on fresh weight production (% of that at pF 2.3) of various crops in the spring (A) and in the autumn (B). The individual points of curve B were omitted, as the variation was nearly equal to that of A.
TABLE 1. The effect of irrigation before harvest on: fresh weight, dry matter production and water content of lettuce

<table>
<thead>
<tr>
<th>Harvested</th>
<th>Mean moisture tension (pF)</th>
<th>Fresh weight (gms/container)</th>
<th>Dry matter production (gms/container)</th>
<th>Water content (gms. of water/gm. dry matter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>L 2.1</td>
<td>656</td>
<td>29.5</td>
<td>21.2</td>
</tr>
<tr>
<td>Irrigation</td>
<td>H 3.2</td>
<td>366</td>
<td>20.1</td>
<td>17.1</td>
</tr>
<tr>
<td>After</td>
<td>L 2.1</td>
<td>687</td>
<td>31.5</td>
<td>20.8</td>
</tr>
<tr>
<td>Irrigation</td>
<td>H 2.9</td>
<td>546</td>
<td>24.5</td>
<td>21.2</td>
</tr>
</tbody>
</table>

It can be seen that the fresh weight of the dry plot (H) increased from 366 to 546 gms., after irrigation, whereas the change in mean moisture tension was relatively small. The increase in fresh weight is mainly due to the rise of water content from 17.1 to 21.2, the latter value being nearly equal to the water content of the wet plot. Dry matter production is, therefore, less affected than fresh weight production by water supplied before harvest. In practice, vegetable growers usually irrigate some vegetable crops shortly before harvest in order to obtain higher yields in fresh weight.

Beside the above mentioned four moisture treatments, two groundwater tables (30 and 50 cm.) were used with lettuce to obtain, together with the above experiment, a wide range in mean pF. The effect of moisture stress on fresh and dry weight production is given in fig. 4. It is evident that a sharp maximum in fresh weight production occurs at approximately pF 1.9. The decrease at lower tensions may be due to restricted aeration. The water content of the heads was 12.7, 16.6 and 6.6, gms. of water per gm. dry matter with a pF of 1.5, 1.9 and 3.3, respectively. Dry matter production, therefore, shows a relatively smaller decrease than fresh weight production, resulting in a broad maximum. The same trend was observed in experiments with other vegetables.

In the field a large decrease in fresh weight with an increase in the mean moisture tension was observed as well (STOLP, 1956).

Thus far, no exception to this was found when testing a large number of crops, both in field- and in pot experiments.

2.3. Effect of soil moisture content on some other plant aspects

A period of high moisture stress during certain growth stadia may have a detrimental effect on various plant aspects of certain vegetable crops, which cannot be compensated for by a low moisture stress later on. With pulses, for
The effect of mean moisture tension during blooming till first picking date of dwarf French beans

example, a large influence of soil moisture tension on vegetative growth was observed. The final yield of pods, however, is determined to a great extent by the moisture regime during blooming and podset. In fig. 5 the pod-yield of dwarf french beans is plotted against the mean pF over the period from blooming till the first picking date. A rather stunted growth appeared if before blooming the moisture stress in the top foot of soil increased to pF 3.6. No decrease in yield was found in this case, provided a low tension was maintained during blooming. A large decrease was observed with a high tension during blooming. This fact may be attributed to abscission of flowers or young fruits.

Losses due to a decrease in quality are at least as important as the height of yield itself, especially for vegetable crops. Often, at higher stress regimes, a lower percentage of marketable products is harvested. Although irrigation before harvest increases to a great extent fresh weight of some crops under a dry regime – lettuce for example – (table 1), no compensation in quality was obtained. This has been demonstrated in fig. 6, in which are pictured some lettuce heads grown at different moisture regimes. The numbers 1 to 4 relate to objects irrigated when tension limits of 2.5, 3.0, 3.5 and 4.0 respectively, were reached. It is evident that no marketable heads were obtained with a tension limit of 3.0 or higher, due to their unfavourable appearance, tipburn and bolting.

With other crops also, e.g. strawberry and cauliflower, yield response to a high stress at certain periods is not compensated for by a low stress later on.

The growth of roots is strongly affected by increasing moisture stress. Bierruizen and Ploegman (1958) found a marked decrease in root elongation at high moisture stresses using various vegetable crops. A tension rise to pF 3.0, corresponding with 50% of the available water used, resulted in a growth rate that was 40 to 90% lower than the one at field capacity. Drying out of the topsoil will result in a more intensive root development in the subsoil, provided the tension in this layer is low (fig. 7). However, this cannot always prevent a decrease of vegetative growth, as was found for example for dwarf french beans. This effect may be partly attributed to the unavailability of nutrients.
FIG. 6. The effect of irrigation regime on quality of lettuce in sand (1 to 4 represent tension limits of 2.5, 3.0, 3.5, and 4.0 respectively)

FIG. 7. a. Root development in successive periods of one week drawn from root chambers with glass panels and b. increase of leaf area for wet (A) and dry (B) plots. Arrow indicates irrigation of dry plot
3. EFFECT OF SOME EXTERNAL FACTORS ON THE RELATION BETWEEN SOIL MOISTURE AND PLANT GROWTH

Soil characteristics and climatic conditions can affect the relation between soil moisture and plant growth. When advising on irrigation one cannot exclude those factors.

3.1. Influence of soil type

The pF curve of the clay soil (fig. 1B) is quite normal above field capacity. The air content, however, is higher than in most clay soils. The curve for the sandy soil (fig. 1A) deviates from the normal type in this sense, that a smoother slope in the range between pF 2.0 to pF 2.5 or pF 3.0 is more characteristic for sandy soils. No difference in yield reaction was found on the above mentioned soils, as was shown in figure 3. Certainly a different reaction may occur on other soils. On soils with a low air capacity, for example, the highest yield will not be found at or near field capacity, but at a higher mean stress. This is shown in fig. 8, where the yield of broad beans both on sandy and loess soils are given. The curve found for the loess soil indicates that the potential productivity of such a soil is lower than that of soils with sufficient aeration (see figure 1A and 1C). At a low stress the air content is the limiting factor in the loess soil, whereas under conditions of sufficient aeration in this soil moisture tension will be too high for an optimal productivity.

Most sandy soils show a smoother slope of the curve in the range between pF 2.0 to pF 2.5 or 3.0, than the sandy soil used in our experiments. In those cases more available water is present in this pF range. It may be possible, therefore, that a less pronounced reaction will be found on such soils.

3.2. Seasonal influences

The significance of the season is shown in fig. 3. For various crops the relation between soil moisture tension and yield is represented for crops grown in spring and in autumn. At high stress, the higher transpiration conditions from March to May cause a sharper depression in fresh weight than is found for the same crops grown in the period from September till November (container experiments in the glass house). An identical effect can be expected to occur for early grown crops and for crops with the greatest part of their vegetation period in the summer months. In the Netherlands the probability of periods with high rainfall deficits and high potential evapotranspiration is the highest in June.
FIG. 9. Probability of differences between rainfall (R) and evapotranspiration (E) during the year. Calculated for twenty-day periods and a reduction factor 0.7 for E (after Stol, this report). E was calculated from meteorological data by Penman's formula over a twenty-year period (first approximation).

and July (Stol, 1958). It is obvious that critical periods of crop response generally coincide with the above mentioned period, as is shown in fig. 9. The lines A and B indicate periods in which strawberry (var. Jucunda) resp. dwarf french beans are more susceptible to drought than in other periods of their growing cycle.

4. DISCUSSION AND CONCLUSIONS

The relation between plant growth and soil moisture has been studied as a basis for advice on sprinkler irrigation. Various aspects affecting this relationship were investigated.

It was observed that a moderate soil moisture stress already causes a considerable decrease in vegetative growth and fresh weight production, as is shown in figs. 2, 3 and 4. This reduction in growth was mainly due to a decrease in cell size and water content, and in general not a result of a reduction in the number of leaves or internodes nor in the number of cells per leaf. The dry matter production is influenced to a much lesser extent by increasing soil moisture tension, indicating that the assimilation is not decreased at a moderate stress. The decrease in fresh weight, due to a high moisture stress, can be partly neutralized to some degree by irrigation later on (table 1), increasing the water content of the plant due to passive absorption.

In certain horticultural crops, however, a detrimental effect on quality was observed, which cannot be compensated for by later irrigation. Moreover, also a reduction in yield due to a high soil moisture stress in certain stages of growth, e.g. during blooming and podset (for pulses) or growth of receptacles (for
strawberries), cannot be influenced by irrigations later on, whereas a high stress during other periods does not, or only to a lesser extent, influence the yield.

At low evapotranspiration conditions, limitation of water availability is less important. So the fresh weight differences between plants grown under low and high moisture tensions will be less pronounced (fig. 3). WITTE (1956) stresses this fact from a practical point of view, stating that the irrigation response of crops grown early in the season is less than half of that found for summer grown crops. This effect may be partly attributed to the higher moisture content of the soil at the date of planting or sowing and to a higher frequency of excess of rain over evapotranspiration early in the season.

It can be concluded from a large series of experiments, both in the glass house and in the field, that maintaining a low stress during the whole growth period generally results in the highest yield and quality. This leads to important consequences as regards the irrigation frequency for vegetable crops. In most soils in the low tension range (say between pF 2.0 and pF 2.5) no more than 20 to 25 mm. water can be consumed in a soil layer with a depth of 40 cm. Under conditions of high evaporation and low rainfall, the period between sprinklings must therefore not exceed 7 to 10 days, provided irrigation water is not scarce. This frequency also determines the capacity of the installation, taking into account of course the acreage planted with crops of high marketing value, since for those the above statements only hold true. On soils with a low air content at field capacity the above mentioned frequency of sprinklings could result in restricted aeration and in that case may cause detrimental effects in crop response.

RÉSUMÉ

L'influence de l'humidité du sol sur la croissance et le rendement de certains végétaux

On a exposé quelques résultats d'essais traitant les réactions de légumes sous l'influence de différences dans l'approvisionnement d'eau. L'expertise a eu lieu en partie en serre et en partie en pleine terre. L'approvisionnement d'eau a eu lieu après la constatation d'une certain degré de dessèchement. Pour la caractérisation de l'humidité du sol on s'est servi de courbes-pF.

Pour nombre de végétaux on a constaté que la croissance et le rendement de matériaux frais décroîtent à mesure que la tension de l'humidité augmente. La plus grande croissance et le plus grand rendement de légumes frais furent obtenus après une application d'un pF 2.0 à 2.4 en moyenne. Pour certains végétaux on peut réduire les conséquences défavorables de la haute tension d'humidité durant une partie de la saison de croissance en appliquant une adduction d'eau. Certains végétaux subissent par suite d'une tension d'humidité élevée dans le sol, des dégâts irréparables pendant certaines périodes de la croissance. Ceci vaut pour le rendement aussi bien que pour la qualité. En automne la diminution du rendement est moins grande par suite du dessèchement du sol, qu'au printemps. Sur une terre ayant un petit volume d'air, une irrigation fréquente provoqua un baissement du rendement.

Les résultats nous montrent en outre que c'est surtout pendant des périodes de grande évaporation et de peu de pluie qu'on doit augmenter la fréquence de l'irrigation.

ZUSAMMENFASSUNG

Der Einfluss der Bodenfeuchtigkeit auf Wachstum und Ertrag einiger Gewächse

Der Einfluss wechselnder Wasserversorgung auf einige Gemüsegewächse wurde untersucht und die Ergebnisse dieser Experimente wurden dargestellt. Die Untersuchungen sind teilweise in einem Gewächshaus, teilweise im freien Felde durchgeführt worden. Man gab
Wasser wenn der Boden in einem bestimmten Mass ausgetrocknet war. Zur Charakterisierung
der Wassergehaltes des Bodens wurden pF Kurven benutzt.

Die Experimente haben ergeben, dass bei vielen Gewächsen das Wachstum und der Ertrag
frisches Pflanzenmaterial nachlässt im Verhältniss zu einer Zunahme der Bodenfeuchtigkeitsspannung. Das Wachstum war am starksten und der Ertrag frisches Pflanzenmaterials am höchsten bei einem durchschnittlichen pF von 2,0 bis 2,4.

Die schädliche Wirkung einer hohen Feuchtigkeitsspannung während eines Teils der Wachstumsperiode können bei einigen Gewächsen teilweise aufgehoben werden durch späteren zusätzlichen Wassergaben.

Es gibt Gewächse die in bestimmten Wachstumsperioden unwiderbringlich beschädigt werden durch eine hohe Bodenfeuchtigkeitsspannung. Dies kann sowohl den Ertrag wie auch die Qualität angehen.

Im Herbst hat eine starke Austrocknung des Bodens ein geringeres Effekt auf dem Ertrag
frisches Pflanzenmaterials wie im Frühling.

Wenn der Boden nur ein kleines Luftgehalt hat gibt eine häufige künstliche Beregnung bedeutende Ertragssenkungen.

Die experimentellen Erfolge zeigen an dass in Perioden höherer Verdunstung und geringerer natürlichen Niederschläge eine häufige künstliche Beregnung notwendig ist.

References


Stol, Ph. Th. 1958. A statistical analysis of the differences between precipitation and evaporation in the Netherlands. This Report.


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Man hat in der ganzen Welt, insbesondere im letzten Jahrzehnt, keine Mühe gescheut, um festzustellen, wann eine Beregnung zu erfolgen hat. Kulturtechniker, Wasserwirtschaftler, Meteorologen, Bodenkundler, Botaniker und Pflanzenbauer beschäftigen sich intensiv mit diesem Problem, ohne bislang zu einem eindeutig klaren Ergebnis gekommen zu sein. In einem Gebiet mit warmem, trockenem Klima, wo also gewissermaßen der Boden während der ganzen Vegetationszeit verhältnismässig trocken ist, liegen die Dinge vielleicht einfacher als in einem Gebiet mit wechselnder Witterung, wie wir es in Deutschland haben. Dass die Pflanzen für eine maximale Ertragsbildung eine bestimmte Menge Feuchtigkeit bedürfen, ist eine uralte bekannte Tatsache. Schwieriger dagegen ist die genaue Angabe, wieviel Wasser der Pflanze in jedem einzelnen Vegetationsabschnitt als Optimum tatsächlich zur Verfügung stehen muss. Dieses Optimum schwankt beträchtlich und liegt nach unseren Untersuchungen mal in engen, mal in weiten Grenzen, die im einzelnen zahlenmässig nicht genau bekannt sind.


alle meteorologischen Untersuchungen über Gross- und Kleinklima über die einzelnen Witterungsfaktoren, usw.,
alle pflanzenphysiologischen Untersuchungen über Transpiration, Hydratur, Wasserbedarf und Wasserverbrauch der Pflanzen, Verlauf der Nährstoffaufnahme, Ernährung, usw.,
alle pflanzenbaulichen Untersuchungen über Beziehungen zwischen Witterung und Ernteertrag, usw.,
alle diese Untersuchungen sind zwar unbedingt notwendig und es wäre unverantwortlich, sie zu bagatellisieren, aber für sich allein können sie kein sicheres Resultat über die Zweckmäßigkeit der Beregnung geben. Nur durch Zusammenfassung aller Untersuchungsergebnisse gelangen wir zu einem Urteil. Solange wir die Details noch nicht einwandfrei kennen, wird uns der langjährige Feldversuch unter kritischer Betrachtung aller Einfluss habenden Faktoren am raschesten Klarheit bringen.

Würde es bei der Beregnung sich lediglich um eine Ertragserhöhung handeln, so könnte die Anwendung der Beregnung als verh. einfach angesehen werden. Nun ist sie aber eine wirtschaftliche Massnahme, die nur solange gerechtfertigt ist, als die Unkosten durch den Mehrertrag gedeckt werden. Bei uns beträgt die Betriebskosten einer 20 mm/ha Regengabe ohne Verzinsung und Amortisation der Anlage etwa 30,— DM. Etwa ebensoviel machen die stehenden Kosten, Amortisation und Kapitalisierung, aus. Die Ertragssteigerung, die durch jede einzelne Regengabe erfordert wird, muss also mindestens dem Preis von rd. 60,— DM entsprechen. Damit ist aber auch die Zahl der Regengaben begrenzt, da nach dem Wirkungsgesetz der Wachstumsfaktoren der Ertrag nicht gradatim ansteigt.

