Isotope and Radiation Techniques in Soil Physics and Irrigation Studies

PROCEEDINGS OF A SYMPOSIUM, ISTANBUL, 12-16 JUNE 1967
JOINTLY ORGANIZED BY THE IAEA AND FAO

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1967
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IN SOIL PHYSICS AND IRRIGATION STUDIES
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ABSTRACT: Proceedings of a Symposium organized jointly by the Food and Agriculture Organization of the United Nations and the IAEA and held in Istanbul, 12 - 16 June 1967. The meeting was attended by 84 participants from 20 countries and three international organizations.

Contents: Radiation equipment (7 papers); Soil-moisture studies (6 papers); Water-movement studies (11 papers); Soil-water-plant relationships (6 papers); Desalinated water for agriculture (2 papers and General Discussion).

Each paper is in its original language (23 English, 7 French, 1 Russian and 1 Spanish) and is preceded by an abstract in English with one in the original language if this is not English. Discussions are in English.

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FOREWORD

The Symposium on the Use of Isotope and Radiation Techniques in Soil Physics and Irrigation Studies was convened jointly by the Food and Agriculture Organization of the United Nations and the International Atomic Energy Agency, and was held in Istanbul, Turkey, on 12 - 16 June, 1967. Eighty-four participants attended from 20 countries and three international organizations.

The FAO and the IAEA have now held five joint symposia on the applications of radioisotopes and radiation to studies of soils and plant nutrition. But the last symposium was more specialized than the four earlier ones, which had dealt generally with soils and soil chemistry. It was the first symposium to cover soil-water-plant relationships and their vital role in crop production. Instruments that use radiation to measure moisture and density were discussed, as well as the application of these instruments to soil-moisture studies; studies on water movement were also presented. An important feature of the symposium was a session and General Discussion dealing with the price that agriculture could afford to pay for desalted irrigation water under various conditions. Thirty-two papers and a record of the discussions are published in these proceedings.

Large sections of mankind have often been faced with the threat of starvation. However, with the present population explosion, the problem of feeding the peoples of the world has never before been so pressing. Fortunately, spectacular advances in food production are being made through the application of modern science and technology. Among the contributions of nuclear science to the welfare of mankind, radioisotopes and ionizing radiations have provided invaluable aids to research on both the basic biological processes and the technical factors in agriculture. Important information has been obtained that could not have been gained in any other way. For example, the better insight that the new techniques are giving into the movement and availability of water, into soil-moisture changes, and into the leaching of salts will result in greater efficiency of water use, an essential factor in improving food production in areas with low rainfall.

The IAEA and the FAO wish to express their gratitude to the Turkish Government for their generous hospitality and co-operation, and to the authors and participants for making the symposium a success.
EDITORIAL NOTE

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For the sake of speed of publication the present Proceedings have been printed by composition typing and photo-offset lithography. Within the limitations imposed by this method, every effort has been made to maintain a high editorial standard; in particular, the units and symbols employed are to the fullest practicable extent those standardized or recommended by the competent international scientific bodies.

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SECTION I
RADIATION EQUIPMENT
GAMMA-RADIATION DETECTION OF WATER CONTENT IN TWO-DIMENSIONAL EVAPORATION PREVENTION EXPERIMENTS

D. KIRKHAM, D. E. ROLSTON, AND D. D. FRITTON,
AGRONOMY DEPARTMENT,
IOWA STATE UNIVERSITY,
AMES, IOWA,
UNITED STATES OF AMERICA

Abstract

GAMMA-RADIATION DETECTION OF WATER CONTENT IN TWO-DIMENSIONAL EVAPORATION PREVENTION EXPERIMENTS. A $^{137}$Cs gamma scintillation detector system (gamma apparatus) was used to measure water contents in a two-dimensional soil model. The gamma apparatus was built into a lifting apparatus, which accommodates both vertical and horizontal 150-cm-long soil columns and 150 x 30-cm two-dimensional soil models. The lifting apparatus was constructed by using a vertical rectangular frame with internal dimensions of 80-cm width and 70-cm height. Lead cubes, 35 cm on a side, containing a 224-mCi $^{137}$Cs source and a NaI scintillation detector are offset to one side of the vertical rectangular frame in order to scan a vertical cylindrical column. The faces of the lead cubes are 34 cm apart and attached to the rectangular frame so that the gamma beam is midway between the base and top. There are no attachment parts that cross the 24-cm gap between the lead cubes, and this leaves a 24-cm-wide by 70-cm-high space that will allow a two-dimensional model of horizontal columns to be moved horizontally through this space. Vertical movement of the gamma apparatus and horizontal movement of the model then allow two-dimensional scanning of a model. To demonstrate the ability of this design for a gamma apparatus to scan two dimensions, a 92-cm-long, 30-cm-tall, and 10,15 ± 0.05-cm-wide model with three equal 30-cm-long compartments was used to evaluate potential water conservation. A vertical sand mulch, 2 cm thick, was placed on each side of each compartment, a 5-cm-thick sand layer was placed on the bottom, and soil was packed in the rest of the model. The surface treatments were: bare soil, 1 cm soil over 1 cm of sand mulch, and 1 cm of sand mulch. Water contents in two dimensions were determined for 3-cm simulated rainfall applications for the three treatments. When a subsurface sand mulch was used, the mulch acted as a barrier to infiltration. Therefore, the surface-sand mulch conserved more water than did the subsurface-sand mulch, but both the surface and the subsurface sand mulches conserved water as compared with no sand mulch layers.

In addition, soil columns, 6.9 cm in diam. and 38 cm tall, were used to study the effectiveness of various thicknesses of surface-sand mulches in preventing evaporation. Thicknesses of sand mulches did not greatly influence the amount of water conserved if the sand layer was 1 cm or more thick.

1. INTRODUCTION

Laboratory investigations of the soil-water content along the length of soil columns have been greatly facilitated by the use of gamma-radiation attenuation. Gamma-radiation attenuation provides a rapid, non-destructive means of measuring soil bulk density and soil-water content.

If a collimated beam of gamma-rays is allowed to penetrate a material, the number of rays passing through depends upon the density and thickness of the material. Gurr and Marshall [1] and Gurr [2] measured the soil density and water content, for steady-state conditions, of an unconsolidated porous material in the laboratory with a $^{137}$Cs source of gamma radiation. Ferguson and Gardner [3] used a similar technique for extremely slow transient water flow in uniformly packed soil columns. Using additional equipment and a source of greater intensity, Rawlins and Gardner [4] obtained more frequent measurements from the same soil studied by Ferguson and Gardner. Davidson et al. [5] refined the technique further by a method of making a rapid and frequent measurement of rapidly changing water contents in laboratory soil columns. Gurr [6] described a method for calculating water contents of undisturbed field samples of unknown initial conditions from gamma-ray data. The use of gamma radiation has become a fairly widespread method for non-destructive determinations of soil bulk density and water content.