In unseren langjährigen Versuchen ermittelten wir, dass der Nutzeffekt der Beregnung in den einzelnen Wachstumsabschnitten sehr unterschiedlich sein kann. Wir fanden ferner, dass jede Kulturart spezielle Ansprüche stellt. So konnten wir feststellen, dass
1. die Beregnung bei einer Reihe von Kulturarten nur in ganz bestimmten Wachstumsphasen wirkt,
2. ferner, dass die Beregnung eine Ertragsdepression herbeiführen kann, wenn sie im unrichtigen Zeitpunkt erfolgt,
3. dass bei anderen Kulturarten wiederum die Beregnung jederzeit eine erhebliche Ertragssteigerung verursacht,
4. dass es aber auch Pflanzen gibt, bei denen die Beregnung in der Regel keinen Einfluss auf den Ertrag ausübt.

Im einzelnen darf ich dazu folgendes aufführen:

Wintergetreide

Die ertragsbestimmenden Faktoren sind Ährenbestandsdichte, Zahl der Körner an der Ähre und Korngewicht. Die Verbesserung dieser Ertragskomponenten kann durch die Beregnung in mehr oder weniger beträchtlichem Ausmaße geschehen. Der 1. Termin, eine Beregnung vorzunehmen, wäre die Periode, in der die Bestockung erfolgt, also bei uns etwa Ende April bis Anfang Mai. Ein Erfolg ist aber nur dann zu erwarten, wenn der Bestand unter den Unbilden des Winters gelitten hat und infolgedessen dünn steht. Bei gleichmässig gutem Stand wird die Beregnung überflüssig. Die Wärme spielt insofern...
eine Rolle, als bei niedrigen Temperaturen (unter 9°C D.T.) die Natur Voraussetzung für eine gute Bestockung schafft, während bei höheren die Pflanzen rasch zum Schossen gelangen, worunter die Bestockung leidet.


Verh. sicher wirkt dagegen die Beregnung, um die Zeit der Blüte – kurz vor bis kurz nach der Blüte. Wir erzielten in fast allen Jahren erstaunliche Ertragsverbesserungen, die noch weiter erhöht wurden, wenn wir eine kleine zusätzliche Volldüngung verabfolgten. Als Ursache war nicht nur eine Erhöhung des 1000-Korngewichtes, sondern auch eine Vermehrung der Kornzahl an der Ähre festzustellen.

SOMMERGETREIDE


Während des Schossens und Ährenschiebens ist die Beregnung zur besseren Ausbildung der Ähren bzw. Rispen um so erwünschter, je trockener es ist.

Am wertvollsten ist nach unseren Untersuchungen die Beregnung in der Zeit kurz vor und kurz nach der Blüte, wo sie dieselbe Wirkung wie bei Wintergetreide hat. Ebenso hat die zusätzliche KPN-Düngung einen erstaunlich hohen Nutzeffekt.

MAIS

Der Mais ist eine subtropische Pflanze. Eine Beregnung bis zur Blüte hat nach unseren Versuchen unabhängig von der Witterung keine oder eine unzufriedenheitliche Wirkung gehabt. Dagegen lohnte sich dieselbe gut, wenn sie in der Zeit Anfang Blüte bis beginnendem Kolbenansatz vorgenommen wurde.

LEGUMINOSEN


Eine Beregnung der Buschbohnen (Phaseolus), die wesentlich höhere Ansprüche an die Temperatur als Pisum und Vicia stellen, führt vor Eintritt der

KARTOFFELN


RÜBEN
Die Beregnung zu Rüben erfolgt nach unseren Untersuchungen am zweckmässigsten erst, wenn nach dem Vereinzeln die Reihen wieder geschlossen sind, d. i. etwa 80 Tage nach dem Aufgang. Vorher haben wir auch bei trockenem Wetter keinen wirtschaftlichen Nutzen gehabt. Es besteht die Gefahr, dass die Zahl der Schossen infolge eines Schockes ganz wesentlich vermehrt wird. Der Erfolg der späteren Beregnung ist zurückzuführen auf Erhaltung der Blattmasse im Juli und August, wodurch das Dickenwachstum der Rübenwurzeln angeregt wird. Eine späte Beregnung ab Mitte August ist kaum mehr in der Lage das Wurzelgewicht zu verbessern, wohl aber wird der Blattwuchs gefördert.

Unmittelbar nach einer Regengabe ist eine Zuckergehaltsdepression von 2–3 % zu bemerken, die aber im Laufe des weiteren Wachstums wieder eingeholt wird. Etwa 4 Wochen nach der letzten Regengabe gleicht sich wieder der Zuckergehalt der beregneten dem der unberegneten Rüben an.

TABAK
Der hohe Wasserbedarf der Tabakpflanzen reizt dazu, sie so zu stellen, dass sie niemals unter Wassermangel zu leiden haben. In heissen, trockenen Jahren

In Jahren mit normaler Witterung hat die Beregnung erst dann Erfolg, wenn die Pflanzen eine Höhe von 40–50 cm erreicht haben, d.i. etwa 40 Tage nach dem Setzen, also nach dem Häufeln. Höhere Mehrerträge werden dann erzielt, wenn die erste Beregnung auf den völlig geschlossenen Bestand gegeben wird. Am besten wirkt sich die Beregnung aus, wenn bei ihrem Einsatz der Vegetationspunkt bereits zwischen den Blättern sichtbar geworden ist. Die Gefahr, durch Beregnen Schaden anzurichten, wird mit Zunahme der Entwicklung der Tabakpflanzen immer geringer. Nach dem Köpfen erweist sich die Beregnung nicht mehr als notwendig.

**Klee und Kleegras**

Klee und Kleegras verlangt während der ganzen Vegetationszeit viel Feuchtigkeit. Die Beregnung hat sich ausschliesslich nach der Witterung zu richten und kann auch bei uns fast immer als wirtschaftlich angesehen werden. Ähnliches gilt für fast alle einjährigen Futterpflanzen und Futterpflanzengemische. Bei diesen Pflanzen liegt das Problem der Beregnung darin, zu ermitteln, wann eine Beregnung nicht mehr lohnt. Das erscheint mir eigentlich wichtiger als zu untersuchen, wann man mit der Beregnung beginnen muss. Selbstverständlich ist bei diesen Pflanzen die Frage der Wirtschaftlichkeit, also der Deckung der Unkosten, durch die Ertragssteigerung nicht zu übersehen.

**Grünland**


Auf Gemüse, Wein, Obst, Öl- und Faserpflanzen kann ich nicht näher eingehen. Doch sind auch hier die Erfolge der Beregnung je nach Kulturart unter-

**Summary**

*Time of sprinkling as determined by the growing stage of the crops*

It is very difficult to answer the question what is the exact water requirement of crops during the succeeding growing periods while the yield of crops is determined by various factors, all of which have to be considered.

The conclusion following many years of extensive sprinkling experiments in the field is, that the results are highly dependent of the kind of crop. It was found, that

1. there are many crops, on which sprinkling in certain periods of growth has a marked and favourable effect;
2. when applied in a wrong period a decrease in yield is obtained;
3. on other kinds of crops sprinkling has a favourable effect at any time in the growing season;
4. there are some crops, on which sprinkling in normal years has no effect at all.

**Winter grain crops**

Sprinkling during the stooling stage of the crops only has a favourable effect if damage has been caused by frost. If sprinkling is applied during the shooting stage, rye and oats give higher yields in very dry years only. Sprinkling of winter wheat during the first half of June sometimes gives very good results. The largest effect can be expected from sprinkling during the flowering stage in every year. A small amount of NPK improves the yield.

**Summer grain crops**

On barley, oats and wheat sprinkling may be applied about two to four weeks after coming-up if the temperature is above 10 to 13 °C. The effect of sprinkling during the shooting stage is dependent on the dryness of the weather. The main effect occurs during the flowering stage. In that period a small amount of NPK is favourable.

**Maize**

No effect of sprinkling before the flowering stage is to be expected. The favourable period is that from flowering up to the formation of the spadix.

**Leguminous crops**

Sprinkling during the flowering stage increases the amount of shells and the amount and size of seeds.

**Potatoes**

Sprinkling before the flowering stage only gives an effect during very dry years. There was found an increasing effect of sprinkling during the flowering stage with increasing dryness of the weather. A small supplemental fertilization during this time is favourable.

**Sugar- and fodder beets**

Sprinkling is most favourable if the soil is completely covered, during July and August therefore. After this time only the leaf growth is improved.

**Tobacco**

If sprinkling is applied too early, a decrease in yield will be obtained. The most favourable effect is obtained about 40 days after planting.

After cutting-off the tops sprinkling is not needed anymore.

**Clover and grass**

Sprinkling is favourable during the whole growing season and the amount of water applied is dependent on weather conditions. The effect of sprinkling on grass crops is dependent on temperature. In the case of grazing no effect can be expected after the third grazing period.
NEUE ERKENNTNISSE ZU GRUNDLEGENDEN FRAGEN DER DIREKTEN FROSTSCHUTZBEREIGNUNG

K. WITTE
(Wesseling, Bez. Köln-Marhof, Deutschland)


Die Enttäuschung über vereinzeltes Versagen der Frostschutzberegnung im Frühjahr 1957 dürfte vorwiegend darauf zurückzuführen sein, dass das Wissen um diese Faktoren und ihre gegenseitige Beeinflussung bis zu diesem Zeitpunkt unzureichend war.

Diese Faktoren sind:
1. Die Unterbrechungsdauer, bzw. der zeitliche Abstand der Benetzung
2. Die Regendichte (= Regenhöhe mm/st, in der Folge kurz als RD bezeichnet)
3. Der Windeinfluss
4. Der Einfluss der Höhe und der Auffangfläche der Pflanzen
5. Die Aufhebung der Unterkühlung

Unsere Untersuchungen über diese Faktoren wurden teils in einem Tiefgefrierraum des Institutes für Obstbau der Universität Bonn, teils im Freigelände der Versuchswirtschaft Marhof durchgeführt.

1. DIE UNTERBRECHUNGSDAUER

Im Tiefgefrierraum wurde zunächst der Einfluss der unterschiedlichen Unterbrechungsdauer bei steigenden Regendichten untersucht. An zwei Kurvenbildern möchte ich Ihnen die Ergebnisse dieser Untersuchungen erläutern.

**Fig. 1.**
Einfluß unterschiedlicher Unterbrechungsdauer auf die Blattemperatur bei -10°C und einer Regendichte von 1,5 mm

Die Kurven der ersten Figur stellen den Einfluss der Unterbrechungszeiten von 1-4 min. auf dem Temperaturverlauf an der Blattunterseite bei der extrem niedrigen Raumtemperatur von -10°C bei einer Regendichte von nur 1,5 mm.
Dar. Bei keiner der vier gewählten Unterbrechungszeiten ist bei \(-10^\circ C\) die Temperatur am Pflanzenblatt auf der zur Frostschadenverhütung notwendigen Höhe von \(-0,5\) bis \(-1,0^\circ C\) gehalten worden. Bei 1 min. Unterbrechungsdauer zwischen den einzelnen Benetzungen schwankt die Blattemperatur um etwa \(1^\circ C\) und erreicht jeweils einen Tiefstwert von \(-7^\circ C\). Bei 2 min. Unterbrechungsdauer schwankt die Temperatur zwischen den einzelnen Benetzungen um \(2^\circ C\) und sinkt bis auf \(-8^\circ C\). Die Temperatur fällt bei der längsten Unterbrechungszeit von 4 min. sogar bis auf \(-9^\circ C\). Bei zunehmender Unterbrechungsdauer wird die Temperaturschwankung zwischen den einzelnen Regenschauern immer grösser, weil trotz gleichbleibender Regendichte mehr Wasser je Benetzung versprüht wird.

Die zweite Figur zeigt ebenfalls bei \(-10^\circ C\) das andere Extrem unserer Versuchsserie, den Einfluss der unterschiedlichen Unterbrechungsdauer bei der höchsten zur Anwendung gekommenen Regendichte von 6 mm. Auch bei dieser sehr hohen Regendichte wirken sich die verlängerten Unterbrechungszeiten im Prinzip gleichartig auf den Temperaturverlauf am Blatt aus. Das graduelle Ausmass der Temperaturschwankungen ist bei der höheren Regendichte jedoch erheblich kleiner geworden. Das linke Kurvenbild zeigt, dass die Erstarrungswärme vom 6 mm/st bei 1 min. Unterbrechung ausreicht, die Pflanzentemperatur nicht unter die für sicheren Frostschutz notwendige Höhe absinken zu lassen. Bei längerer Unterbrechungszeit reicht selbst diese überaus hohe Regendichte zur Frostschadenverhütung nicht mehr aus.

Diese unter extremen Temperaturbedingungen gewonnenen Ergebnisse zeigen eindeutig die Bedeutung der kurzen Unterbrechungszeit für die rationelle Ausnutzung des verregneten Wassers für die angestrebte Schutzwirkung.

2. DIE REGENDICHTE

Über die Höhe der Regendichten, die zur Verhütung der Frostschäden bei den unterschiedlichen in Frage kommenden Froststärken notwendig sind, gibt die nachfolgende Übersicht Auskunft. (Tabelle 1).

Diese Zahlen sind das Ergebnis der in den Jahren 1956/57 in Labor und Freiland bei unterschiedlichen Tiefsttemperaturen durchgeführten Untersuchungen an bodennahen Kulturen bei Windgeschwindigkeiten bis zu 0,5 m/sec. Es überrascht die verhältnismässig gute Übereinstimmung der Ergebnisse zwischen den Labor- und Freilandversuchen! Aus dem Vorhergesagten folgender stellen wir fest, dass zur Verhütung von Frostschäden bei gleicher Tiefstemperatur und einer Unterbrechungsdauer von 1 min. die niedrige Regendichte von 1,5 mm ausreicht, während bei 4 min. Unterbrechung die doppelte Regendichte,
TABELLE 1. Grenzwerte unterschiedlicher Regendichten bei steigenden Unterbrechungszeiten, bei niedrigen Kulturen
Marhof 1956/1957

<table>
<thead>
<tr>
<th>Rd mm/st</th>
<th>Tiefsttemperaturen, bis zu denen die Regendichten Schutz gewähren bei Unterbrechung der Benetzung in Minuten</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Labor*</td>
</tr>
<tr>
<td>1,5</td>
<td>-4,5</td>
</tr>
<tr>
<td>1,9</td>
<td></td>
</tr>
<tr>
<td>2,2</td>
<td>-6,0</td>
</tr>
<tr>
<td>3,0</td>
<td>-7,0</td>
</tr>
<tr>
<td>3,4</td>
<td>-9,3</td>
</tr>
</tbody>
</table>

*) Ohne Wind. **) Windgeschwindigkeit bis 0,5 m/sec

somit 3,0 mm benötigt werden. In gleicher Weise genügt bei 1 min. Unterbrechung die Regendichte von 3,0 mm um gegen -6°C wirksam zu sein. Bei 4 min. Unterbrechung ist auch hier die doppelte Regendichte notwendig.

Diese rationale Ausnutzung des verregneten Wassers bei kurzer Unterbrechungszeit gewährleistet sparsamen Wasserverbrauch mit allen hiermit verbundenen Vorteilen. Weiter zeigen die Zahlen dieser Tabelle, dass bei Windstille oder nur sehr schwachem Wind bis 0,5 m/sec mit einer Regendichte von ca. 2 mm und einer Unterbrechungsdauer bis 2 min. nur Fröste mit Tiefstemperaturen bis -5,0°C abzuwehren sind, und dass bei stärkeren Frösten bis -6,0°C bei 1 min. Unterbrechung eine Regendichte von 3 mm notwendig wird.

Die Schutzwirkung einer bestimmten Regendichte ist somit nicht fest begrenzt, sondern sie hängt im Wesentlichen von der Länge der Zeitspanne ab, die zwischen den einzelnen Benetzungen liegt. Als begrenzender Faktor für die Schutzwirkung gegen bestimmte Frostgrade darf somit nicht die Regendichte allein angesehen werden, sondern stets müssen Temperatur, Regendichte und Dauer der Unterbrechung – im praktischen Betrieb durch Umdrehungsgeschwindigkeit der Strahlrohre bedingt – als eine Einheit betrachtet werden.

3. DER WINDEINFLUSS


Wie die nachstehenden Zahlen beweisen, verlangt zunehmende Windgeschwindigkeit bei gleichbleibender Temperatur für vollkommene Schutzwirkung eine höhere Regendichte. Sinkende Temperaturen und stärkerer Wind erfordern demnach besonders hohe Regendichten. (Tabelle 2).