The attenuation of monoenergetic gamma radiation is described by

$$ I = I_0 \exp (-\mu \rho x) $$

where $I_0$ is the radiation intensity with no interference, $\mu$ the mass-absorption coefficient (cm$^2$/g) of the absorber for the quantum energy of the radiation, $\rho$ the density of the material (g/cm$^3$), and $x$ the thickness of the sample (cm). The necessity for the radiation to be monoenergetic can be met by the use of instrumentation having energy discriminators.

This paper discusses the application of gamma radiation for determining soil bulk density and soil-moisture distribution in two-dimensional soil models. Soil models were used to study the influence of surface-sand mulches on evaporation prevention and infiltration.

Wiegand and Taylor [7] reviewed literature on soil mulches. They presented a graph summarizing several studies of evaporation rate versus mulch thickness. They conclude that a mulch must be greater than 0.3 to 0.6 cm thick to reduce evaporation rates. The necessary thickness increases with increase in coarseness of the underlying soil. They state that, for a mulch to be effective, it must make vapour diffusion the rate-limiting process in evaporation. Teslitscheva [8] presents data for various mulch thicknesses of dry soil and an equation that describes evaporation as a function of the thickness of the mulch layer, evaporation from a wet soil surface, and soil properties. Kolp et al. [9] showed that tallow alcohol, when added to the top 1 cm of soil, decreased evaporation by allowing the surface 1 cm of soil to dry more rapidly than a bare soil surface. This allowed vapour diffusion to become the rate-limiting factor in the evaporation more rapidly for the tallow-alcohol-treated soil than for the bare soil. The effect was even greater in a sand. Kolp et al. also determined the moisture contents after a 1-cm application of water for two durations of evaporation. After 33% of the added water had been evaporated from each treatment (3.5 h with bare soil and 20 h with a 2.5-cm tallow alcohol surface-treated soil), the water had penetrated deeper in the tallow alcohol-treated soil than in the bare soil.
The purpose of this paper is to compare the influence of infiltration and evaporation under three conditions: bare soil, surface mulch, and subsurface mulch. These three treatments were studied in a two-dimensional model. In addition, the influence of mulch thicknesses on evaporation was studied in columns under evaporating conditions only. These columns were initially saturated and allowed to evaporate for 18 d. Soil-water contents at various depths were obtained by using gamma attenuation in both experiments.

2. EXPERIMENTAL EQUIPMENT AND CALCULATION PROCEDURE

The soil-density and moisture measuring equipment (gamma apparatus) consists of a low-energy gamma source, a detecting and analysing system, and a lifting mechanism for the source and detector section. The lifting mechanism and the source and detector section are shown in Fig.1. The source of gamma radiation consists of a 251-mCi $^{137}$Cs capsule. Although $^{137}$Cs does not emit a strictly monoenergetic gamma-ray, the greater part of the radiation has an energy of 0.66 MeV. The half-life of $^{137}$Cs is 27 yr. The $^{137}$Cs capsule is placed in the centre of a lead cube, 25 cm on a side, as depicted in Fig.1. This lead cube reduces the external radiation to a safe level (less than 0.1 mrad/h). A 5-mm-diam. hole 12.5 cm long located in the centre of this cube collimates the radiation. A second lead cube of the same dimensions and containing a scintillation detector is located opposite the source cube. The detector cube also has a 5-mm-diam. hole 12.5 cm long located at its centre to collimate the radiation reaching a scintillation crystal in the centre of the detector cube. The collimated holes were lined up by the use of X-ray film. The crystal is a thallium-activated NaI crystal 2.5 cm in diam. and 2.5 cm thick. The voltage for the detector photomultiplier is supplied from power supplies incorporated in an analyser/scaler (Nuclear-Chicago, Model 8727). Pulses from the detector are amplified by a linear amplifier. The base line and window width on the pulse-height analyser is manually adjustable and, for this study, was set to accept all gamma radiation above 0.50 MeV. By setting the analyser to accept all radiation
above 0.50, the entire $^{137}$Cs energy peak is accepted, and the problem of a base-line shift at high count-rates is essentially eliminated. The pulse-pair resolution of the analyser is 1.5 $\mu$s. Pulses from the analyser drive the scaler. The analyser/scaler is equipped with an automatic digital printing lister.

The source and detector cubes are attached 24 cm apart to a vertical rectangular frame (support frame Fig. 1) with internal dimensions of 80-cm width and 70-cm height. The cubes are offset to one side of the rectangular frame to facilitate the placing of vertical soil columns within the gamma beam. There are no attachment parts that cross the 24-cm gap between the lead cubes, and this leaves a 24-cm wide by 70-cm high space which allows a two-dimensional model or horizontal column to be moved horizontally through this space. A removable slide is placed horizontally within the rectangular frame to support models and columns and to allow their horizontal movement. The vertical rectangular frame supporting the lead cubes moves vertically up and down on 275-cm-long and 3.8-cm-diam. stainless-steel rods connected to the floor and ceiling of the laboratory. The rectangular frame is raised and lowered on the rods by a cable hooked to a motor-driven winch. Vertical movement of the gamma apparatus and horizontal movement of the model then allow two-dimensional scanning of a model.

To find the bulk-density and moisture profiles of the models from gamma-ray attenuation, values for the mass-absorption coefficients ($\mu$) of lead, Plexiglas, water, soil, and sand had to be determined. The mass-absorption coefficients for these materials were determined by essentially the same methods as those of Davidson et al. (5) (determining quantities in equation (1) except $\mu$, for which there is a solution). The mass-absorption coefficients were found to be 0.1036 cm$^2$/g for lead, 0.0806 cm$^2$/g for Plexiglas, 0.0802 cm$^2$/g for water, 0.0889 cm$^2$/g for soil, and 0.0525 cm$^2$/g for sand.