Diesen Ergebnissen liegen Freilanduntersuchungen, die unter Einsatz eines Gebläses im März dieses Jahres auf dem Marhof durchgeführt wurden, zugrunde. Durch Einsatz des Gebläses war es möglich, den Faktor Wind in dem
TABELLE 2. Einfluss des Windes und sinkender Temperaturen auf die notwendige Regendichte (Unterbrechung der Benetzung 1 min.)

<table>
<thead>
<tr>
<th>Lufttemperatur °C</th>
<th>RD mm/st</th>
<th>Pflanzentemperatur °C bei Windgeschwindigkeiten m/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>bis 0,5 m/sec</td>
</tr>
<tr>
<td>-2,5 bis -3,5</td>
<td>1,0-1,5</td>
<td>-0,5</td>
</tr>
<tr>
<td></td>
<td>1,5-2,5</td>
<td>-0,4</td>
</tr>
<tr>
<td></td>
<td>2,5-3,5</td>
<td>-0,3</td>
</tr>
<tr>
<td>-4,7 bis -5,1</td>
<td>1,5-2,5</td>
<td>-1,5</td>
</tr>
<tr>
<td></td>
<td>2,5-3,5</td>
<td>-0,9</td>
</tr>
<tr>
<td></td>
<td>3,5-4,5</td>
<td>-0,4</td>
</tr>
<tr>
<td>-6,0 bis -7,3</td>
<td>2,5-3,5</td>
<td>-2,0</td>
</tr>
<tr>
<td></td>
<td>3,5-4,5</td>
<td>-0,8</td>
</tr>
<tr>
<td></td>
<td>5,5-6,5</td>
<td>-0,5</td>
</tr>
<tr>
<td>-7,3 bis -8,8</td>
<td>2,5-3,5</td>
<td>-2,9</td>
</tr>
<tr>
<td></td>
<td>3,5-4,5</td>
<td>-0,8</td>
</tr>
<tr>
<td></td>
<td>5,5-6,5</td>
<td>-0,4</td>
</tr>
</tbody>
</table>

*) in 100 cm Höhe.

gewünschten Ausmass abzustufen und unter Kontrolle zu halten. Im einzelnen ist zu den Zahlen der Übersicht folgendes zu sagen:

Bei Strahlungsfrosten von –1,5 bis –2,5 °C genügen zur Schadenverhütung 1,5 mm Niederschlag, bei Advektivfrosten mit Windgeschwindigkeiten von 1,5 bis 2,5 m/sec wird dagegen bereits eine Regendichte von 1,5 bis 2,5 mm benötigt, um die Pflanzentemperatur nicht unter –1,0 °C sinken zu lassen.

Bei stärkeren Strahlungsfrosten mit Tiefsttemperaturwerten von –4,7 bis –5,1 °C, in deren Bereich die meisten auftretenden Spätfröste in unserem Klimabereich fallen, werden 2,5 bis 3,5 mm Niederschlag benötigt. Bei Advektivfröstern mit Wind der bereits genannten Geschwindigkeit steigt die benötigte Regendichte auf 3,5 bis 4,5 mm an.

Bei Strahlungsfrosten mit Temperaturen von –6,0 bis –7,3 °C, die verhältnismässig selten auftreten, werden bereits 3,5 bis 4,5 mm benötigt, während bei Advektivfröstern mit der bereits mehrfach genannten Windgeschwindigkeit bis 2,5 m/sec, wie sie im Frühjahr 1957 vereinzelt aufgetreten sind, Regendichten von 5,5 bis 6,5 mm notwendig werden. Diese Regendichten sind bereits so hoch, dass sie bei schweren Böden in der Ebene zur Verschlammung und am Hang zur Erosion führen können.

Die letzte Temperaturstufe beweist, dass bei Strahlungsfrosten von –7,3 bis –8,8 °C Schäden noch mit der gleichen Regendichte verhindert werden können, wie bei Temperaturen von –6,0 bis –7,3 °C, dass aber bei Advektivfrost mit der höchsten von uns zum Einsatz gekommenen Regendichte von 5,5 bis 6,5 mm keine Schutzwirkung mehr erzielt werden konnte. Hier liegt also die Grenze der Wirksamkeit der Frostschutzbewegung.

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4. DER EINFLUSS DER HÖHE UND DER AUFFANGFLÄCHE DER PFLANZEN

Zur Klärung der Frage nach der Temperaturbeeinflussung als Folge unterschiedlicher Auffangfläche wurden dünne Obstbaumzweige, auf die mehrere Fiederblättchen aufgelegt worden waren, an Stelle von Weinreben in 100 cm Höhe ausgelegt und die Messelemente dicht daran angebracht. Die Temperaturen wurden mit denjenigen verglichen, die in 20 cm Höhe an Erdbeerpflanzen gemessen wurden.

Bei der nachfolgenden Auswertung wurden nur solche Messstellen miteinander verglichen, die eine möglichst gleiche RD und Windgeschwindigkeit aufwiesen.

<table>
<thead>
<tr>
<th>TABELLE 3. Einfluss der Kulturhöhe auf die Pflanzentemperatur bei unterschiedlichen Lufttemperaturen, Windgeschwindigkeiten und Regendichten</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lufttemperatur °C</td>
</tr>
<tr>
<td>Höhe über dem Erdboden cm</td>
</tr>
<tr>
<td>RD mm</td>
</tr>
<tr>
<td>Windgeschwindigkeit m/sec</td>
</tr>
<tr>
<td>Tiefstemperatur °C</td>
</tr>
<tr>
<td>Temperaturdifferenz °C</td>
</tr>
</tbody>
</table>

Mit Ausnahme der Temperaturstufe von -2,7 °C bis -3,1 °C zeigt Tabelle 3, dass die verringerte Auffangfläche in 100 cm Höhe einen Temperaturabfall von 0,5 °C bis 0,8 °C gegenüber der bodennahen Messstelle aufweist. Unter der Voraussetzung, dass 1 qcm in 100 cm Höhe die gleiche Wassermenge erhält wie in 20 cm Höhe, kann diese Differenz unseres Erachtens nur darauf zurückzuführen sein, dass die in 100 cm Höhe frei ausgelegte Messstelle voll von der umgebenden Luft umspült wird, während sich in 20 cm Höhe die freierdende Erstarrungswärme einer vergrößerten Auffangfläche bemerkbar macht. Die registrierten Unterschiede sind – dessen sind wir uns bewusst – verhältnismäßig gering, doch muss auf die sehr kleine Fläche hingewiesen werden, innerhalb deren die Ergebnisse gewonnen wurden. Sie zeigen die Bedeutung der Höhe und der Auffangfläche unterschiedlicher Kulturen in Bezug auf die Wirksamkeit der Frostschutzberegnung. Somit kann ein Frühkartoffelbestand oder Erdbeeranpflanzung mit der gleichen Wassermenge vor einem stärkeren Frost geschützt werden als z.B. ein Weinberg oder bei gleichen Frostgraden kann ein geschlossener niedriger Pflanzenbestand mit einer geringeren RD vor Frostschaden bewahrt bleiben als ein hoher.

5. DIE AUFHEBUNG DER UNTERKÜHlung

Auf den sogenannten Unterkühlungseffekt, wonach gut abgehärtete Pflanzen Temperaturen bis zu etwa -2,0 bis -2,5 °C ohne Schaden ertragen können, sei kurz hingewiesen. Die Unterkühlungsmöglichkeit des Zellsaftes bedeutet, dass Pflanzen oder deren Blüten erst zwischen -2,0 bis -2,5 °C vollständig
erfrieren. Durch die Beregnung wird dieser natürlicher Unterkühlungseffekt vorwiegend durch die Eisschuppierung auf der Pflanze, wahrscheinlich aber auch zusätzlich durch den sogenannten Schütteleffekt der auffallenden Regentropfen aufgehoben. Die beregnete Pflanze kann dann bereits bei etwa -0,5 bis -1,0°C erfrieren wenn nicht durch die Verwendung einer ausreichend hohen Regendichte für die Zufuhr der notwendigen Wärmemenge gesorgt wird. Somit ist der Frostschaden auf unzureichend beregneten Flächen bei schwachen Frösten meist stärker, als wenn überhaupt keine Frostschutzberegnung durchgeführt wird. Wir konnten bei Endivien Salat mehrfach beobachten, dass unberegnet gebliebene Bestände im Spätwinter Temperaturen bis -4°C ohne jeden Frostschaden überstanden, dagegen in der Randzone die unzulänglich beregneten Bestände restlos erfroren waren. Durch Beregnung können die Pflanzen somit grundsätzlich frostanfälliger. Die Anfälligkeit hat weiterhin zur Folge, dass bei starken Frösten 100 %-iger Schaden auftritt, wenn bei zu langer Unterbrechung bzw. zu langsamer Strahlrohrumkehrung die zum Einsatz kommen- den Regendichten nicht voll wirksam werden, oder wenn trotz kurzer Unterbrechung die Regendichten im Verhältnis zu den herrschenden Tiefstemperaturen zu gering sind, um nach Aufhebung der Unterkühlung der Pflanzen diesen noch einen vollen Schutz zu gewähren.

Die Ausführungen haben gezeigt, dass bei Beachtung der spezifischen Wir kungsfaktoren die Frostschutzberegnung einerseits nach wie vor das sicherste Mittel zur Verhütung von Schäden durch Spät- und Frühfröste darstellt, dass ihrer Schutzwirkung andererseits jedoch Grenzen gesetzt sind!

Die von uns für einen sicheren Schutz ermittelten Regendichten stimmen mit den von KIDDER (USA) gemachten Angaben gut überein, sie sind jedoch etwas niedriger als die Angaben von ROGERS (Grossbritannien) BUSSINGER (Niederlande), PEYER (Schweiz) und LEHMANN (Deutschland), möglicherweise dadurch bedingt, dass wir zunächst ausschliesslich mit niedrigen Kulturen gearbeitet haben.

Die von uns gefundenen Regendichten stellen Grenzwerte dar, die zur Erzielung eines vollständigen Frostschutzes jedoch als Minimum zu gelten haben. Diese Regendichten müssen daher auch an jeder Stelle der beregneten Fläche tatsächlich fallen! Je ungleichmässiger die Wasserverteilung eines Regners ist, um so höher muss die zur Anwendung kommende mittlere Regendichte bemessen sein. Die Gleichmässigkeit der Wasserverteilung der Regner spielt bei dem Für und Wider der Frostschutzberegnung daher eine ausschlaggebende Rolle! Bei Windeinwirkung ist wegen des stärkeren Wärmeentzuges und wegen der hier unvermeidbaren schlechteren Wasserverteilung mit wesentlich höheren Regendichten als bei Windstille zu rechnen. So ist bei einer Windgeschwindigkeit von 2,5 m/sec und Frostgraden zwischen -6,0 bis -7,3°C ein sicherer Frostschutz durch Beregnung technisch noch durchaus möglich; wirtschaftlich wird er in diesem Falle jedoch nicht mehr zu vertreten sein!

Bei annähernd gleicher Regendichte wurden in 1 m Höhe von etwa 0,5–0,8°C tiefe Temperaturen registriert als in 20 cm Höhe. Diese Differenz wird darauf zurückgeführt, dass in Bodennähe die Erstarrungswärme einer grösseren Auffangfläche zur Geltung gelangt. Höhe bzw. Auffangfläche der Kulturen sind somit für das Ausmass der Forstschutzwirkung der Beregnung von grosser Bedeutung.
Das Auftreten verstärkter Frostschäden bei Unterberegnung erfordert einen zu erwartenden Tiefsttemperaturen angemessenen gleichmäßig verteilten Regenhöhe je Stunde und daher einen ausreichend engen Abstand der Regner.

Die unvermeidliche Unterbrechung in der Randzone mahnt darüber hinaus zur Vorsicht gegenüber den Nachbarn, erfordert somit einen angemessen weiten Abstand der Regner von der Grenze.

**DISKUSSION**

**VAN DEN BERG:**

Ist der Zweck der Vorwegberegnung eine Anfeuchtung des Bodens oder der Pflanze? Was gilt im allgemeinen für den Einfluss des Bodenwasserhaltes auf die Verhütung von Nacht­frostschäden?

**Antwort:**

Mit der Vorwegberegnung wird die gründliche Anfeuchtung des Bodens einige Tage vor Beginn des Eintretens der Nachtfröste angestrebt. Dabei ist die Anfeuchtung der Pflanze nicht zu vermeiden, an sich aber unerwünscht, da durch die Anfeuchtung der Pflanze, allerdings auch durch die Anfeuchtung der Bodenoberfläche, während und alsbald nach der Beregnung Verdunstungskälte entsteht.

Feuchter Boden leitet dann aber tagsüber bei Sonnenschein eingestrahlte Wärme viel besser. So speichert ein feuchter Boden mehr Wärme als ein trockener. Diese tagsüber gespeicherte Wärme wird in der Nacht wieder an die Bodenoberfläche geleitet und erwärmt so die bodennahen Luftschichten und schützt niedrige Kulturpflanzen bei schwachen Frösten völlig vor Frostschäden. Bei mäßigen Frösten treten nur geringe Schäden auf.

**BROUWER:**

Wie lange können Pflanzen ohne Schaden geringe Fröste ertragen?

**Antwort:**

Im Tiefgefrierraum waren abgehärtete Tomatenjungpflanzen 55 Minuten lang einer Temperatur ausgesetzt, die zwischen 0° und -2,7° C (durch die Thermostatschaltung der Kältemaschine bedingt) schwankte. Während dieser 60 Minuten wurde 3mal eine Tiefsttemperatur von -2,7° C gemessen. Die Pflanzen erlitten hierbei nur sehr leichte Frostschäden an den unteren Blättern. Eine längere Einwirkung dieser Temperaturen auf die Pflanzen wurde bisher nicht untersucht.

**BAARS:**

Durch Beregnung wird der Wassergehalt der Pflanzen vermehrt und dadurch die Salzkonzentration des Zellsaftes verringert. Dadurch wird die Pflanze empfindlicher, weil der Gefrierpunkt des Zellsaftes höher wird; vielleicht ist das auch eine plausible Erklärung für die steigende Empfindlichkeit der Pflanzen bei der Frostschutzberegnung.

**Antwort:**

Durch Beregnung zur Verhütung der Spätfröste dürfte der Wassergehalt der Pflanzen nicht wesentlich ansteigen, da der Boden zu dieser Zeit (Mitte April bis Mitte Mai) meist noch ausreichend feucht ist. Durch ein gegebenenfalls leichtes Ansteigen des Wassergehaltes der Pflanzen kann der Gefrierpunkt jedoch nur unwesentlich in etwa um 0,1-0,2° C heraufgesetzt werden. Bei der Aufhebung der Unterkühlung wird die „kritische“ Temperatur jedoch um 1,5-2,0° C erhöht. Somit dürfte die Aufhebung der Unterkühlung die Hauptursache für das Ansteigen der Frostempfindlichkeit der Pflanzen bei der Frostschutzberegnung sein.

**ASLYNG:**

Wie können Sie den Nacht­frost und seine Intensität voraussagen?

**Antwort:**

BEREGNUNGSVERSUCHE IN DÄNEMARK

FR. HEICK
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In der letzten Hälfte des vorigen Jahrhunderts wurden die Wasserläufe entlang in Dänemark viele Anlagen gebaut, wo man durch Stemming des Wassers und durch Kanalsysteme die niedrig liegenden Flächen überrieselte und hierdurch erreichte man auf oft mageren Erdböden bedeutende Graserträge. Hierbei handelte es sich überwiegend um Düngungsbewässerung, aber als der Kunstdünger allmählich billiger wurde und die Arbeitskraft teuer wurde, wurde es sehr schwierig solche Anlagen mit finanziellem Vorteil zu treiben, und wir haben jetzt nur noch einzelne in Betrieb.


Nach dem Erscheinen der Leichtmetalprohren mit Schnellkupplungsanordnung und drehendem Verteiler sind die Beregnungsversuche wieder vom Staatlichen Versuchsunternehmen für Pflanzenbau aufgenommen worden, aber diesmal auf sehr leichtem Sandboden auf dem staatlichen Versuchshof „Store Jyndevad“.