The values of the mass-absorption coefficients in combination with gamma-ray intensity allowed for the determination of soil bulk density and volumetric moisture content. The empty models were placed in the gamma apparatus and counted. The attenuation of the radiation by the Plexiglas models was described by

$$I_{pl} = I_0 \exp(-\mu_p x)p_l$$

(2)

where $I_{pl}$ was the intensity through the empty Plexiglas model, $I_0$ was the intensity through air, $\mu_{pl}$, $\rho_{pl}$, and $x_{pl}$ were the absorption coefficient, density, and thickness, respectively, of Plexiglas. The intensity $I_0$ was beyond the capacity of the instrumentation; thus, an indirect method of obtaining $I_0$ must be used. A standard lead disc was placed in the gamma beam, and the transmitted gamma-rays counted. The intensity through the standard lead disc was then related by

$$I^* = I_0 \exp(-\mu_p x)_{Pb}$$

(3)

where $I^*$ is the intensity through a standard lead disc and $\mu_{Pb}$, $\rho_{Pb}$, and $x_{Pb}$ are the absorption coefficient, density, and thickness, respectively,
of lead. Therefore,

\[ I_0 = I^0 \exp(\mu x)_{p_0}^p \]  

(4)

Equation (4) is then substituted into (2) to obtain

\[ I_{p_1} = I^0 \exp \left[ \left( \mu x \right)_{p_0}^p - \left( \mu x \right)_{p_1}^p \right] \]  

(5)

for the intensity through the empty model. The intensity \( I^0 \) is also used in the attenuation equations for the bulk-density and moisture content.

The intensity through the dry soil is related by

\[ I_{d_s} = I^0 \exp \left[ \left( \mu x \right)_{p_0}^p - \left( \mu x \right)_{p_1}^p - \left( \mu x \right)_{d_s} \right] \]  

(6)

where \( I_{d_s} \) is the intensity through dry soil and \( \mu_{d_s} \), \( \rho_{d_s} \), and \( x_{d_s} \) are the absorption coefficient, bulk density, and thickness, respectively, of dry soil. By dividing equation (6) by (5) and simplifying, the bulk density of the soil in the models is

\[ \rho_{d_s} = \frac{-\ln(I_{d_s}/I_{p_1})}{(\mu x)_{d_s}} \]  

(7)

The intensity through the moist soil is

\[ I_{m_s} = I^0 \exp \left[ \left( \mu x \right)_{p_0}^p - \left( \mu x \right)_{p_1}^p - \left( \mu x \right)_{d_s} - \left( \mu x \right)_{d_w} \right] \]  

(8)

where \( I_{m_s} \) is the intensity through moist soil, \( \mu_w \) is the absorption coefficient of the water, \( \rho_w \) is the density of water, \( \theta \) is the volumetric water content, and \( d \) is the thickness of the soil. Therefore, \( x_{d_s} \) is the same as \( d \). Dividing equation (8) by (6) and simplifying, the volumetric water content of the soil model is

\[ \theta = \frac{-\ln(I_{m_s}/I_{d_s})}{(\mu x d)_{w}} \]  

(9)

If \( I_{p_1} \) of equation (5) is above the capacity of the instrumentation, as is true for our model, then including a lead disc with the empty model in the gamma beam is necessary to decrease the count-rate sufficiently. Another term for the lead disc is then added to the exponential parts of equations (5), (6), (7) and (8). Detailed equations need not be presented here.

3. PROCEDURE

3.1. Vertical soil-column evaporation experiment with mulches

Five Plexiglas columns, 6.9 cm inside diam., 33 cm tall, and 3 mm wall thickness, were packed with a soil mixture (soil mix) containing two
parts Edina silt loam, A1 horizon, and one part Clayton white silica sand, 0.25-1.00-mm particle size. Five surface treatments were used: bare-soil mix, 1 cm Clayton sand mulch (1 cm mulch), 2 cm Clayton sand mulch (2 cm mulch), 4 cm Clayton sand mulch (4 cm mulch), and 1 cm Clayton sand below 1 cm of soil-mix (subsurface mulch). The depth of soil-mix, plus surface layers, was 33 cm for all columns. After packing, the columns were wetted with water from the bottom with a small head until they were near saturation. Initial water added varied from 522 to 544 g.

The five soil columns and a column containing open water were then placed 13 cm from the centre of a round table rotating at 1.5 rev/min and maintained level by four adjustable wheels. The columns were surrounded by a drum-like framework covered with aluminium foil to keep infra-red light from entering the columns at any point other than the column surface. A single 250-W infra-red reflector heat lamp was centred 23 cm above the top of the columns. The column containing water was used to characterize the evaporation potential. This column was kept full by adding water as it was evaporated. All six columns were weighed at daily intervals during the first few days and at 2- or 3-d intervals later in the experiment. At the end of 18.5 d, the columns were placed in the gamma apparatus and scanned. The count-rates were used to calculate the volumetric moisture content at 1-cm depth intervals. The driest layer occurred in the 1 cm of soil above the subsurface mulch and was used as the zero moisture content. In calculating moisture contents from the scanning, it was assumed that the thickness and density of plastic and the bulk density of the soils were uniform.

3.2. Two-dimensional model experiment

A two-dimensional model constructed with 1-cm-thick Plexiglas, containing three identical compartments, 30 cm long, 30 cm tall, and 10.15±0.05 cm wide, was used in this experiment. Since the model was to be used for infiltration, air-escape holes were drilled along each side, 2 cm from the bottom of the model. Before packing, the model was scanned by the gamma apparatus. The bottom 3 cm of each compartment was filled with Clayton sand. A vertical sand mulch, 2 cm thick, was placed on each side of the compartments, with soil-mix packed in the rest of the model. The surface treatments were: bare soil, subsurface mulch, and 1 cm surface mulch. All final surfaces were at the same height. The compartments packed with soil were scanned by the gamma apparatus, and bulk densities calculated.

A 2-cm application of water was then applied to each compartment. The model was allowed to equilibrate for 4 h and then scanned by the gamma apparatus, and moisture contents were calculated. (A measured air-dry moisture-content correction of 3.22% was made for all bulk-density and moisture measurements with the two-dimensional model.) The model was then placed 1 m below a bank, 120 cm long, of five 300-W reflector spot-lamps, equally spaced on a line, for 24 h. The bank of lamps provided an evaporation potential of 1.43 cm/24 h as measured from the open-water column. Moisture contents were again determined at 42 points in each compartment.

A second application of a 2-cm depth of water was added to the same model after the 24-h evaporation period. The model was allowed
to set 10 h before the moisture contents were determined. The model was then placed under the heat lamps for 24 h. The evaporation potential was 1.30 cm/24 h for this second 24-h evaporation. At the end of this period, moisture content was determined again.

A third 2-cm application of water was added to the model at the end of the second evaporation period. The model was allowed to set 4 h before moisture contents were taken. Then, the model was placed under the heat lamps for 83 h. The total evaporation potential during this period was 4.77 cm. A final moisture content was taken at 42 points in each compartment.

4. RESULTS

4.1. Soil-column experiments

Figure 2 shows water loss from three (1-cm mulch, 4-cm mulch, and bare soil) of the five treatments in the experiment involving soil columns. The average evaporating potential measured by an open-water surface with an area of 44.2 cm² was 1.68 cm/24 h or 74.1 g/24 h. The 2-cm
FIG. 4. Bare-soil model moisture distribution. Slashed areas are coarse sand. Lines of equal moisture content are shown for 20, 25, and 30%.

FIG. 5. Same as Fig. 4 except for a 1-cm subsurface sand mulch.

FIG. 6. Same as Fig. 4 except for a 1-cm surface sand mulch.
mulch and the subsurface-mulch curves lie on or between curves shown. After 1377 g of open-water loss, the 1-cm mulch column lost 168 g compared with 314 g for bare soil and 130 g for the 4-cm mulch. The 2-cm mulch column lost 128 g and the subsurface-mulch column lost 135 g.

Figure 3 shows moisture content with depth for two (bare soil and 1-cm mulch) of the five treatments used in the column experiment. Data for the other three treatments are not shown because the other mulch-treatment curves of moisture content with depth are not significantly different from the curve for 1-cm mulch.

The temperature after one day of evaporation of the columns was measured on the outside surface near the base of the columns with a mercury-in-glass thermometer and was 27.1°C. Surface temperatures measured by an aluminium-foil-covered mercury-in-glass thermometer were 33.2°C.

4.2. Two-dimensional model experiment

Figures 4 (bare soil), 5 (subsurface mulch), and 6 (1-cm mulch) show the volumetric water content for 42 points measured. The values shown are final moisture contents after three 2-cm applications of water for a total of 6 cm and after three evaporation periods with potential evaporation of 1.43 cm, 1.30 cm, and 4.77 cm, for a total of 7.50 cm. The initial soil was at an air-dry moisture content of 3.22%. Lines of equal water content are shown for 20.0%, 25.0%, and 30.0% moisture by volume. Associated with each figure are the average moisture contents of the surface 1 cm for the three wettings. These moisture contents were obtained by averaging the middle four moisture contents for the surface row of measurements.

For Fig. 4 these values are 33.4% for the first wetting, 25.7% for the second, and 29.1% for the third. The point in Fig. 4 at x = 3 and y = 1 is -10%, an absurd value. We suspect that the soil surface settled so that the measurement of intensity for moist soil was partly through air instead of soil.

In Fig. 5 the average moisture contents of the surface 1 cm for the three wettings are 41.6% for the first wetting, 34.7% for the second, and 33.5% for the third. The point in Fig. 5, x = 3 and y = 1, -9.8%, is absurd for the same reason given for the point x = 3 and y = 1 in Fig. 4. The point x = 3 and y = 1 in Fig. 5 is 42.2%, another absurd value because the soil was visibly dry. We believe this resulted when the gamma beam was partially going through air when the dry soil intensity was established. This also occurred at x = 27 and y = 1 (54.4%) in Fig. 6. These absurd points bring out the problems in lining the gamma beam initially and the change that occurs when the soil settles.

Variation in soil bulk density for the three compartments will have some influence on the moisture contents. The average bulk density of 30 points for Fig. 4 is 1.34 g/cm³, for Fig. 5 is 1.32 g/cm³, and for Fig. 6 is 1.29 g/cm³. The extreme values for the entire experiments were 1.21 and 1.39 g/cm³.
5. DISCUSSION

5.1. Vertical soil columns

In the column experiment, the columns were initially wetted to a water content near saturation. When evaporation started, the 1-cm mulch was almost immediately effective in reducing evaporation (Fig. 2) because the sand dried quickly and the underlying layers were composed of a fine-textured material. The 4-cm mulch lost a greater amount of water during the initial stages because the 4-cm sand layer was initially wet and could easily conduct water vertically for a small distance. After 800 g (18.1 cm) of evaporation potential, the 4-cm mulch became more effective than the 1-cm mulch. The 2-cm mulch and the 1-cm subsurface-mulch curves were identical and intermediate to the curves shown for 1-cm mulch and 4-cm mulch. Evidently, 2 cm of dry material, whether soil or sand, offers very nearly the same resistance to vapor flow.

All mulch treatments saved water when compared with the bare soil after 31.2 cm (1377 g) of evaporating potential. The water saving is large \( \frac{(314-168)/314}{100} = 46\% \), to \( \frac{(314-128)/314}{100} = 59\% \) (see section 4). This large water saving was partly due to the high moisture content with which we started the experiment since the water was initially trapped below the mulches.

Figure 3 shows the distribution of the saved water at the end of the experiment when 1377 g (31.2 cm) of open water had evaporated. The surface 4-cm layer of the bare soil was dried to a low moisture content. Below 6 cm, the moisture content was approximately constant at 30%. In comparison, the 1-cm mulch had allowed the surface 4-cm layer to dry considerably, but not to the extent that drying had occurred under bare surface. Also, a much greater amount of water was stored below 6 cm by the mulch treatment. The subsurface mulch (results not shown in Fig. 3) also showed a high amount, about the same as the 1-cm mulch of stored water in the lower depth. This storage was possible because the soil was initially near saturation. In a field situation, the soil would be saturated only after infiltration had occurred. Since a subsurface mulch is known to inhibit infiltration, we included vertical mulches to help infiltration in the two-dimensional model experiment.

5.2. Two-dimensional soil models

The two-dimensional model was used to investigate the influence of bare soil, a 1-cm-surface mulch, and a 1-cm-subsurface mulch when vertical sand mulching was included. The vertical sand mulching at the sides of the model should at least partly overcome the infiltration problems involved with the subsurface mulch, which inhibits infiltration. The vertical sand mulch did improve infiltration for all three treatments since the soil-mix transmitted water much more slowly than did the vertical mulch sand.

Results in section 4.2 show that the 1-cm layer of soil above the subsurface mulch in the model retained a greater amount of water than the top 1 cm of the bare-soil treatment. For the first 2-cm addition of water, the subsurface mulch caused 41.6% water content to be held.
compared with 33.4% for the bare soil; for the second 2-cm addition the subsurface mulch caused 34.7% water content to be held, compared with 25.7% for the bare soil; and for the third addition of 2 cm the subsurface mulch caused 35.5% water content to be held, compared with 29.1% for the bare soil. This comparison shows that the 1-cm-surface layer of soil above a subsurface mulch retains 4.4% to 9% more moisture than a homogeneous soil. Then, when evaporation occurs, the water held above the subsurface mulch is lost before the subsurface mulch becomes effective in reducing water loss. This effect does not occur in the surface mulch.