Die ersten Versuche wurden hier im Jahre 1946 angefangen und sie wurden mit nur zwei Abteilungen durchgeführt, nämlich beregnet und unberegnet. Die Versuche waren einjährig, und sie wurden mit normalgedüngten Früchten wie Gerste, Kartoffeln, Runkelrüben und Kleegras durchgeführt. Nach dem Versuchsplan wurde die Regenmenge in Mai bis 60 mm ergänzt, und die in Juni bis 80 mm, die in Juli bis 100 mm, und die in August bis 120 mm ergänzt. Die Regenmenge von jeden zehn Tagen wurde bis zu einem Drittel der obigen Zahlen ergänzt.

Die Bonitätszahlen der Versuchsfläche sind 20–22 auf einer hundert teiligen Skala, und die Beschaffenheit geht aus folgenden Zahlen hervor:
Das Wasser wurde einem Wasserlauf entnommen. Es hatte einen Inhalt von 2,2 mg N/l, Spuren von P, 2,6 mg K/l und 70,4 mg CaO/l. Das Wasser enthielt also nur winzige Mengen von Pflanzennährstoffen.

Die Versuche dauerten sechs Jahre und die Ergebnisse sind im 456. Bericht vom Staatlichen Versuchsunternehmen für Pflanzenbau veröffentlicht. Von den Hauptergebnissen soll genannt werden, dass Gerste im Durchschnitt 82 mm Kunstregen per Jahr bekam. Der Körnertrag stieg von 16,8 hkg per Hektar auf 26,2 hkg per Hektar oder mit 56 %. Die Kartoffeln bekamen 78 mm Kunstregen und hier stieg der Trockenstoffertrag der Knollen von 49,1 hkg auf 59,6 oder mit 21 %. Der gesamte Trockenstoffertrag der Wurzel und des Krauts der Futterzuckerrüben ergab für unberegnet 123,2 hkg und für beregnet 144,9 hkg. Im Verhältnis zu Getreide sind grosse Erträge von Runkelrüben auf dem leichten Boden geerntet worden. Die Steigerung des Trockenstoffertrags betrug 18 %.

Klee grasse wurde in den Versuchs jahren durchschnittlich 117 mm Kunstregen zugeführt, und hier wurde der Ertrag sowohl im grünen Zustand als auch in Trockenstoff und Eiweißinhalt gemessen. Das zur Beregnung benutzte Grassfeld war mit einer Mischung von Klee und Gras bewachsen, und durch die Beregnung wurde der Ertrag des Klees grösser als der des Grases. Die Ertragssteigerung wurde 113 % als Grünmasse, 68 % als Trockenstoff und 77 % für den Inhalt von Eiweiss.

Die Beregnung ist technisch leichter in einem Grassfeld durchzuführen als in anderen Früchten und da es so aussieht wie wenn die Ertragssteigerung hier sowohl am sichersten als auch am grössten ist, und da der Klee für unsere Milchkühe sehr wertvoll ist, ist es berechtigt wenn die Gras- und Kleefelder bei der Beregnung ein Vorrecht haben.

Linie parallel mit der Hauptwasserleitung, und die Abteilung, die der Leitung am nächsten war, wurde nach Bedarf beregnet. In jeder Abteilung wurde ein Düngungsversuch eingelegt mit folgenden vier Fragen:

a. vollständig gedüngt
b. ohne Phosphorsäure
c. ohne Kali
d. ohne Stickstoff


Auf zwei Versuchsanstalten haben wir jetzt eine Beregnung nach Verdampfungsmesser begonnen. Bei einer Nettoverdampfung von 20 mm geben wir Kleegras 20-30 mm, beziehungsweise 40 mm Kunstregen.


In speziellen Versuchen haben wir die Wirkung der Beregnung zur Verhinderung von Frostschaden in Frühkartoffeln untersucht. Die Frostschutzwir-
kung der Beregnung ist ja hier auf der Konferenz von Herrn Dr. Witte in einem speziellen Vortrag behandelt worden, und ich will hier nur auf Bericht Nummer 565 von dem Staatlichen Versuchsunternehmen für Pflanzenbau hinweisen, der leider nur auf dänisch vorliegt. Hier sind Versuche von fünf Jahren auf Store Jyndevad referiert worden und Schutzwirkungen bei ungefähr 3° Celsius scheinen sicher. In unserem Fall handelt es sich um Temperatursenkung auf Grund grosser Wärmeausstrahlung unter gewissen Wetterverhältnissen. Eine frostschützende Wirkung ist bei direkter Beregnung in Frostnächten und am Tage vorher, so dass der betreffende Boden gut durchweicht war, gemessen. Es handelt sich in diesem Fall wahrscheinlich um eine Wirkung, die von der Erhöhung der spezifischen Wärme und Wärmeleitungseigenschaft des Bodens herstammt.


**SUMMARY**

*Sprinkling experiments in Denmark*

Experiments carried out during the period 1919 to 1924 showed that sprinkling of crops as strawberries, peas, flower cabbage and early potatoes was remunerative. This was not true at least on loamy soils in the case of grain crops. From 1946 experiments were carried out on light sandy soils. Especially when sprinkling barley, potatoes, fodder beets and clover grass pastures large increments of yield were obtained. Sprinkling of grain crops as a cover crop for clover and grass gave a favourable effect on the yield of the pastures in the next year.

In a crop rotation experiment a clear interrelation between sprinkling and fertilization was found in particular with potassium and nitrogen.

In the case of grassland the yield increased linearly with the amount of irrigation water applied, even at rates of 200 mm. per month during summer. Other experiments are now carried out in Denmark on the properties of sprinkling water taken from open canals and ditches and from pumping wells, on sprinkling as a method to prevent damage caused by night frost, on the technical aspects of sprinkling, as well as on the right time of sprinkling.

**DISCUSSION**

**Smith:**

What is a fodder unit used to measure the increased yield resulting from irrigation and fertilizing.

**Answer:**

1 fodder unit = 1 kg. barley.
During the last 20 years sprinkling irrigation has become more and more common in Sweden. In this connection the question of using water from the Baltic for irrigation purposes has also been discussed. If this were possible, large areas of arable land along the eastern coast of Sweden, where the precipitation in the early summer is generally low, could be irrigated. The salt content in the Baltic varies considerably, but broadly speaking it decreases towards the north and increases rapidly with the depth. Thus, in the sound of Kalmar, the salt content at the surface is 0.7 to 0.8 per cent, whereas off Stockholm it is about 0.5 per cent.

In order to determine if it is possible to use water from the Baltic, some field experiments have been carried out by the Institute of Agricultural Hydrotechnics at two different places. The first series of these experiments were performed on a permanent pasture at the estate of Häringe, situated on the coast, the second series at the farm of Edesnäs on the island of Utö. Both places lie about 3 Swedish miles south of Stockholm, and in both cases the salt content of the water was approximately 0.6 per cent. The soil at Häringe was a loamy clay and at Utö a sandy, very permeable, soil.

In the experiments at Häringe the effect of salt water was compared with the effect of fresh water (groundwater), in the Edesnäs experiments only the effect of salt water in relation to unirrigated plots was studied. The vegetation on the experiment field of Häringe consisted of a mixture of different grasses and white clover; at Edesnäs single grasses and leguminous plants were tested, e.g. white clover and red clover, lucerne, cock's foot grass (Dactylis glomerata), fescue grass (Festuca pratensis), meadow grass (Poa pratense), and timothy grass (Phleum pratense).

As to the yields in the different experiments, it may be mentioned that on the clay soil there was an increase with irrigation with salt water as well as with fresh water, but the effect of fresh water was considerably higher. Thus, as an average for four years and for different irrigation intensities, the effect of the salt water was about 55 % of that of the fresh water. However, even if the salt water had a lower effect than the fresh water, the conclusion could be drawn from the Häringe experiments that irrigation with water from the Baltic was very valuable for increasing the grass yield during dry periods, which of course is very important in the case of pastures.

In the Edesnäs experiments, the effect on the yields of the different grasses and leguminous plants was in most cases very good. Generally speaking, no decrease with the time in the salt water effect was noted during an experiment period of four years. For the grasses there was an average increase in yield of about 60 %. It could also be stated that among the different grasses tested, the real pasture types, e.g. fescue grass and meadow grass, were very resistant to the salts added by the water. The salt water effect on the timothy grass, on the
other hand, was positive as well as negative, and for that reason the value of the irrigation in this case can be discussed.

As to the leguminous plants, the salt water irrigation had a still higher effect with increases in yield above 100%. However, not all of the tested leguminous crops were resistant. Thus, after four years, only white clover, bird's foot trefoil (*Lotus corniculatus*) and lucerne was left. The white clover certainly gave the best results of all in the beginning, but its production capacity decreased with the time. Red clover, brown bean, soy bean and lupin seemed to be especially sensitive to salt water.

It may also be mentioned, that in the Edesnäs experiments the salt water had an average effect that was higher than the fresh water effect in the experiments at Häringe.

Irrigation with salt water caused considerable changes in the salt uptake. For all the plants the uptake of Na was strongly increased, whereas the uptake of Ca successively decreased with the result that the food became more and more poor in Ca. As to the P content in the plants, there was a general increase due to the irrigation.

Due to the amounts of salts added by the irrigation, there were marked changes in the chemical composition of the soils. A strong leaching of Ca and an accumulation of Na occurred. After two year's irrigation, 25% of Na added by the water was accumulated in the layer 0 to 50 cm. of the sandy soil, and between 40 and 90%, depending on the irrigation intensity, in the layer 0 to 60 cm. of the clay soil. It proved that there was no decrease of exchangeable K in the soil, in spite of the fact that the molar ratio Na:K in the salt water was about 50:1. Contrary to Ca, there seems to be no risk for the salt water irrigation to produce any unfavourable effect on the content of K in the soil available for the plants.

In some laboratory experiments carried out some years ago I was interested in determining if the permeability of the soil could be decreased by salt water irrigation. In these experiments such an effect was clearly noted. A corresponding effect in the field experiments at Häringe and Utö, however, was not found.

From the results carried out in Sweden concerning the possibilities to irrigate with salt water, it seems therefore justified to make the conclusions that if the salt content is not higher than 0.6%, there are no risks for irrigation of pastures. Even if water from the Baltic has not the same effect on the vegetation as fresh water, it can evidently be a good substitute. It must be noted, that all grasses and leguminous plants have not the same tolerance to salt water. On the other hand, after some time the composition of the vegetation cover ought to have changed in such a direction that it is well fitted to the altered conditions.

As far as can be judged from the field experiments, sea water with a concentration of 0.5 to 0.6% has no such unfavourable effects on the soil that its use in the long run may be limited. Of course some leaching owing to ionic exchange, especially of Ca, cannot be avoided. This leaching must when needed be compensated therefore by chalking and, consequently, the cost for it must be included in the irrigation costs.

If water from the Baltic where the salt concentration is higher than in the experiments here discussed can be used is difficult to state. It is possible that even water from the sound of Kalmar (salt content approximately 0.8%) will not have any unfavourable effects, but the experiments do not justify such a suggestion. Here the best way seems to be direct observations and experiments.
in the field. Anyhow, the water in the sound no doubt has a too high salt content for being useful for irrigation purposes.

**Summary**

For a long time the question of using water from the Baltic has been a subject for discussion in Sweden. If this were possible, large areas of arable land along the eastern coast could then be irrigated. In two places south of Stockholm, on a clay soil and a sandy soil respectively, the Institute of Agricultural Hydrotechnics has carried out some field irrigation experiments with salt water. The Baltic has there a salt content of 0.6%. The vegetation cover in one case consisted of a mixture of different grasses and leguminous plants, in the other single pasture plants were tested. In both experiments considerable increases in the yields were obtained. Yet, the effect of salt water was inferior to the effect of fresh water. Not all plants, however, had the same tolerance to salt water. Thus, timothy grass, red clover and lupins seemed to be too sensitive. The uptake of Na was strongly increased in all the plants tested, whereas the uptake of Ca successively decreased. There was also a considerable leaching of Ca from the soils. No decrease in the permeability of the soil was found.

**Zusammenfassung**

*Bewässerung mit Salzwasser in Schweden*

Since 1941 a number of irrigation experiments have been carried out in Sweden by the Institute of Agricultural Hydrotechnics at the Royal Agricultural College. During the first years the experiments mainly concerned the effect of irrigation upon different farm crops, especially permanent pastures. This is quite natural, because irrigation is a rather new method in Swedish agriculture. Thus, it was for the farmers of primary interest if the yields could in average be increased by irrigation to a more considerable extent for a series of years. Now it seems evident that this is the case. In this connection it may only be mentioned that the irrigation experiments on permanent pastures in the middle of Sweden have given in average a yield increase of about 30%.

However, there are many other questions than the effect upon the crops alone that are of importance in sprinkling irrigation. Sprinkling is an effective, but also rather expensive irrigation method. Thus, it is of great economical importance that the irrigation water is used by the plants in the best possible way. During the last years some experiments have been performed by the Institute of Agricultural Hydrotechnics concerning among other things the loss of water and how the water penetrates into the soil and is distributed in the root zone.

In these investigations two different types of sprinklers were used. The first one was a sprinkler of the hitherto common type with a capacity of approximately 8 to 10 mm. per hour. The second one was a small sprinkler with a rather low capacity, approximately 3 mm. per hour. This latter type is now more and more used in practical irrigation in Sweden. The two sprinkler types were compared during different weather conditions with regard to temperature, wind velocity and relative air humidity.

The field experiments were performed on a permanent pasture on a sandy soil at Ultuna. In order to determine the amount of water lost by evaporation during the irrigation, a water measurer was fixed to the pressure pipe. A great number of simple rain gauges with a spacing of 2 × 2 metres were placed over the area reached by the sprinkler. A comparison between the pumped quantity of water, according to the water measurer and the sum of water spread over the area, measured in the gauges, then gave the amount of water evaporated during the time the sprinkler was in action.

Furthermore, from the rain gauge data the uniformity of the water distribution within the irrigated area could also be determined, as well as the possibilities of counteracting irregularities in this distribution by placing the sprinklers in different ways (triangular or rectangular).

Some data from irrigation experiments in 1955 and 1956 are given in table 1. From the table it appears very strikingly that the loss of water was much greater at day irrigation than at night irrigation, owing to the higher temperature and wind velocity and the lower relative air humidity in the first case. In this respect...
the loss of water was on the whole independent of the type of sprinkler. Thus, under unfavourable weather conditions, the loss of water exceeded 30 %, whereas the evaporation was generally very low when sprinkling at night, about 2 to 6 %. From an economical point of view, sprinkling at night must no doubt be very advantageous compared with day sprinkling.

Table 1. Results from irrigation experiments by the Institute of Agricultural Hydrotechnics, 1955 and 1956

<table>
<thead>
<tr>
<th>Experiment nr.</th>
<th>Wind velocity m/sec</th>
<th>Temp. °C</th>
<th>Rel. air humidity</th>
<th>Irrigated area m²</th>
<th>Distributed water m³</th>
<th>Measured water in the system m³</th>
<th>Loss of water in per cent</th>
<th>Irrigation run/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>I D</td>
<td>3.0</td>
<td>25</td>
<td>42</td>
<td>924</td>
<td>19.12</td>
<td>12.87</td>
<td>32.7</td>
<td>2.3</td>
</tr>
<tr>
<td>II N</td>
<td>0.1</td>
<td>13</td>
<td>89</td>
<td>1256</td>
<td>19.12</td>
<td>18.86</td>
<td>1.4</td>
<td>2.5</td>
</tr>
<tr>
<td>III N</td>
<td>2.0</td>
<td>18</td>
<td>73</td>
<td>1040</td>
<td>18.80</td>
<td>17.97</td>
<td>4.4</td>
<td>2.4</td>
</tr>
<tr>
<td>IV D</td>
<td>2.1</td>
<td>23</td>
<td>40</td>
<td>756</td>
<td>18.40</td>
<td>14.56</td>
<td>20.9</td>
<td>2.8</td>
</tr>
<tr>
<td>V D</td>
<td>3.7</td>
<td>23</td>
<td>45</td>
<td>1148</td>
<td>38.75</td>
<td>33.57</td>
<td>13.4</td>
<td>9.8</td>
</tr>
<tr>
<td>VI D</td>
<td>5.1</td>
<td>26</td>
<td>35</td>
<td>1268</td>
<td>38.71</td>
<td>33.22</td>
<td>14.2</td>
<td>8.5</td>
</tr>
</tbody>
</table>

Results from 1955

I N | 2.8 | 13 | 68 | 900 | 16.29 | 14.90 | 8.5 | 3.0
II D | 5.3 | 18 | 41 | 712 | 16.04 | 12.36 | 22.9 | 3.8
III N | Calm | 7 | 89 | 1364 | 17.47 | 16.43 | 6.0 | 2.1
IV D | 5.0 | 23 | 54 | 728 | 17.27 | 11.27 | 34.7 | 4.0
V N | 0.8 | 13 | 95 | 2700 | 47.86 | 46.88 | 2.1 | 5.9
VI D | 7.4 | 17 | 63 | 1827 | 53.96 | 46.14 | 11.7 | 9.1
VII N | 1.2 | 13 | 75 | 3069 | 34.50 | 33.95 | 1.6 | 5.4
VIII D | 3.2 | 25 | 36 | 2205 | 51.34 | 41.92 | 37.8 | 7.8

Results from 1956

IX D | 4.7 | 17 | 79 | 493 | 15.19 | 12.59 | 17.1 | 5.6
X D | 3.2 | 22 | 42 | 605 | 16.76 | 12.12 | 27.7 | 4.6
XI D | 3.7 | 20 | 50 | 1152 | 33.99 | 28.70 | 15.6 | 9.8
XII D | 4.5 | 14 | 73 | 1087 | 33.11 | 30.35 | 8.3 | 10.4

D = sprinkling in day-time  N = sprinkling at night

1955 I-IV results with the small sprinkler, V-VI results with the big one

1956 I-IV results with the small sprinkler, V-VIII results with the big one

IX-X

From the results, however, we can see that the loss of water was somewhat greater by using the small sprinkler than when the big one was used, especially in day irrigation. This is evidently due to the considerably longer irrigation time in the first case with the continuously wetted soil surface exposed to evaporation. Thus, this type of sprinkler generally ought to be used at night, if loss of water should be avoided in the best possible way.

The sprinkling experiment showed very clearly that both sprinklers were to about the same extent rather sensitive to the wind. Even at a wind velocity of about 2 to 3 m/sec there were considerable deformations of the irrigated area and irregularities in the water distribution. Only when it was quite calm, the distribution was regular, but also in this case there were differences in irrigation
intensity with the distance from the sprinkler, in so far that the irrigation intensity decreased from the sprinkler to the periphery. In spite of the fact that the sprinklers used in the experiments were no doubt technically well constructed, there was a marked gradient and as mentioned, with wind there were also more or less deformations of the irrigated area. It is doubtful if it is on the whole possible to construct a sprinkler giving an ideal water distribution together with being less sensitive to the wind.

However, in practical irrigation the deficiencies here mentioned are not of the same importance. Since the sprinkler during its rotation irrigates a circular, or a fairly circular area, it is necessary that these areas to some extent overlap each other, otherwise there will be some spots that are not irrigated. And by this overlapping the irregularities of the water distribution are markedly counterbalanced at the same time. In table 2 some data are presented by which this is illustrated. The irrigation data in the table are obtained by supposing the sprinklers to be placed in the corners of a triangle, resp. a rectangle. It appears from the table how the overlapping increases with decreased spacing.

**Table 2. Distribution of water by single sprinklers in combination, irrigation experiments 1956**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Sprinklers between sprinklers in m</th>
<th>Sprinklers in combination, m²</th>
<th>Irrigated area by single sprinkler, m²</th>
<th>Irrigated area by sprinklers in combination, m²</th>
<th>Relative irrigated area, %</th>
<th>Irrigation intensity, mm/hour</th>
<th>Over-irrigation at arrangement of sprinklers, %</th>
<th>Uniformity coefficient at arrangement of sprinklers</th>
</tr>
</thead>
<tbody>
<tr>
<td>III N</td>
<td>24×24</td>
<td>1364</td>
<td>576</td>
<td>42.2</td>
<td>4.8</td>
<td>87.5</td>
<td>91.7</td>
<td>71.1</td>
</tr>
<tr>
<td></td>
<td>24×30</td>
<td></td>
<td>720</td>
<td>52.9</td>
<td>3.8</td>
<td>68.9</td>
<td>79.4</td>
<td>82.6</td>
</tr>
<tr>
<td></td>
<td>30×30</td>
<td></td>
<td>900</td>
<td>66.0</td>
<td>3.0</td>
<td>46.2</td>
<td>51.6</td>
<td>76.8</td>
</tr>
<tr>
<td></td>
<td>30×36</td>
<td></td>
<td>1080</td>
<td>79.2</td>
<td>2.5</td>
<td>26.7</td>
<td>28.9</td>
<td>56.8</td>
</tr>
<tr>
<td>IV D</td>
<td>18×18</td>
<td>728</td>
<td>324</td>
<td>44.5</td>
<td>5.8</td>
<td>88.9</td>
<td>88.9</td>
<td>71.3</td>
</tr>
<tr>
<td></td>
<td>18×24</td>
<td></td>
<td>432</td>
<td>59.3</td>
<td>4.4</td>
<td>62.0</td>
<td>65.7</td>
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<td></td>
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<td></td>
<td>576</td>
<td>79.1</td>
<td>3.3</td>
<td>25.7</td>
<td>27.8</td>
<td>37.3</td>
</tr>
<tr>
<td>VII N</td>
<td>36×36</td>
<td>3069</td>
<td>1296</td>
<td>42.2</td>
<td>12.6</td>
<td>88.2</td>
<td>91.7</td>
<td>64.8</td>
</tr>
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<td></td>
<td>36×42</td>
<td></td>
<td>1512</td>
<td>49.3</td>
<td>10.8</td>
<td>75.6</td>
<td>82.2</td>
<td>64.0</td>
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<td></td>
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<td>1764</td>
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<td>VIII D</td>
<td>24×24</td>
<td>2205</td>
<td>720</td>
<td>32.7</td>
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<td></td>
<td>900</td>
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<td>89.0</td>
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<td></td>
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<td>1080</td>
<td>49.9</td>
<td>12.9</td>
<td>74.2</td>
<td>80.0</td>
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<td></td>
<td>36×36</td>
<td></td>
<td>1296</td>
<td>58.8</td>
<td>10.8</td>
<td>54.2</td>
<td>63.2</td>
<td>65.6</td>
</tr>
</tbody>
</table>

1) Relative irrigated area = $100 \times \frac{\text{irrigated area by sprinklers in combination}}{\text{irrigated area by the single sprinkler}}$

2) 4 m² non-irrigated
3) 28 m²
4) 12 m²
5) 9 m²

In the two last columns the so-called uniformity coefficients are given. This coefficient is obtained by the following formula

$$F = 100 \left(1 - \frac{\sum(x - \bar{x})^2}{xn}\right)$$
where

$$\frac{\Sigma (x - \bar{x})}{n}$$

is the average deviation from the mean irrigation $\bar{x}$, and $n$ the number of observations within the irrigated area. The higher the numerical value of the coefficient, the better is the water distribution.

From table 2 it is easily seen that a considerable overlapping is necessary, at least 50 to 60%, in order to get a good distribution. Thus, it is no disadvantage that overlapping cannot be avoided in sprinkling irrigation, on the contrary, it is advantageous from the point of view of water distribution. With great spacing between the sprinklers, the best distribution is obtained in triangular arrangement of the sprinklers, with decreased spacing an equally good or better distribution can be obtained in rectangular arrangement.

It is important to note that the irrigation intensity obtained by sprinklers in combination is considerably higher than the intensity with a single sprinkler. It is also probable that the loss of water, due to evaporation during the sprinkling, will be somewhat smaller if several sprinklers are used at the same time. This was not studied more closely in the experiments. Anyhow, there is a certain tendency in table 1, where the four last experiments of 1956, numbers IX to XII, were carried out using two identical sprinklers at the same time.

Finally, some data may also be mentioned concerning the distribution of the irrigation water in the soil, obtained in the experiments.

At a number of places within the irrigated area, the water content in the soil in each 10 cm. horizon, down to a depth of 50 cm., was determined immediately before irrigation, also 2 to 4 hours and 2 to 2½ days after irrigation. On the whole there was a fairly good correspondence between the quantity of water added by irrigation and the amount of water found in the soil profile 3 hours after irrigation. It can also be stated that after 2 days there was a marked change of the water distribution in the profile in so far that the water content had decreased in the top soil (down to 20 cm.) and increased in the underlying horizons. As soon as the field capacity of the soil in an experiment was exceeded, the excess of water rapidly percolated under the root zone depth. It must be remembered, however, that the soil was a fairly permeable sandy one.

**SUMMARY**

During the years 1955 and 1956 some sprinkling irrigation experiments concerning the loss of water by evaporation have been carried out by the Institute of Agricultural Hydrotechnics on a sandy soil at Ultuna, Uppsala. The experiments clearly indicated that the loss of water is much greater in day- than in night irrigation. The losses increase to some extent if the sprinkling time is increased. For that reason preferably sprinklers with a relatively small irrigation intensity ought to be used in night irrigation.

All types of sprinklers now in the market have probably about the same sensitiveness for changes of the weather conditions. Irregularities in the water distribution almost always occur. It is doubtful whether it is possible to construct a sprinkler giving an ideal water distribution. Yet, these irregularities are markedly counterbalanced if the sprinklers are placed in such a way that a fairly great overlapping (at least 50 to 60%) is obtained. It must be noted, however, that the irrigation intensity under such conditions is much higher than the intensity obtained by a single sprinkler. Preliminary experiments also indicated that the loss of water by evaporation is diminished if several sprinklers are used at the same time in combination.
ZUSAMMENFASSUNG

Wasserverluste bei künstlicher Beregnung


Die Beregnungsapparate, welche heutzutage zur Verfügung stehen, zeigen nahezu immer dieselbe Empfindlichkeit bei Änderungen der Witterung. Dies hat notwendig eine unregelmässige Wasserverteilung zur Folge. Es ist sogar fraglich, ob es überhaupt im Bereich des Möglichen liegt ein Apparat mit idealer Wasserverteilung zu konstruieren. Diese unregelmässige Verteilung des Wassers jedoch kann zum grössten Teil nivelliert werden wenn man die Apparate in dieser Weise hinstellt dass eine grosse (wenigstens 50-60\%) Überlappung erreicht wird. Es sei jedoch darauf hingewiesen, dass unter diesen Umständen die Beregnungsintensität bedeutend höher ist als die, welche man erhält bei einem einzigen Apparat. Wie aus den Ergebnissen einiger vorläufigen Experimente hervorgeht, werden die Wasserverluste infolge der Verdunstung kleiner, wenn man gleichzeitig mehrere Beregnungsapparate in Kombination benutzt.
SOME PRINCIPLES AND POSSIBILITIES OF SUBSOIL IRRIGATION (particularly in relation to sandy soils)

C. Kalisvaart

(Landbouwwetenschappelijke Afdeling, Directie Wieringermeer, Kampen, Nederland)

At this conference subsoil irrigation (subirrigation) can be discussed best by comparing it where possible with sprinkler irrigation.

As sprinkling may be called artificial (controlled) rainfall, so subirrigation may be called artificial (controlled) seepage.

Sprinkler irrigation is supplying the suspended water in the root zone of the soil directly by infiltration from the surface. Subirrigation is supplying the free groundwater by maintaining a certain water level in the water conduits (ditches, trenches, tile lines) from which through the subsoil the water infiltrates (seeps) into the field.

The water supplied by sprinkling is directly available for the plants; the groundwater supplied by subirrigation has still to rise by capillary action into the root zone. Here is a fundamental difference between the two methods of irrigation as regards the water provision in the root zone. This is schematically shown in the figures A and B for a coarse sandy soil with 40% pores, a field capacity of 15 volume %, a height of capillary rise of 50 cm. and an assumed root zone of 30 cm.

When this soil is dry and under arid conditions water is supplied by sprinkling (see fig. A) the water content in the root zone will vary periodically between 15 and n % (n depending on different circumstances which need not be mentioned here). When, however, by subirrigation the groundwater table is maintained at a fixed height, there will be a constant water content above the groundwater table as shown by line c in figure B. In this case the water content in the root zone is dependent on the height of the soil surface above the groundwater table. With the soil surface corresponding with S 1 in the figure the root zone of 30 cm. will be totally dry and the crop will not benefit from subirrigation. Not before the soil surface corresponds with S 4 will the whole root zone be moist, and it may be supposed that in this case the soil surface at S 5 (that is with the groundwater table 40 cm. beneath the soil surface) will give the best results for the crops. The water content in the root zone then varies in the figure from approximately 8 % at its top to appr. 38 % at its base.

It may be admitted, that for the plants it would be better if the water content was higher at the top and lower at the base, as is the case with sprinkling. At the base there is a possibility of air deficiency causing a shallower rooting.

Under arid conditions there is also the possibility of salinization of the soil, resulting from the continuous upward movement of groundwater during the growing season, which is not overcome by an equal or greater downward movement of rain-water. Therefore, in general, subirrigation cannot be satisfactorily applied in arid and semi-arid regions.
In humid and fairly humid regions there are, however, other complications, caused by the irregularly changing of the weather conditions during the irrigation season, of which in general the rainfall is the most important one, although changes in temperature, atmospheric humidity, etc. affect these conditions as well.

Sprinkling is subject to the effect of the natural rainfall only in so far as its application scheme is affected by it and drainage problems may occur. In the case of subirrigation, rain, however, gives a totally different pattern of the water content in the soil, as is shown in figure B by line r. Suspended water is added to the capillary risen water. If rain is abundant, the groundwater table will also rise and the water content in the root zone and the air deficiency will increase still more (for instance S 5 will become S 6). This means that the groundwater table has to be lowered by lowering the water level in the supply ditches.

It will be necessary to determine the groundwater table for each situation which gives the best water/air ratio for the crops. But this can only be done by reasoning, for it is practically impossible to determine exactly by experiments in the field, what the optimal groundwater table has to be under the frequently varying weather conditions of a humid climate.

But even if one could determine it exactly, it would be impossible to realize it completely in practice, because it would require too great a capacity and intensivity of the supply and discharge conduits and constructions, especially of the tile lines. It would also lead to an excessive use of water and labour. In one word it would be too expensive. This signifies in practice that the water level in the supply conduits is maintained at a „normal” level except under extreme weather conditions. This means again that the groundwater table in the fields may be somewhat too high or too low in wet and dry periods, respectively. But it does not follow that the crop yields will decrease, for although op-
tima no doubt exist, in practice there will always be a margin between too dry and too wet. In principle it is the same problem as when deciding in practice on the frequency of sprinkling.

This "normal" water level in the subirrigation conduits, however, is not always the same. It varies under influence of the season, the crops and the soil. In the beginning and at the end of the growing season it is generally lower than in the rest of the season. Regarding the influence of the crops on the required water level, it may be said that, for instance, a pasture and a field of sugar beets are different in their requirements. Grass begins to grow and to evaporate already early in the spring and generally is shallow rooting, whereas sugar beets are late in spring and deep rooting. Therefore the normal level for sugar beets will begin later and will be somewhat lower.

Of greater importance is the influence of the soil type as is shown in the table and in figure C for three sandy soils in the Northeast Polder. It is not only the height of the capillary rise which is important but also its rapidity. This rapidity of the capillary rise is in some way proportional to the permeability of the soil and inversely proportional to the height above the groundwater table. It is for this reason, that the very fine Blokzijl sand has a desirable groundwater table in continuous dry periods of 60 cm., although the capillary rise is 120 cm.

Characteristics (average data) of three sandy soils in the Northeast Polder

<table>
<thead>
<tr>
<th></th>
<th>Urk sand</th>
<th>Ramspol sand</th>
<th>Blokzijl sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay content</td>
<td>2%</td>
<td>6%</td>
<td>6%</td>
</tr>
<tr>
<td>Humus</td>
<td>0.3%</td>
<td>0.6%</td>
<td>0.8%</td>
</tr>
<tr>
<td>Calcium carbonate</td>
<td>0.2%</td>
<td>7%</td>
<td>7%</td>
</tr>
<tr>
<td>Fineness of the sand fraction, expressed in U-figure (specific surface)</td>
<td>55</td>
<td>75</td>
<td>275</td>
</tr>
<tr>
<td>Capillary rise</td>
<td>40 cm.</td>
<td>50 cm.</td>
<td>120 cm.</td>
</tr>
<tr>
<td>Permeability (in 24 hours)</td>
<td>4 m.</td>
<td>3 m.</td>
<td>0.3 m.</td>
</tr>
<tr>
<td>Desirable groundwater table in continuously dry periods</td>
<td>-35 cm.</td>
<td>-40 cm.</td>
<td>-60 cm.</td>
</tr>
<tr>
<td>Harmless groundwater table in wet periods?</td>
<td>-40 cm.</td>
<td>-50 cm.</td>
<td>-90 cm.</td>
</tr>
<tr>
<td>Maximum distance of the tile lines</td>
<td>30 m.</td>
<td>25 m.</td>
<td>8 m.</td>
</tr>
</tbody>
</table>

It follows also that in these fine sandy soils it is less permissible to maintain a "normal" level in the water conduits under varying weather conditions. On soils which are still more impermeable it will be totally impossible to subirrigate.