Figures 4, 5, and 6 have shown the end result of infiltration of relatively small amounts of water followed by relatively high intensity evaporation for the three treatments. The overall average moisture content for these three figures is of interest. This moisture content can be found by averaging the six values for a moisture measurement depth shown on a figure and by weighting this average for the thickness of the soil layer it characterizes. Using this method we found that the average water content for Fig. 4 was 21.2%; for Fig. 5, 23.3%; and for Fig. 6, 25.0%. The average water content can be converted to a volume of water by multiplying the values by the total volume of soil. The volume of soil is 26 cm length x 25 cm height x 10 cm width = 6500 cm³. Thus, 21.2% is 1378 cm³ water, 23.3% is 1514 cm³, and 25.0% is 1625 cm³. The initial water present in the soil was 3.2% or 208 cm³, and the added water was 3 x 600 cm³, equalling a total of 2008 cm³. Then 2008 cm³ - 1378 cm³ = 630 cm³ was evaporated from the bare soil; 494 cm³, from the subsurface-mulch treatment; and 383 cm³, from the surface-mulch treatment. Thus, the subsurface-mulch treatment saved 630 cm³ - 494 cm³ = 136 cm³ or (136/630) (100) = 21.6% of the water evaporated from the bare-soil treatment; and the surface-mulch treatment saved 630 cm³ - 383 cm³ = 247 cm³ or (247/630) (100) = 39.2% of the water evaporated from the bare-soil treatment.

The lines in Figs. 4, 5, and 6 connect points of equal water content. In Fig. 4, the line for 20% water content lies deeper than in Figs. 5 and 6. This shows that the bare-soil treatment caused more drying at the lower depths than the other treatments. For example, the deepest point of the 20% line in Fig. 4 is 15 cm below the surface; and for Figs. 5 and 6, 12 cm below the surface. The 25% line in Fig. 4 is 19 cm below the surface and is about 4 cm below the 25% line in Fig. 5 at 17 cm depth and about 4 cm lower than the 25% line in Fig. 6 at 15 cm depth. The 30% line in Fig. 6 is much higher than in Figs. 4 and 5. All the lines curve upwards when they lie near the edges where vertical coarse sand mulches had an effect. The vertical mulches increased infiltration, which caused the wetting fronts in the model compartments to advance from the sides and bottom as well as from the top. This type of phenomenon can be described quantitatively rather than qualitatively by using the gamma-ray attenuation procedure.

5.3. Comparison of soil column and two-dimensional model results

There are two differences between the experiment with soil columns and the experiment with the two-dimensional model. The differences are initial moisture contents, and the wetting and drying procedure.
The soil in the columns was initially nearly saturated, while the soil in the two-dimensional model was initially air-dry. Thus, in the soil columns, we are concerned only with evaporation. Since mulches cause early surface drying, the surface treatments in the column experiment are only working as a vapour diffusion resistance. In the two-dimensional model, the surface treatments are acting as a resistance to three processes: upward capillary movement, vapour diffusion, and infiltration. Consider the top 2 cm of soil-mix and or sand in the three compartments of the model. During infiltration, the 1-cm-surface mulch and the 1 cm of soil below it offer less resistance than the top 2 cm of the bare-soil treatment. The top 2 cm of the bare-soil treatment offer less resistance to infiltration than do the top 2 cm of surface if there is 1 cm of sand below 1 cm of soil. This means that the subsurface mulch should be less effective when infiltration and evaporation are involved than when evaporation alone is involved, when compared with a surface mulch. This is true as seen from the water saved in both cases. In the column experiment (see Results, section 4.1) the 1-cm-surface mulch saved

\[
\frac{(314-168)}{314} (100) = 46.5\
\]

and the 1-cm-subsurface mulch saved

\[
\frac{(314-135)}{314} (100) = 57.0\%
\]

These values, 46.5% and 57.0%, for the columns may be compared with corresponding values, 39.2% and 21.6%, for the model as found in section 5.2. From the four percentages, 46.5, 57.0, 39.2, and 21.6, we see that the surface mulch was 46.5 - 39.2 = 7.3% less effective under the conditions of the two-dimensional model, while the subsurface mulch was 57.0 - 21.6 = 35.4% less effective.

6. CONCLUSIONS

1. A gamma apparatus was used to measure soil-bulk density and water content in two-dimensional models as well as in vertical columns, and results were compared for different types of mulching.

2. When the soil columns were initially saturated and when one of the treatments (1 cm sand, 2 cm sand, 4 cm sand, or 1 cm sand below 1 cm of soil) was used, there was a saving of water of 46-59% for an 18-d evaporation period, compared with the situation for bare soil.

3. Water content in the 1 cm of soil above the subsurface mulch after a 2-cm irrigation ranged from 4-9% higher than for a bare soil.

4. The use of a 1-cm-surface mulch in a situation involving both infiltration and evaporation resulted in a saving of 39.2% of the water evaporated from a bare soil. The use of a 1-cm-subsurface mulch in a situation involving both infiltration and evaporation resulted in a saving of 21.6% of the water evaporated from a bare soil.

5. A 1-cm-subsurface mulch lost 35.4% of its effectiveness when a situation involving infiltration and evaporation was compared with a situation involving only evaporation.
(6) Two-dimensional models may be used to study further the influence of vertical and horizontal mulches on evaporation and infiltration, to evaluate moisture content above a water table in drainage systems, water contents around the roots of plants growing in a model, and possible lateral movement of water because of different evaporation potentials, such as that due to shading, at the soil surface.

REFERENCES


DISCUSSION

J.A. Damagnez: When we carried out similar experiments in the south of France, we reached markedly different conclusions with 5-cm straw mulch and natural evaporation (different rates by day and night). Under low-potential evaporation conditions \( E_0 = 2-3 \text{ mm/d} \), straw mulch showed lower evaporation values than the control. Under high-potential evaporation conditions \( E_0 = 8 \text{ mm/d} \) the opposite result was obtained. The mulch seemed to reduce the potential evaporation at ground level.

D. Kirkham: I do not believe we can compare sand and straw mulches, because straw has fine pores and therefore may not act as a block to capillary rise. Moreover, straw has quite different thermal properties from sand. We did not carry out diurnal cycling of the applied radiant energy, but I see no physical reason why diurnal cycling would have changed the conclusions we reached for our various treatments with regard to water savings.

N. Aybers: I think that the relative humidity of the outside air, or, in the case of artificial circulation, the rate of movement of the vapour, should have some effect on the measurement. What allowance did you make for this?

D. Kirkham: The soil columns, the reference water column and the two-dimensional model were all exposed to radiation in a large laboratory where there were no forced draughts. As regards relative humidity, we have a recording hygrometer in our laboratory, but I have not got the readings here. However, whatever the ambient relative humidity was, we believe it was the same for all treatments.

J.R. McHenry: In your two-dimensional models, the moisture percentages appear greater near the boundaries, over a U-shaped area. Did you take any temperature measurements from which possible thermal gradients could be seen?

D. Kirkham: We did not take temperature measurements on our two-dimensional models, but did so for our column experiments, as
reported in the paper. The vertical walls of the central compartment of our model will be subject to somewhat different temperatures than the end walls of the two outer compartments. Moisture conditions near the inner walls of the outer compartments should be comparable, so far as temperature is concerned, with moisture conditions near the walls of the inner compartment.

M. DAGG: The rates of evaporation from open water were checked by weighing; were the amounts of evaporation from the soil columns similarly checked by weighing to supplement the figure obtained by integration of the soil-moisture measurements and thus, by direct weighing, to estimate the accuracy of the gamma-ray attenuation method?

D. KIRKHAM: Yes, we weighed the soil columns daily. In a separate experiment, we sectioned a soil column and determined the moisture content of the sections gravimetrically. This sectioning was done after determining the moisture content of the column at different depths by gamma-ray attenuation. There was agreement to within 1% moisture, except near the top and bottom ends of the column, where the difference was about 3%. Some problems associated with errors that can occur at the top and bottom of columns, e.g., gamma-ray over-shooting or under-shooting, are mentioned in the paper.

H.W. SCHAPENSEEL: You used an open water surface as reference for energy input and evaporation, but when making quantitative estimates the fact that the evaporating water surface is smaller than the evaporating soil surface could lead to some uncertainty. Although it is customary to refer to an open water surface, the validity of the practice is questionable.

D. KIRKHAM: The open water surface referred to in our column experiments had the same surface area as the surface cross-sections of soil in our soil columns. We therefore believe that the amount of open water evaporated can be used as a measure of the energy that we applied to the soil columns.

M.Ş. YEŞILSOY: Would you comment on the possibility of applying your results to practical agriculture?

D. KIRKHAM: I hesitate to make recommendations about practical applications, as we have not made field experiments. However, one possibility that should not be overlooked is that sub-surface irrigation and the tubes used for this purpose could also be used for winter drainage for the removal of salts.

W. K.G. KÜHN: I think experiments of the kind you describe should be done with natural soil in a large container and not in the laboratory; i.e., one should move the gamma-ray apparatus rather than the soil. This method would indicate the natural soil and water conditions in a selected case, in relation to all weather influences.

D. KIRKHAM: Data collection in the manner you suggest still has to be carried out. Other types of field experiment also are needed to test the practical implications of our mulching methods. Even in the laboratory, a thicker two-dimensional model than we used would ensure that we were getting two-dimensional effects, rather than possible three-dimensional effects. Use of equal "buffer" compartments, on either side of an internal measurement compartment, could eliminate any three-dimensional distortion effects on moisture distribution in the measurement compartment.
GAMMA-RAY ATTENUATION FOR SOIL-WATER-CONTENT MEASUREMENTS USING $^{241}\text{Am}$

L. G. KING
BATTLE MEMORIAL INSTITUTE
PACIFIC NORTHWEST LABORATORY
RICHLAND, WASH.,
UNITED STATES OF AMERICA

Abstract

GAMMA-RAY ATTENUATION FOR SOIL-WATER-CONTENT MEASUREMENTS USING $^{241}\text{Am}$. For several years, soil-water content has been measured by the attenuation of gamma radiation, both on laboratory samples and in the field. Usually, $^{137}\text{Cs}$ has been used as the radioactive source emitting the gamma rays. This paper describes the use of $^{241}\text{Am}$ as the source for such measurements, gives some advantages for using $^{241}\text{Am}$ instead of $^{137}\text{Cs}$, and describes necessary precautions for the design of counting equipment.

Both isotopes have the desired property of emitting nearly monoenergetic photons. The spectrum for $^{137}\text{Cs}$ shows a major peak at about 662 keV while for $^{241}\text{Am}$, the peak occurs at 60 keV. Thus, the less energetic $^{241}\text{Am}$ source requires substantially less shielding for operator safety than does $^{137}\text{Cs}$. The apparatus can be made smaller, lighter, and less costly; especially if it is desired to traverse the sample with a moving source and detector.

The mass absorption coefficient for water is about 0.086 with $^{137}\text{Cs}$ and about 0.28 with $^{241}\text{Am}$. The optimum thickness for best precision in gamma-ray attenuation techniques is between 1 and 3 half-thicknesses, with preference towards the upper value. Since, for water content measurements, we are primarily interested in the differences in over-all densities between saturated and dry soil, the effective half-thickness for water as it exists in the pores of the soil is an important value. For similar soil conditions, the optimum thickness of water in the soil sample is about 2.3 times greater for $^{137}\text{Cs}$ than for $^{241}\text{Am}$. Thus, if the optimum thickness for $^{137}\text{Cs}$ is 14 cm, the best thickness for $^{241}\text{Am}$ is only 6 cm. For the smaller samples there is greater sensitivity using $^{241}\text{Am}$.

Some precautions must be taken to ensure good counting efficiency for the less energetic $^{241}\text{Am}$ source. The system used in this study included a 1-mm-thick NaI(Tl) crystal coupled to an EMI 9536B photomultiplier tube. The signal from the tube was passed through a special preamplification section with gain of 20 before being fed to the preamplifier section of the NEL scaler and timer.

Data are presented showing the comparison of soil-water content measured volumetrically with the content determined by attenuation of gamma rays from $^{241}\text{Am}$. The sample was contained in a small cell where the moisture content was controlled by controlling the capillary pressure. The water was extracted through a saturated porous material and measured in a calibrated horizontal tube.

1. INTRODUCTION

The importance of moisture content as it influences the flow of water through porous media was recognized as early as 1907 when Buckingham [1] presented his "capillary potential" theory. His theory was equivalent to assuming that Darcy's equation is valid for partially saturated flow where capillary conductivity is not constant but is a function of moisture content. Buckingham was not able to measure capillary conductivity as a function of moisture content, but he did draw a curve based on theoretical reasoning relating these two variables. Other workers including Richards [2], Childs and George [3], Klute [4], and Gardner and Mayhugh [5] have demonstrated

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the necessity for measurements of moisture content. In fact, the theory is well developed for describing the movement of water through stable porous media under isothermal conditions. To use the theory for prediction of water movement, the porous media must be characterized as to the relations between moisture content, capillary conductivity (or permeability), and capillary pressure (or suction), or desirable combinations of these variables. In the interest of rapidity and ease of measurement, a nondestructive method of obtaining the moisture content is desirable. For certain studies, a nondestructive method to determine the moisture content without disrupting the system may be essential. The absorption of gamma rays from a radioactive isotope provides the basis for such a method and is the subject of this paper.

The idea of using the absorption of gamma rays to measure the density of thickness of material or, more specifically, the moisture content of porous media is not new but has existed for several years. Various isotopes have been used or suggested as sources of the gamma rays, including $^{60}$Co [6], $^{137}$Cs [7], $^{57}$Fe, $^{85}$Sr, $^{75}$Se, $^{103}$Cd, $^{170}$Tm, and $^{241}$Am [8]. Probably because of its limited availability to the public until 1962 [9], $^{241}$Am has not received wide attention as yet. The most commonly used source for measurement of soil moisture content has been $^{137}$Cs.