Also a field with great horizontal differences in soil type does not lend itself so well to subirrigation.

The maximum distance apart of the tile lines is also a matter of permeability. In general, this distance should be fixed so as to ensure that an evapotranspiration of 4 to 5 mm. in 24 hours causes not more than 10 cm. difference between the water table above the tile lines and in the middle of two lines.

The possibilities of subirrigation compared with those of sprinkling largely depend upon the natural hydrological condition of the field. It must be possible to maintain the required groundwater table without too great losses of water through the subsoil; in other words the natural groundwater table must not be too deep. When subirrigating, not only these subsoil water losses have to be provided for, but to reach the desirable water table between the tile lines, their
distance apart has to be relatively smaller. A water loss equal to the above mentioned evapotranspiration, already means a doubling in number of the tile lines. Moreover, seepage may be initiated or increased in the surrounding district. In this case it will be more rational to apply sprinkler irrigation, the more so as the drainage costs of tile lines can then mostly be saved entirely.

It will be clear that in undulating areas, subirrigation will require a greater amount of levelling operations than sprinkler irrigation.

**ZUSAMMENFASSUNG**

Einige Grundsätze und Möglichkeiten der Untergrundbewässerung (besonders in bezug auf Sandböden)

Die Wasserversorgung der Gewächse bei Untergrundbewässerung und bei Beregnung zeigen einige fundamentale Unterschiede. In den Figuren A und B ist dieses schematisch dargestellt für einen groben Sandboden mit 40% Porien, maximal 15 Volumen % pendulärem Filmwasser, einer kapillaren Steigung des Bodenwassers von 50 cm und einer bewührzten Zone von 30 cm.


Dieser normale Wasserstand variiert aber unter Einfluss der Jahreszeiten, der Gewächse und der Bodenarten.

Im Frühjahr und im Spätsommer sind die Wasserstände niedriger als in der Hochsaison. Für Weideland ist der erwünschte Wasserstand höher und auch früher im Jahre höher als für ein Zuckerrübenfeld. Von grösstem Einfluss ist aber die Bodenart; dieses wird deutlich wenn wir uns Figur C und die Tabelle ansehen. Die Höhe der kapillaren Steigung in erster Stelle, aber auch ihre Geschwindigkeit sind bestimmend für den erwünschten Wasserstand. Der geringen Geschwindigkeit wegen ist z.B. für den feinen Blokzijlsand der erwünschte Grundwasserstand in dauernd trockenen Perioden nur 60 cm, obwohl die kapillare Steighöhe 120 cm ist. Für noch undurchlässigere Böden wird Untergrundbewässerung unmöglich sein.


**LITERATUR**


**DISCUSSION**

HALLGREN:

A limiting factor for the irrigation methods mentioned by Mr. KALISVAART seems to be the permeability of the soil. The soil must evidently have a good permeability and, furthermore, be homogeneous permeable. Another question: it is possible to use ordinary tile pipes without risk for damages of the pipes due to infiltration by silt and fine sand. In Sweden this method, as I know, is not used, anyhow not to an extent worthwhile. But a similar method in some places is used, viz. damming up the water in the open ditches in diked areas where the soil
often has a certain amount of gyttja and therefore has a good permeability owing to the permanent cracks.

*Answer:*

There is a great influence of the permeability on the possibilities of subirrigation. The soil has also to be as much as possible homogeneous, specially in horizontal direction. In vertical direction different soil layers will give complications, but will not always make subirrigation impossible, especially if there is a permeable layer of sufficient thickness under the desirable water table.

Normally there are used earthenware or concrete ordinary drainpipes; the joints are covered with peat. There is no abnormal risk for stops. Principally there is not a difference in using tile pipes or open trenches. In general subirrigation of heavy soils will be impossible because of their being impermeable or their becoming impermeable when subirrigating.

**Molemaar:**
The method of subirrigation described by Mr. KALISVAART is a method of water table control; a method which depends on a permeable subsoil for its successful use. A variation of this method is practiced in the Upper Snake River Valley of the State of Idaho, where a shallow top soil overlies a gravelly subsoil. There the water table is at weekly intervals raised quickly to the surface of the soil and then immediately dropped to below the crop root zone.

The method described by Mr. VUORINEN is independent of the level of the water table and is truly a method of applying irrigation water below the surface of the land. Several other methods of supplying the growing crop with moisture from below are practiced in various parts of the world and all of them can be thought of as methods of subirrigation.

**Visser:**
In my opinion the suggestion of Mr. MOLENAAR to distinguish between soil-water level control and subirrigation might be useful. Soil-water level control, as a dual purpose method might comprise drainage as well as irrigation. Subsoil irrigation might mean the application of water in the subsoil without the help of the watertable. We should ask our colleagues from England and U.S.A. to coin the right terminology.

**Schonnopp:**
Definitionen der verschiedenen Typen von Subirrigation in Deutschland:

2. Graben-Einstau = Auffüllung der Bodenfeuchte mit Fremdwasser vom Graben her.

**Mohrmann:**
Proposal to split up the term subirrigation in:
1. subirrigation by water level control
2. intermittant subirrigation

**Højendaal:**
It must be considered a definite advantage of subsoil irrigation that it is possible to use such nasty smelling waste water as the sewage from towns or villages.

*Answer:*
Ich befürchte dass Benützung von nicht vorgereinigtem schmutzigen Abfallwasser für Unterflurbewässerung Beschwerde aufliefern wird durch Verstopfung der Grabenwände oder eventuell der Röhren und ihre Umgebung.
THE ECONOMIC STATUS OF SPRINKLING IRRIGATION IN DESERT SANDY SOILS OF EGYPT

ZEIN EL ABEKINE

(Department of Soil Science, Cairo University, Egypt)

INTRODUCTION

Agriculture in Egypt is almost totally dependent on artificial irrigation with Nile water. Only 55% of the annual discharge of 79 km$^3$ of the river water is used, the rest, is still to be harnessed by constructing more water controls and reservoirs.

The presently available water serves about 75% of the cultivable area of 3.2 million hectares, which is formed by the river valley and delta. When a complete control over the river is achieved it will be necessary to expand into the adjacent desert. Reconnaissance soil surveys show that, with the exception of the coastal region, almost all the soils, of levels not more than 20 m. above the adjacent valley floor, have coarse or fine sandy textures. The coastal region is formed of loam or clay loam calcareous grey semi desert soils.

The use of these areas for agriculture will need mechanical lifting up of water from the river, thus their requirements would be of major economical importance. Irrigation by flooding is the system used now in Egypt, and although it is feasible and economical in alluvial soils that need no lifting up of water and permit very little losses through percolation, yet it will be most uneconomical in areas of sandy soils of comparatively high levels to be made arable in the future.

Four factors render the flooding system of irrigation uneconomical, namely:

a. The undulating or hilly topography of the desert which needs expensive levelling or terracing.

b. The low water retentive power of sand which demands repeated irrigation at short intervals thus doubling or trebling the usual requirements.

c. The high permeability of the sand which causes considerable water losses in both water conveyance and irrigation application.

d. The continual losses of soil nutrients under the leaching effect of excessive irrigation.

All four difficulties may be overcome by replacing the flood system with a sprinkling irrigation system.

RESEARCH

Three years of experimentation in Tahreer Province, which is an area typical for the adjacent desert soils, proved a full success and a complete suitability of the sprinkling irrigation system for growing main crops on a sound economical basis.
The studies included determination of:

a. Mechanical analyses of typical soil profiles.
b. Field capacity and moisture equivalent of representative profiles.
c. Moisture gains and losses.
d. Water use by main crops.
e. Field observations on wind effect on water distribution by sprinklers.

RESULTS AND CONCLUSIONS

The prevailing soil texture in Tahreer Province is sandy with coarse and fine sand fractions between 80 % and 97 %. All samples contain calcium carbonate between 0.5 % and 3.0 %. Gravel exists in some profiles, forming up to 20 % of the soil. A few profiles contain accumulations of gypsum at a depth of about 2 to 3 feet.

The moisture equivalent ranges from a minimum of 2 % and a maximum of 10 % with an average of 6 %, while the field capacity of the top 60 cm. of the profiles ranges between 2.5 and 10.0 cm. of water.

The climate prevailing in Tahreer Province is that of sub-tropic arid regions. Meteorological observations started in the district in 1954. The figures in table 1 represent mean values of 4 years.

### TABLE 1. Climatological normals of Tahreer Province 1954-1957

<table>
<thead>
<tr>
<th>Months</th>
<th>Temperature °C</th>
<th>Relative humidity mean of day</th>
<th>Rainfall mm.</th>
<th>Wind velocity mean of day 0–12</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max.</td>
<td>Min.</td>
<td>mean of day</td>
<td>Max.</td>
</tr>
<tr>
<td>January</td>
<td>19.4</td>
<td>5.1</td>
<td>12.1</td>
<td>67</td>
</tr>
<tr>
<td>February</td>
<td>20.8</td>
<td>5.9</td>
<td>13.5</td>
<td>58</td>
</tr>
<tr>
<td>March</td>
<td>24.3</td>
<td>8.5</td>
<td>16.8</td>
<td>55</td>
</tr>
<tr>
<td>April</td>
<td>28.9</td>
<td>11.8</td>
<td>20.6</td>
<td>48</td>
</tr>
<tr>
<td>May</td>
<td>32.8</td>
<td>15.4</td>
<td>24.4</td>
<td>44</td>
</tr>
<tr>
<td>June</td>
<td>36.4</td>
<td>18.9</td>
<td>27.0</td>
<td>44</td>
</tr>
<tr>
<td>July</td>
<td>36.8</td>
<td>20.6</td>
<td>27.9</td>
<td>50</td>
</tr>
<tr>
<td>August</td>
<td>36.5</td>
<td>20.4</td>
<td>27.7</td>
<td>55</td>
</tr>
<tr>
<td>September</td>
<td>33.6</td>
<td>18.3</td>
<td>25.9</td>
<td>57</td>
</tr>
<tr>
<td>October</td>
<td>31.0</td>
<td>15.5</td>
<td>23.5</td>
<td>58</td>
</tr>
<tr>
<td>November</td>
<td>26.3</td>
<td>11.5</td>
<td>19.6</td>
<td>63</td>
</tr>
<tr>
<td>December</td>
<td>21.0</td>
<td>6.9</td>
<td>14.1</td>
<td>66</td>
</tr>
<tr>
<td>Mean</td>
<td>29.0</td>
<td>13.2</td>
<td>21.1</td>
<td>56</td>
</tr>
</tbody>
</table>

The distribution of water by sprinklers is fairly uniform on calm days. Insignificant irregularities take place with northern or north-western breezes, but distorted distribution occurs when southern to western winds prevail, that accompany the passage of atmospheric depressions during February, March and April.

Water consumption of alfalfa, clover (Trifolium), beans (Vicia faba), potatoes, groundnuts, wheat, barley, flax and maize were determined and their consumptive use coefficients are presented in table 2.

The total water requirements for any area cultivated under a 3 years rotation, as the one presented in table 3, would be 1030 mm. a year.
Table 2. Consumptive use of main crops

<table>
<thead>
<tr>
<th>Crop</th>
<th>Period</th>
<th>Consumptive factor for period F</th>
<th>Total Consumptive use U</th>
<th>Consumptive use coefficient for period</th>
</tr>
</thead>
<tbody>
<tr>
<td>alfalfa</td>
<td>All year</td>
<td>71.3</td>
<td>60.0</td>
<td>0.85</td>
</tr>
<tr>
<td>clover</td>
<td>Oct. 15-May 10</td>
<td>34.3</td>
<td>25.7</td>
<td>0.75</td>
</tr>
<tr>
<td>beans</td>
<td>Nov. 1-Apr. 30</td>
<td>28.2</td>
<td>15.2</td>
<td>0.56</td>
</tr>
<tr>
<td>potatoe</td>
<td>Feb. 1-May 15</td>
<td>18.8</td>
<td>10.4</td>
<td>0.55</td>
</tr>
<tr>
<td>groundnuts</td>
<td>May 1-Aug. 15</td>
<td>26.6</td>
<td>15.9</td>
<td>0.60</td>
</tr>
<tr>
<td>wheat</td>
<td>Nov. 10-May 10</td>
<td>27.4</td>
<td>11.5</td>
<td>0.42</td>
</tr>
<tr>
<td>barley</td>
<td>Nov. 15-Apr. 30</td>
<td>25.8</td>
<td>10.3</td>
<td>0.40</td>
</tr>
<tr>
<td>flax</td>
<td>Nov. 15-Apr. 30</td>
<td>25.8</td>
<td>15.5</td>
<td>0.60</td>
</tr>
<tr>
<td>maize</td>
<td>July 1-Oct. 15</td>
<td>25.2</td>
<td>15.1</td>
<td>0.60</td>
</tr>
</tbody>
</table>

Table 3. Three years rotation

<table>
<thead>
<tr>
<th>Percent of area</th>
<th>1st year</th>
<th>2nd year</th>
<th>3rd year</th>
</tr>
</thead>
<tbody>
<tr>
<td>33.3</td>
<td>clover — fallow</td>
<td>wheat — groundnuts</td>
<td>flax — fodder</td>
</tr>
<tr>
<td>33.3</td>
<td>wheat — groundnuts</td>
<td>flax — fodder</td>
<td>clover — fallow</td>
</tr>
<tr>
<td>33.3</td>
<td>flax — fodder</td>
<td>flax — fodder</td>
<td>wheat — groundnuts</td>
</tr>
</tbody>
</table>

Table 4 gives the water requirements for this rotation given in mm. for half monthly periods, the duration of irrigation cycles, considering that the gift of water is 30 mm. in each application, and the percentage of the area occupied by crops.

Table 4. Total water requirements, irrigation cycles and occupied areas in a 3 years rotation

<table>
<thead>
<tr>
<th>Date</th>
<th>Requirements</th>
<th>Cycle days</th>
<th>Occupied area %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan. 1-15</td>
<td>48</td>
<td>9</td>
<td>100</td>
</tr>
<tr>
<td>Nov. 1-15</td>
<td>54</td>
<td>8</td>
<td>100</td>
</tr>
<tr>
<td>Feb. 1-15</td>
<td>49</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>Nov. 16-28</td>
<td>49</td>
<td>9</td>
<td>100</td>
</tr>
<tr>
<td>March 1-15</td>
<td>54</td>
<td>8</td>
<td>100</td>
</tr>
<tr>
<td>June 1-15</td>
<td>51</td>
<td>7</td>
<td>85</td>
</tr>
<tr>
<td>May 1-15</td>
<td>51</td>
<td>7</td>
<td>85</td>
</tr>
<tr>
<td>June 16-30</td>
<td>45</td>
<td>6</td>
<td>63</td>
</tr>
<tr>
<td>July 1-15</td>
<td>48</td>
<td>6</td>
<td>63</td>
</tr>
<tr>
<td>Aug. 1-15</td>
<td>42</td>
<td>6</td>
<td>58</td>
</tr>
<tr>
<td>Sept. 1-15</td>
<td>37</td>
<td>6</td>
<td>53</td>
</tr>
<tr>
<td>Oct. 1-15</td>
<td>34</td>
<td>6</td>
<td>48</td>
</tr>
<tr>
<td>Nov. 1-15</td>
<td>31</td>
<td>7</td>
<td>43</td>
</tr>
<tr>
<td>Dec. 1-15</td>
<td>27</td>
<td>7</td>
<td>38</td>
</tr>
<tr>
<td>Dec. 16-31</td>
<td>24</td>
<td>8</td>
<td>38</td>
</tr>
</tbody>
</table>

129
These water requirements include an addition of 20% for losses by evaporation during the irrigation process, and 30% for losses from conveyance and percolation. Without the sprinkling system these requirements could not be given, distributed over the land surface, because of the previously mentioned difficulties.