2. THEORY FOR GAMMA RAY ABSORPTION

2.1. Development of Equations

For a sample of soil in the laboratory, it is possible to maintain a fixed relation between the source of gamma rays on one side of the sample, and the detector crystal on the other. For such a relation, the attenuation of monoenergetic gamma rays through dry soil is described by the equation

$$I_d = I_0 \exp\left(\frac{-\gamma_s \rho_s t_s - \gamma_c \rho_c t_c}{\mu_a \rho_a t_a - \mu_a \rho_a t_a}ight)$$

(1)

where $I_d$ is the intensity of the beam at the detector crystal after passing through the dry sample, $I_0$ is the intensity of the gamma beam at the source, $\mu$ is the mass absorption coefficient, $\rho$ is the density, $t$ is the thickness, and the subscripts $s$, $c$, and $a$ denote the soil, sample container, and air, respectively. In Equation (1), $\gamma_s$ is the bulk density of the dry soil, $t_s$ is the inside measurement of the soil sample container, and $t_a$ is the thickness of air between the source and detector outside the sample. If the sample has moisture contained in the pores, Equation (1) becomes

$$I_w = I_0 \exp\left(\frac{-\gamma_s \rho_s t_s - \gamma_c \rho_c t_c - \gamma_w \rho_w t_w}{\mu_a \rho_a t_a - \mu_a \rho_a t_a}ight)$$

(2)

where $I_w$ is the intensity of the beam at the detector crystal after passing through the moist soil, $S$ is the saturation of the soil, i.e., the fraction of the pore volume filled with water, and $\mu_w$ and $\rho_w$ are the mass absorption coefficient and the density, respectively of the water.

Dividing Equation (1) by Equation (2) gives

$$\frac{I_d}{I_w} = \exp\left(\mu_a \rho_a f t_s S + \mu_w \rho_w f t_w S\right)$$

(3)

or

$$\frac{I_d}{I_w} = \exp\left[f t_s S (\mu_w \rho_w - \mu_a \rho_a)\right]$$

(4)

For stable media (constant porosity, $f$), Equation (4) could be used for calculating the saturation, $S$, if $\mu_w$ and $\mu_a$ were known and the intensities
\[ I_d/I_w = \exp(\int_0^L S \mu_w \rho_w) \]  

Equation (5) can be used only when a count rate can be determined with the sample completely dry \((I_d)\) is defined only for \(S = 0\). Usually, except for some artificial media, even air dry samples contain some moisture, and it is necessary to derive the equations to account for this initial moisture content. If Equation (2) is satisfied for some saturation \(S_i\) with a resulting \(I_i\) and this result is used with the general Equation (2), the equation replacing Equation (5) becomes

\[ I_i/I_w = \exp(\int_0^L \rho_w f_t (S - S_i)) \]  

after neglecting the attenuation by air within the soil sample. If a count rate is obtained when the soil is completely saturated \((S = 1, I_w = 1)\), Equation (6) for this specific case becomes

\[ I_i/I_w = \exp(\int_0^L \rho_w f_t (1 - S_i)) \]  

Combining Equations (6) and (7) gives

\[ (S - S_i)/(1 - S_i) = \ln(I_i/I_w)/\ln(I_i/I_1) \]
Thus, by measuring the saturation S₁ by an independent method and obtaining the corresponding count rate I₁ (and likewise for complete saturation the count rate Iₙ₁), the saturation of the sample may be calculated from the corresponding count rate Iₚ by using Equation (6).

As checks on experimental results, Equation (7) may be used to calculate the mass absorption coefficient for water. This coefficient may also be calculated from Equation (6) if the values of S are measured by independent methods. Equation (6) may be rewritten

$$\log \left( \frac{I_\text{w}}{I_\text{n}} \right) = -\mu_{\text{w}} \rho_{\text{w}} f t_s (S - S_1) \log e$$

which is the form of an equation of a straight line on semi-log paper. The mass absorption coefficient, $\mu_{\text{w}}$, can be determined from the slope, $\mu_{\text{w}} \rho_{\text{w}} f t_s \log e$, of this straight line. By using complete saturation (S = 1) as a reference in Equation (2), we can derive the equation

$$\frac{I_\text{w}}{I_\text{n}} = e^{\left[ \mu_{\text{w}} \rho_{\text{w}} f t_s (1 - S) \right]}$$

The mass absorption coefficient determined from the slope of the straight line can be used in either Equation (6) or Equation (10) to compute saturation for comparison with the independently measured values. Of course, the mass absorption coefficient might also be determined from a semi-log plot of Equation (10).

2.2. Limitations of Equations

As stated near the beginning of Subsection 2.1, Equations (1) through (10) describe the absorption of an incident beam of monoenergetic gamma rays as they penetrate the absorbing material and are received at the detector. The gamma ray photons may be absorbed or scattered as a result of interaction with a material. Absorption is characterized by the disappearance of a photon, while scattered photons are deflected from their original direction either with or without a decrease in energy. The total probability for attenuation per unit thickness of an absorber is the sum of the probabilities of occurrence of the various absorption and scattering processes.

The three processes of primary importance to gamma ray attenuation are the photoelectric effect, Compton scattering, and pair production. Of secondary importance may be Rayleigh scattering which can occur for photons of low energy. The photoelectric effect involves the absorption of a photon with subsequent ejection of an atomic electron and is the most important process for low energy photons. Since photons with energy in extreme excess of that required to eject an electron are unlikely to be absorbed, the absorption coefficient for the photoelectric effect decreases rapidly with increasing photon energy. In Rayleigh scattering, a photon may be deflected with no loss in energy. The probability for occurrence of Rayleigh scattering is large only for low energy photons where photoelectric absorption is the main contribution to the total attenuation coefficient.

In the middle energy range (0.5 to 5 MeV), Compton scattering predominates. In this process, a photon is deflected from its original direction with a loss in energy which is transferred to an atomic electron which, in turn, recoils out of the atom. The production of electron-positron pairs requires a photon energy on the order of 1 MeV or greater and, hence, is not involved in the absorption to be discussed in this paper.