ECONOMICAL VIEWPOINTS

Apart from the better managing-economy of these desert soils under a sprinkling irrigation system, there is a greater economy in the use of Nile water. It has been estimated by the Ministry of Public Works that the total expenses of controlling, storing and distributing 1 km.³ of the Nile water are about 0.5 million Egyptian pounds i.e., about one shilling for a hundred cubic metres of water.

Thus from the point of view of water-economy, sprinkling irrigation is of very great importance in the future expansion into the desert of arable soils, bearing in mind the limited resources of the Nile river.

According to the present prices of initial installation of sprinkling irrigation in Egypt, the following figures are estimated for furnishing and running a unit area of 1 acre (0.42 hectare) with this system, where the lifting head is 20 m.:

<table>
<thead>
<tr>
<th></th>
<th>(£.E.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Initial installations</td>
<td></td>
</tr>
<tr>
<td>Motors and pumps</td>
<td>4,000</td>
</tr>
<tr>
<td>Main, secondary and fly lines</td>
<td>76,000</td>
</tr>
<tr>
<td>Buildings for motors</td>
<td>4,000</td>
</tr>
<tr>
<td>Total</td>
<td>84,000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>(£.E.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Annual depreciation and running expenses</td>
<td></td>
</tr>
<tr>
<td>Motors and pumps</td>
<td>840</td>
</tr>
<tr>
<td>Main and secondary lines and nozzles</td>
<td>5,100</td>
</tr>
<tr>
<td>Buildings repairs</td>
<td>300</td>
</tr>
<tr>
<td>Water used about 4,350 m.³</td>
<td>2,050</td>
</tr>
<tr>
<td>Power: 1,170 kw. hour × 0.007 (£.E.)</td>
<td>8,190</td>
</tr>
<tr>
<td>Total</td>
<td>16,480</td>
</tr>
</tbody>
</table>

It may be stated that these initial costs are nearly the same as those for levelling, canal-digging, and lining of the same area under a flood irrigation system, but the running expenses are definitely lower for sprinkling irrigation, considering the following points:

1. The water requirements for the flooding system are about 3500 mm. a year.
2. The power needed to lift up 100 mm. at 7 atmospheres in the sprinkling system is equal to the power that lifts up 3500 mm. at 2 atmospheres in the flooding systems.
3. The man power needed for the sprinkling irrigation is 16% of that needed in flooding.
4. The sprinkling system allows for introducing mechanized agriculture, while the flooding system is a hindrance, owing to its network of canals, ditches and ridges and small plots.
5. Considerable amounts of money and energy are wasted in clearing canals.
and ditches and keeping them in good order, as they are highly susceptible to wind- and water erosion especially in the first few years of use.

6. In the flood system, from 10% to 15% of the served area is wasted in ditches and canals and their embankments, whereas nothing is wasted in the sprinkling system.

**Summary**

When full control over the total discharge of the Nile river is achieved, considerable areas of Egyptian desert-regions are bound to be reclaimed and used for agriculture. The soils of these areas are of fine or coarse sandy texture having not less than 80% of sand fraction, between 0.5% and 3.0% CaCO₃, and moisture equivalents between 2% and 10%. A flooding system of irrigation will not be economical on these soils because of their hilly topography, their low retentive power, and high permeability.

Three years of experimentation in Tahreer Province, a typical area for these soils, proved a full success and the suitability of the sprinkling irrigation system for growing main crops on an economical basis. By determining the consumptive use coefficients for main crops it was found that the total water requirements for an area under 3 year rotation that includes growing wheat, groundnuts, flax, green fodder and clover, would be about 1000 mm. a year. Irrigation cycles did range between 10 days in winter and 6 days in summer, using 30 mm. in every cycle.

The initial costs for an Egyptian acre - 0.42 hectar -, would be about 84 £.E., with annual depreciation and running expenses of about 16.5 £.E.

The initial costs are nearly the same as those of levelling, terracing, and canal digging and lining for flood irrigation, but the running expenses are definitely lower considering the following points:

1. The water requirements for the flooding system are about 3500 mm.
2. The power needed to lift up 1000 mm. at 7 atmospheres in the sprinkling system is equal to that needed to lift up 3500 mm. at 2 atmospheres in the flooding system.
3. Man power needed for sprinkling is 16% of that needed for the flooding system.
4. The sprinkling system allows for introducing mechanized agriculture, while flooding systems are a hindrance owing to the network of canals, ditches and ridges and small plots.
5. Considerable amounts of money and energy are wasted in clearing canals and ditches and keeping them in good order, as they are highly susceptible to wind- and water erosion, especially in the first years of use.
6. In the flood system from 10% to 15% of the served area is wasted in ditches and canals and their embankments, whereas nothing is wasted in the sprinkling system.

**Zusammenfassung**

Die Wirtschaft der künstlichen Beregnung auf sandigem Boden der ägyptischen Wüste

Wenn in der Zukunft die Abflussverhältnisse des Nils vollständig kontrollierbar sein werden, können ausgedehnte Gebiete der ägyptischen Wüste melioriert und für die Landwirtschaft benutzt werden. Die Böden dieser Gebiete sind aus Fein- oder Grobsande zusammengestellt, die Sandfraktion umfasst mehr als 80% des Materials, der Gehalt an CaCO₃ der Sande beträgt 0,5% bis 3,0% und die Wasserkapazität 2% bis 10%. Auf Grund der topographischen Verhältnisse (hügelig) und der Bodenbeschaffenheit (starke Durchlässigkeit und niedrige Feuchtigkeitsgehalte der Böden) können von wirtschaftlichem Standpunkte aus Bewässerungssysteme nicht angelegt werden.

In der Tahreer Provinz, ein charakteristisches Gebiet für diese Böden, wurden für den Bau von Hauptgewächsen mit gutem Erfolg während drei Jahre künstliche Beregnungsexperimente durchgeführt. Der Wasserverbrauch der Hauptgewächse wurde bestimmt, wobei es sich zeigte, dass der Gesamtbedarf an Wasser für das Gebiet mit einer dreijährlichen Fruchtfolge von Weizen, Erdnüsse, Flachs, Grünfutter und Klee ungefähr 1000 mm/Jahr beträgt. Die Bereg-
nungszykli schwanken zwischen 10 Tage im Winter und 6 Tage im Sommer; in jeder Periode war der Verbrauch 30 mm.

Der Grundpreis einer ägyptischen „acre“ (0,42 Hektar) beträgt rund £ 84; die jährliche Abschreibung und die Betriebskosten rund £ 16.5. Der Grundpreis ist nahezu derselbe als sämtliche Kosten für Egalisierung, Terrassierung und die Anlage von Gräben für die Bewässerung. Die Betriebskosten jedoch sind niedriger und zwar:

1. Der Wasserbedarf für das Bewässerungssystem beträgt rund 3500 mm.
2. Die Kraft um im künstlichen Beregnungssystem bei 7 Atm. 1000 mm aufzuheben ist dieselbe wie die Kraft um im Bewässerungssystem bei 2 Atm 3500 mm zu heben.
3. Die Arbeitskräfte welche man braucht für künstliche Beregnung sind nur 16% von jenen welche nötig sind für das Bewässerungssystem.
4. Bei der künstlichen Beregnung ist es möglich die Landwirtschaft mechanisch zu treiben, das Netzwerk von Kanälen, Gräben, und kleine Parzellen beim Bewässerungssystem verhindert jedoch die Mechanisierung der Landwirtschaft.
CALCULATION OF THE REMUNERATIVENESS OF SPRINKLER IRRIGATION

C. BAARS

(Proefstation voor de Akker- en Weidebouw, Wageningen, Nederland)

Up to now much attention has been paid to the research concerning the most favourable water supply. However, there is still a great lack in our knowledge of the remunerativeness of supplemental irrigation and only few investigations have been made on this part of the problem.

Ultimately the farmer wants to reach better financial results by means of sprinkling. When he intends to change over to sprinkler irrigation, he will make inquiries about its remunerativeness. It is not sufficient to tell him how much the increase in yield per crop, the water requirements of the crops and the costs of water per mm. per ha. will be. The relation of costs and returns is not so simple at all, for as a consequence of sprinkler irrigation the whole management changes and must of necessity change if sprinkler irrigation will be remunerative.

On dry soils mainly cereals are grown. It is well-known that in Western Europe only little profits can be made by sprinkling cereals. For a remunerative application of sprinkler irrigation it is necessary to change over to a more intensive management. The cereals have to be partly replaced by root crops, leguminous plants, grassland and eventually vegetables. As a consequence the gross income of the farm rises considerably but at the same time the expenses and the labour requirements go up. When we place the value of the increase in production against its costs, the difference will be the remunerativeness of the irrigation. Both the increase of returns and its costs are influenced by various factors, which are different for each farm.

If it is desired to know beforehand the remunerativeness of sprinkler irrigation for a certain farm, it is necessary to make an estimate, taking into account the particular circumstances of the farm such as available labourers, available capital, knowledge and interest of the farmer, waterholding capacity of the soil, parcelling, available buildings and machinery, etc.

In non-agricultural business economic planning is a standing procedure; for small farms it is not. There it is customary to rely on intuition, but if a drastic measure like irrigation is introduced without thorough preparation, the best result is never reached.

For drawing up an estimation of the remunerativeness a number of data are required, such as labour norms, manuring norms, feeding norms, production norms for irrigated crops, norms for the need of irrigation, etc. Specific norms for sprinkler irrigation are not available. In the Netherlands these norms are gathered on 15 experimental farms for sprinkler irrigation, among which are 2 co-operative farms. They are situated on various soils. Here the average yields of irrigated crops, the average need of irrigation and the need of labour for sprinkling under practical farming conditions are determined. With the
help of these norms estimates can be drawn up of the remunerativeness of sprinkler irrigation for other farmers intending to change over to sprinkling. In this way the farmer in question is informed about the profit that sprinkler irrigation of his farm may give, but at the same time he will notice how the farm management should change, how much should be invested and how much the labour requirements will increase.

With the help of an example we shall now consider the various constituent parts of the estimate of remunerativeness of sprinkler irrigation.

1. Estimate of the Increase in Income

In table 1 the value of the increase in yield in consequence of sprinkler irrigation has been calculated. On the debit side the yields of the non-irrigated farm occur, on the credit side those of the irrigated farm. For the non-irrigated farm we take the usual cropping scheme and the average yields which were really reached. Another method of calculation is only applied if it is evident that considerably higher yields could have been reached under existing conditions. For the yields of the irrigated farm we take the norms based on the yields obtained on well-managed experimental farms for sprinkler irrigation.

In drawing up the cropping scheme for the irrigated farm, one generally starts with grassland and fodder crops. Therefore it is necessary to establish first the desirable number of cattle. As a rule the available stable room is the limiting factor. Such a number of grass and fodder crops must be included in the cropping scheme that the fodder requirements of the cattle can be met. The remaining soil is available for the culture of cash crops. In drawing up a cropping scheme for the last mentioned crops, not only the financial profit should be considered but also the crop rotation and the labour requirements.

The yield of cash crops is evaluated at the mean market prices of the last few years. The grass and the fodder crops are evaluated on the basis of animal products, viz. the milk yield and the live-weight increase of the cattle. The milk yield per cow can be estimated higher for the irrigated farm only, if it is sure that without irrigation every year a considerable depression in milk yield occurred as a consequence of dryness. For the live-weight increase of the cattle a fixed norm is used.

2. Estimate of the Costs of Increase in Yield

Against the increase in the value of the yield are many extra expenses.

a. Operating costs of the sprinkler installation

Before drawing up a calculation of the operating costs of the sprinkler installation, it is necessary to make a scheme including an estimate for the irrigation equipment; only then the most important costs, as depreciation and interest, can be figured. For the fixed main lines and the pumping unit the depreciation may be spread over 20 years, for the portable laterals with sprinklers over 10 years. As a consequence of the depreciation the interest must be calculated on an average of 55 % of the invested capital.

In order to be able to calculate the cost of electricity or fuel, it is necessary to know at first the average annual time of application. From the observations on the experimental farms for sprinkler irrigation, norms have been drawn up for the average need for irrigation of the various crops on soils with different
### Table 1. Calculation of the value of the increase in yield by means of sprinkling 10 ha of the total of 11.44 ha; in Dutch guilders

<table>
<thead>
<tr>
<th>Without sprinkling</th>
<th>With sprinkling</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5 ha rye (2200 kg/ha; f 0.24 per kg)</td>
<td>f 1320</td>
</tr>
<tr>
<td>straw (4500 kg/ha; f 50 per 1000 kg)</td>
<td>f 563</td>
</tr>
<tr>
<td>2.3 ha oats with barley (2200 kg/ha; f 0.25 per kg)</td>
<td>f 1265</td>
</tr>
<tr>
<td>straw (3500 kg/ha; f 30 per 1000 kg)</td>
<td>f 242</td>
</tr>
<tr>
<td>1.0 ha potatoes (20000 kg/ha; f 50 per 1000 kg)</td>
<td>f 1000</td>
</tr>
<tr>
<td>0.5 ha peas (2300 kg/ha; f 0.40 per kg)</td>
<td>f 460</td>
</tr>
<tr>
<td>straw (2500 kg/ha)</td>
<td></td>
</tr>
<tr>
<td>0.3 ha fodder beet (55000 kg/ha)</td>
<td></td>
</tr>
<tr>
<td>0.6 ha red clover (6000 kg hay per ha)</td>
<td></td>
</tr>
<tr>
<td>0.1 ha carrots</td>
<td></td>
</tr>
<tr>
<td>(1.5) ha stubble turnips</td>
<td>for cattle ①</td>
</tr>
<tr>
<td>4.14 ha grassland</td>
<td></td>
</tr>
<tr>
<td>milk $7 \times 4000$ kg; f 0.27 per kg</td>
<td>f 7560</td>
</tr>
<tr>
<td>increase in live-weight $7 \times f 250$</td>
<td>f 1750</td>
</tr>
<tr>
<td>money earned by supplying pasture for 4 head of young cattle</td>
<td>f 400</td>
</tr>
<tr>
<td>gross increase in income by sprinkling</td>
<td>f 6848</td>
</tr>
<tr>
<td><strong>f 21408</strong></td>
<td><strong>f 21408</strong></td>
</tr>
</tbody>
</table>

1) 7 milk cows
2) 2 head of young cattle, 1 to 2 years old
3) 3 head of young cattle, less than 1 year old

### Notes

① 7 milk cows
② 4 head of young cattle, 1 to 2 years old
③ 4 head of young cattle, less than 1 year old
<table>
<thead>
<tr>
<th>Labour for</th>
<th>Hectares or number</th>
<th>Jan</th>
<th>Feb</th>
<th>March</th>
<th>Apr</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>Aug</th>
<th>Sept</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Total</th>
</tr>
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<tr>
<td>Rye</td>
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<td></td>
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<td>172.0</td>
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<td>Oats with barley</td>
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<td>Peas</td>
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<td>Fodder beet</td>
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<td>Sugar beet</td>
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<td></td>
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<td>456.0</td>
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<tr>
<td>Turnips (stubble crop)</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>260.0</td>
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<tr>
<td>Westerwolth rye grass (stubble crop)</td>
<td>(1.5)</td>
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<td>260.0</td>
</tr>
<tr>
<td>Ley</td>
<td>(4.50)</td>
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<td></td>
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<td>144.0</td>
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<tr>
<td>Permanent pasture (not sprinkled)</td>
<td>(1.44)</td>
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<td></td>
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<tr>
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<td>Haymaking</td>
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<td>152.0</td>
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<tr>
<td>Silage making</td>
<td>38 x 1000 kg</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>152.0</td>
</tr>
<tr>
<td>Dung dressing</td>
<td>100 x 1000 kg</td>
<td>1.5</td>
<td>100</td>
<td>50</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
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<tr>
<td>Milking and care of the milk cows and their calves</td>
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<td>216</td>
<td>220</td>
<td>220</td>
<td>220</td>
<td>176</td>
<td>176</td>
<td>176</td>
<td>216</td>
<td>176</td>
<td>176</td>
<td>220</td>
<td>220</td>
<td>2376</td>
</tr>
<tr>
<td>Porkers (average)</td>
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<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>1080</td>
<td></td>
</tr>
<tr>
<td>Chickens (average)</td>
<td>200</td>
<td>60</td>
<td>20</td>
<td></td>
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<td></td>
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<td></td>
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<td>140.0</td>
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<tr>
<td>Soil cultivation</td>
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<td></td>
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<td></td>
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<td>1080</td>
</tr>
<tr>
<td>Total, excluding sprinkling</td>
<td></td>
<td>310</td>
<td>410</td>
<td>484</td>
<td>452</td>
<td>591</td>
<td>608</td>
<td>546</td>
<td>511</td>
<td>446</td>
<td>548</td>
<td>536</td>
<td>544</td>
<td>5986</td>
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<tr>
<td>Sprinkling (maximum)</td>
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<td>120</td>
<td>120</td>
<td>95</td>
<td>95</td>
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<td>430.0</td>
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<tr>
<td>Total including sprinkling (maximum)</td>
<td></td>
<td>310</td>
<td>410</td>
<td>484</td>
<td>452</td>
<td>711</td>
<td>728</td>
<td>641</td>
<td>606</td>
<td>446</td>
<td>548</td>
<td>536</td>
<td>544</td>
<td>6416</td>
</tr>
<tr>
<td>Available (2 men)</td>
<td></td>
<td>528</td>
<td>528</td>
<td>528</td>
<td>528</td>
<td>616</td>
<td>616</td>
<td>616</td>
<td>616</td>
<td>616</td>
<td>616</td>
<td>528</td>
<td>528</td>
<td>6864</td>
</tr>
<tr>
<td>Shortage of labour (maximum)</td>
<td></td>
<td>528</td>
<td>528</td>
<td>528</td>
<td>528</td>
<td>616</td>
<td>616</td>
<td>616</td>
<td>616</td>
<td>616</td>
<td>616</td>
<td>528</td>
<td>528</td>
<td>6864</td>
</tr>
</tbody>
</table>
waterholding capacity. With the aid of these norms and the cropping scheme we can calculate the average annual water demand. As the pump capacity is known, the number of operating hours per year can be found and from this the cost of electricity or fuel may be calculated.

The labour necessary for operating the equipment consists mainly of moving the sprinkler lines. We suppose that a modern plant is used with a permanent main and portable lateral lines with rotary sprinklers. If it is known how many metres of pipe should be moved on an average per position (L), how many metres of pipe one man can move as an average per hour (f) and the number of times that the sprinkler line must be moved on the average per year, then the number of man hours can be calculated.

The number of times that the pipes must be moved on the average, can be calculated by dividing the average annual need for irrigation of the farm in litres (B) by the quantity that is given per position. This quantity can be found by multiplying the area in m² (O) by the application per position in mm. (d).

\[
\text{Labour requirements} = \frac{L \times B}{f \times O \times d}
\]

The area O can be calculated from the number and the spacing of the sprinklers. The application per position is also known; this is mostly 20 to 30 mm. The factor f, the length of sprinkler line in metres that one man can move per hour, is to be fixed on 150 for galvanized iron pipes of 60 and 70 mm. and on 200 for aluminium pipes 60 and 76 mm. These norms have been found on the experimental farms for sprinkler irrigation. In table 3 on the credit-side the cost of operating the sprinkler irrigation plant can be found.

**TABLE 3. Estimate of the remunerativeness of sprinkling**

<table>
<thead>
<tr>
<th>Gross increase in income (see table 1)</th>
<th>f 6848</th>
<th>Direct costs and labour requirements of sprinkling:</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. interest and depreciation</td>
<td>f 900</td>
<td></td>
</tr>
<tr>
<td>b. electricity</td>
<td>- 340</td>
<td></td>
</tr>
<tr>
<td>c. labour requirements of sprinkling 223 man hours (^1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>extra labour needed for the new cropping scheme 1215 man hours (^2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>extra costs of fertilizers</td>
<td>- 530</td>
<td></td>
</tr>
<tr>
<td>extra costs of seed</td>
<td>- 150</td>
<td></td>
</tr>
<tr>
<td>extra costs of concentrates and litter for extra cattle 4 × f 250</td>
<td>- 1000</td>
<td></td>
</tr>
<tr>
<td>other extra costs</td>
<td>- 735</td>
<td></td>
</tr>
<tr>
<td>net increase in income</td>
<td>- 3193</td>
<td></td>
</tr>
</tbody>
</table>

\(^1\) In this case the extra labour (1438 man hours) could be done by the two men available, so extra expenses were not necessary.

**b. Extra costs of fertilizers**

In consequence of the modification in the cropping scheme the consumption of fertilizers changes too. From the old and future cropping scheme and with the aid of the usual manuring norms, the extra costs of manuring can be calculated. In table 3 these costs have been stated on the credit-side.
c. Extra costs of seed

In consequence of the modification of the cropping scheme the costs of seed also change.

The calculation of this modification needs no further explanation. The extra costs are stated in table 3.

d. Extra costs of concentrates and litter for the cattle

In the new cropping scheme sufficient fodder for the cattle has to be planned. However, the extra milk cows need concentrates and litter too. For this a fixed norm per milk cow can be taken. The extra costs are included in table 3.

e. Various extra costs

These are: the increase of interest and depreciation, of the expenses for maintenance, insurance, etc., in consequence of the expansion of buildings, inventory and cattle. This item is often rather high. The extra costs have been stated in table 3. The investments in question have been mentioned in table 4.

f. Extra costs of labour

The labour required for operating the sprinkler system has already been considered.

In consequence of the intensification, the labour requirements of the whole farm do increase. For calculating the labour requirements we can take the usual norms of labour. From the cropping scheme and the stock of cattle of the old and new farm, the increase in labour requirements can be calculated. However in order to gain a better insight into the increase in the labour requirements and its costs, it is desirable to make a plan for the labour requirements per month of the whole irrigated farm, inclusive the sprinkler irrigation. The available supply of labour is included. From the plan it is seen in which months there is a shortage of labourers. If sufficient seasonal labourers can be found the calculation of the extra costs of labour is not difficult. In most cases, however, seasonal labour cannot be found, a permanent labourer must be employed and should be employed fully. Therefore it is important that the labour is spread favourably over the year and that the occurrence of peak periods is prevented when drawing up the cropping scheme. Peak periods can be smoothed out by mechanization and finally it is possible to use in this period a contractor.

In our example the labour requirements have increased considerably in consequence of the irrigation. In summer the labour requirements are higher than the supply of labour of two adult men, especially when there should be sprinkled to a large extent. As in this period the farmer's wife can assist, if necessary, no extra labourer will be needed. In this case full employment is reached by the irrigation.

In table 2 the data about labour requirements and supply of labour of the irrigated farm are given.

In table 3 the increase in income and its costs of production have been given. In the mentioned case the family income can increase considerably by means of sprinkler irrigation.
3. Estimate of the Investments

It is not only important that the farmer is informed about the remunerativeness of sprinkler irrigation; he also ought to know how much must be invested. Besides the cost of purchase of the irrigation equipment, large investments are necessary for the buying of extra cattle, for enlarging buildings and for the purchasing of extra machinery. Without these investments sprinkling will be less remunerative; but as a rule the farmer will highly undervalue these.

In table 4 the estimate of the investments is given. In this case the total amount is not high.

<table>
<thead>
<tr>
<th>Sprinkling equipment</th>
<th>$9,850</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 milk cows with their calves</td>
<td>$-5,000</td>
</tr>
<tr>
<td>Enlargement of cattle-house</td>
<td>$-1,500</td>
</tr>
<tr>
<td>1 fodder silo</td>
<td>$-500</td>
</tr>
<tr>
<td>1 haymaking machine</td>
<td>$-1,500</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$18,350</strong></td>
</tr>
</tbody>
</table>

Finally it should be remarked that the remunerativeness of irrigation cannot be predicted exactly, since the prices are subject to continual fluctuation.

However, for the existing price and cost level, we will be able to judge if irrigation of a farm will be remunerative and which working plan will be the most suitable. This is an important aid for the farmer as well for deciding to change over to sprinkler irrigation as for the further farm management.

**Summary**

For the farmer, who considers buying sprinkler equipment it is very important to know how much he will earn by sprinkling his farmland. Yet there are only few data available on this question. The difficulty is that the remunerativeness does not only depend on the water-holding capacity of the soil, but also to a large extent on the management of the farm. Sprinkling does pay only if the management is intensified. Fewer cereals will have to be grown and more root crops, pulses and eventually vegetables, and more cattle will have to be cultivated and kept. To what extent this is possible depends mainly on the labourers available. On every farm the degree of intensification will be different and so will the increase in income per acre. For every case, costs and returns of the non-irrigated farm have to be compared with the estimated costs and returns of the irrigated farm planned. Only in this way we can predict to what extent the changing over will presumably pay.

For such an estimate we need norms, not only the usual standards for labour, fertilization and feeding, but also standards for the yields of sprinkled crops, for the need for sprinkling and for the labour needed for moving the sprinkling tubes. In the Netherlands these specific irrigation standards are determined with the aid of 15 experimental farms for sprinkler irrigation.

**Estimate of the increase in yield**

We can calculate the value of the increase in yield by comparing the planned cropping scheme (with sprinkled crops) with the old one of the non-irrigated farm. For the value of the cash crops the average market price is taken. For the value of grass and other fodder plants, that of the gain in milk and the live-weight of the cattle is taken.

**Estimate of the expenses for obtaining the increase in yield**

The extra expenses are the following:

1. costs of the sprinkler equipment (depreciation, interest and cost of electricity or fuel);
b. costs of extra fertilizers for the new cropping scheme;
c. costs of extra seed for the new cropping scheme;
d. costs of extra concentrates and litter for the larger stock of cattle;
e. extra costs (depreciation, interest, cost of maintenance and insurance) for the larger buildings, the greater number of cattle and the extra machinery;
f. costs of extra man hours for moving the sprinkler equipment and for the new cropping scheme. For every month of the year the labour requirements of the to be sprinkled farm have to be compared with the labour available. If the new cropping scheme plus the moving of the sprinkler equipment will require more man hours, we must find out, how the gap will have to be filled and how much this will cost.

The remunerativeness of sprinkler irrigation is the difference between the value of the increase in yield and the expenses needed for obtaining this.

Such a calculation of the remunerativeness shows the farmer the profit of sprinkling and at the same time gives him a working plan. Besides that, he is informed on the extra labour requirements of the farm, when sprinkled, and on the investments needed.

ZUSAMMENFASSUNG

Die Berechnung der Rentabilität der Beregnung


Voranschlag des Mehrertrags


Voranschlag der Erzeugungskosten des Mehrertrags

Dies sind folgende Kosten:
a. Betriebskosten der Regenanlage (Abschreibung, Zins und Energiekosten);
b. Mehrkosten für die Düngung infolge der Änderung des Anbauplanes;
c. Mehrkosten für Saat- und Pflanzgut infolge der Änderung des Anbauplanes;
d. Mehrkosten für Viehfutter infolge der Erweiterung des Rindviehbestandes;
e. Verschiedene Mehrkosten: Abschreibung, Zins, Versicherung, Unterhalt, usw. für die Erweiterung der Gebäude und des Viehbestandes und für zusätzliche Maschinen;
f. Mehrkosten für Arbeit infolge der Beregnung und der Intensivierung des Betriebs. Man muss den Arbeitsbedarf des künftigen beregneten Betriebs für jeden Monat des Jahres mit
der vorhandenen Arbeitskraft vergleichen. Ist nicht genügende Arbeitskraft vorhanden, so ist zu untersuchen, wie der Mehrbedarf gedeckt werden kann und wieviel das kostet.

Die Rentabilität der Beregnung ist der Unterschied zwischen dem Wert des Mehrertrags und dessen Erzeugungskosten.


DISCUSSION

MUNDJERG:
The cost of sprinkling irrigation in Denmark.
The work was done by sending questionaires to 120 farmers who have irrigation systems. Irrigated area: 34 ha. Power: 32 hp. Power cost: 2.12 kr/h. Capacity: 45 m³/h. Cost of installations 32,500 Kr, per ha 950 Kr. Operating 600 hours for 80 mm/ha.

Men hours: 300 hours at 4 Kr.
Cost per ha: 10 years: 203 Kr.
15 years: 171 Kr.
20 years: 163 Kr.
incl. 225 Kr. per year for maintenance.

Antwort:
Die Investitionskosten sind in Holland etwas grösser, weil die Betriebe etwas kleiner sind. Die Betriebskosten sind dadurch auch etwas höher.

HALLORGEN:
In my work during 15 years of planning irrigation systems one of the most difficult things has always been to estimate the labour costs. We have made some labour studies in Sweden, but the material concerning this problem is very small. It were therefore very valuable if the investigations in the Netherlands on the labour costs, mentioned by Mr. BAARS would be continued. Concerning Mr. MUNDJERG’s figures I will mention that it is not always true that a low installation cost will give the best economical results. We must also take into consideration the labour costs. These tend to increase with decreased installation costs.

MULENAAR:
Total annual costs of irrigation in the Western United States vary from about $ 75 to $ 100 per ha. Labour costs are low in comparison to other costs, because of the relatively few irrigations per season, but the total is high in comparison to European costs because of the much higher total seasonal application of water.

SCHONNAPP:
Jahreskosten in Deutschland vergleichsweise etwa so hoch wie in Dänemark. Arbeitsaufwand der Beregnung kann durch das Verfahren der Schwachberegnung herabgedrückt werden. KTL-Veröffentlichung K.F. KLEIN „Handhabung und Arbeitswirtschaft der Beregnung im Bauernbetrieb“.


Antwort:
Auf kleineren Betrieben ist Schwachberegnung vorzuziehen. Auf grösseren Betrieben mit einer Anlage von mehr als 100 m³/Stunde Fördermenge, werden in Holland noch mittelgrosse Regner benutzt, weil in diesem Fall der Arbeitsbedarf kleiner ist.
FINAL DISCUSSION
ON SUPPLEMENTAL IRRIGATION RESEARCH

Since the Food and Agricultural Organization of the United Nations has installed an European „Working Group on Supplemental Irrigation“ (as a sub-group of the Commission on Agricultural Research) it seemed useful to have a final discussion on the possibilities of future international cooperation in the research carried out in this field.

Many suggestions from participants came forward, covering various aspects of supplemental irrigation. Although no final conclusion could be drawn, it might be interesting to summarize those points on which it was felt necessary further investigations should be carried out.

1. In many regions (among which the countries with retarded development) sufficient data to calculate potential evapotranspiration are lacking. Simple calculation or measuring methods should be developed. In this respect the attention was drawn to:
   a. The calculation method of TURC, this being a simple method having probably wide possibilities of application.
   b. The evaporimeter of ASLYNG, a screened evaporation pan, giving directly the amount of potential evapotranspiration, under the circumstances existing in Denmark.

2. A better understanding of root growth is necessary. On the one hand research on root growth (together with soil moisture measurements) can give an insight in the drying out of the soil profile, on the other hand the study of soil profile factors affecting root growth is of importance.

3. Evapotranspiration calculations are based on data obtained from studies on grass cut short. Other crops should be investigated in this respect.

4. Useful research could be done on the interrelation between irrigation and fertilization.

5. The use of small quantities of water with the best possible results should be investigated, in particular for regions where water is scarce. In this respect BROUWER’S theory on the need of water in the different growing stages of plants deserves closer attention.

6. Water balance studies of either small or big areas are of importance since they make it possible to take into account many physical and biological factors simultaneously.

7. It will be useful to check the data of MOHRMANN’S maps, on water deficiency in Europe, with results obtained regionally.

8. The growing scarcity of labourers in European agriculture gives importance to the investigation of labour-saving methods in the technique of sprinkling irrigation.

9. Farm management practices and economics, in relation with the introduction of sprinkling irrigation, should be investigated in order to find out where sprinkling is remunerative.

10. Since many research workers in the field of irrigation research are only slightly conversant with the work done by their colleagues, a survey of workers and investigations should be made.
PROGRAM OF THE CONFERENCE
ON SUPPLEMENTAL IRRIGATION, COPENHAGEN, 1958

JUNE 30
9.00-11.00 Registration
11.00-12.30 Opening Session
14.00-16.00 1st main lecture: H. C. ASLYNG,
"Climatic aspects of supplemental irrigation"
16.00-17.30 Communications

JULY 1
9.00-11.00 2nd main lecture: W. C. VISSEr,
"Soil science and sprinkler irrigation"
11.00-12.00 Communications
13.00-19.00 Excursion to: Climate and Water Balance Station of the
Hydrotechnical Laboratory. Trip to north Seeland

JULY 2
9.00-12.00 Communications
14.00-18.00 Communications

JULY 3 AND 4
Excursion in Jutland

JULY 4
17.00 Closing of the Conference at St. Jyndevad
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