A radionuclide source does not emit entirely monoenergetic gamma rays, but emits a complete spectrum. A desirable source for absorption
techniques would have a rather well defined high intensity peak at a narrow band of energies. The peak should be well separated from any other lower intensity peaks and should be, preferably, the highest energy of any appreciable intensity. Secondary peaks, of lower energy than the primary peak, can sometimes be effectively removed by passing the photons through an absorbing filter without sacrificing much intensity of the primary radiation peak. If the effects of incident photons of higher energy than the peak of interest could be eliminated, the equations for monenergetic gamma rays should apply. The use of a circuit to discriminate against the higher energies on the output of the detector should give good results by counting all energies below. However, certain characteristics of NaI crystal detectors, such as the iodine X-ray escape [11], could introduce errors. A more desirable method would be the use of a pulse height analyzer to count only a narrow band of energies at the peak of interest. The use of the pulse height analyzer would eliminate any need for filtering and consequent reduction of peak intensity.

Use of the equations derived in Subsection 2.1 also depends upon knowing the thickness of absorber and upon preventing the radiation scattered from material outside the volume of interest from reaching the detector. Such scattered radiation contributes to background and can cause significant deviations from the straight line of Equation (9). Some scattered radiation will always reach the detector and increase the intensity of the transmitted beam over the intensity predicted by the absorption equations. Proper collimation of the gamma beam at both the source and detector can reduce this scattered radiation to a negligible level.

Of course, the equations of Subsection 2.1 require that the bulk density (hence, porosity) of the soil remain constant throughout the measurement; that is, no swelling or shrinking is allowed during addition or removal of water from the sample.

2.3. Choice of Gamma Ray Source

In addition to a well defined peak in the spectrum of the type discussed in Subsection 2.2, a desirable source of gamma photons should have long half-life, high specific activity, ready availability, reasonable biological shielding requirements, large variation in transmitted intensity with changes in saturation, and sufficient source strength. A half-life that is long, relative to the duration of desired measurements, eliminates any need for correction to compensate for radioactive decay. High specific activity is important to obtain sufficient strength of gamma beam for the small solid angles required for good collimation. The required source strength depends upon the absorption by all the material placed in the path of the gamma beam, the sensitivity of the detecting device, degree of collimation, time permitted for counting, statistical error of counting, and total distance between source and detector.

3. COMPARISON OF $^{137}$Cs WITH $^{241}$Am

For measurement of soil moisture, $^{137}$Cs has been used most often as the source of gamma rays. In this section, the possibilities for using $^{241}$Am will be examined by comparison with $^{137}$Cs. Both isotopes have the desired property of emitting nearly monoenergetic photons in certain ranges of energy. The spectrum for $^{137}$Cs (Figure 2) shows a major peak at about 662 keV. The intensity of the peak is a factor of 100 greater than

$^{\text{v}}$ Recent work of Dr. W. H. Gardner at Washington State University, Pullman, Washington indicates good promise for concurrent measurement of saturation and bulk density by use of gamma rays of two different energies from two different radioisotopes.
FIG. 2. Spectrum for $^{137}$Cs showing intensity as a function of energy in keV — taken from Allaire [13].

FIG. 3. Spectrum for $^{241}$Am showing intensity as a function of energy in keV — taken from Allaire [13].
the valley between the peak and the Compton plateau characteristic of the Compton scattering within the NaI detector crystal [11]. Such a peak is well suited for absorption techniques using a pulse height analyzer.

The spectrum for $^{241}$Am (Figure 3) has a major peak at about 60 keV and on a scintillation detector shows a lower peak at about 26 keV. Actually, the lower peak is a combination of several events including L X-rays, 26.4 keV gamma ray, and the escape peak from the 59.6 keV gamma ray [12]. Magnusson [12] states that for the 59.6 keV gamma ray, the full width at the half-height is about 11 keV, and the ratio of the peak height to the valley on the low energy side is about 100. Where the intensity of the 59.6 keV gamma ray is 0.359, he also reports gamma rays at 26.4, 33.2, 43.5, 99.0, and 103.0 keV with intensities of 0.025, 0.011, 0.0007, 0.00023, and 0.00018, respectively. The very low intensities (3 orders of magnitude) of the 99 and 103 keV photons relative to the 60 keV energy of interest should not cause any significant error, even when an attempt is made to count the full spectrum. As a further precaution, the use of a thin NaI crystal will reduce the probability of interaction of the higher energy photons with the crystal. However, because of possibilities for interactions at the lower energies, it is recommended that a pulse height analyzer be used with the window set to detect the 60 keV peak.

The less energetic $^{241}$Am requires substantially less biological shielding for operator safety than does the $^{137}$Cs. Using the mass absorption coefficients [10] for lead at photon energies of 60 and 362 keV gives the half-thickness of lead as about 31 times greater for $^{137}$Cs than for $^{241}$Am. These differences emphasize one important advantage of $^{241}$Am over $^{137}$Cs; that is, the apparatus can be made smaller, lighter, and less costly. The light weight is a distinct advantage when a stationary sample is traversed with a movable source and detector.

The radioactive decay is an important consideration in the selection of a source. Long half life compared to the duration of the measurements means that no corrections are needed to account for decay, and that the source need not be replaced frequently. Both $^{137}$Cs, with half life of 33 years, and $^{241}$Am with 486 years are excellent with regard to radioactive decay.

A blanket recommendation cannot be made as to either $^{241}$Am or $^{137}$Cs being a better source than the other for soil moisture measurements. The choice depends upon many factors; however, some general comparisons may be made regarding sample size and sensitivity. It has been stated [13] that for optimum absorption necessary for best precision, the transmitted beam should be between 13 and 37% of the incident beam. These limits may be relaxed somewhat to between 1 and 3 half thicknesses. If the errors are independent of the signal strength of the transmitted beam, the upper value is best, but if the errors are a function of the output signal, the lower value should be used [13]. Since, however, for water content measurements, we are primarily interested in the differences in overall densities between saturated and dry soils, the effective half thickness for water as it exists in the pores of the soil is an important value. Equation (6) may be used to determine this effective half thickness. For the relative values for $^{137}$Cs and $^{241}$Am, the effective half thickness for similar soil conditions reduces to the inverse ratio of the mass absorption coefficients for water. Thus, for similar soil conditions, the optimum thickness of water in the soil sample is about 2.3 times greater for $^{137}$Cs than for $^{241}$Am. If we consider the mass absorption coefficients for concrete from Grodstein [10] to approximate the values for soil, we have $\mu_0 = 0.267$ for $^{241}$Am, and $\mu_0 = 0.077$ for $^{137}$Cs. Neglecting the air and sample container, assuming a porosity of 0.5 and a bulk density of 1.32 g/cm$^3$, and using Equation (2) for dry soil gives half thicknesses of about 2 cm for $^{241}$Am and 7 cm for $^{137}$Cs. For completely saturated soils (S = 1) with the same assumptions, these values are about 1.5 cm for $^{241}$Am and 4.8 cm for $^{137}$Cs. Thus, if the values of 3 half
thicknesse are used, the samples should be about 4.5 to 6 cm thick for $^{241}$Am and 14.5 to 21 cm thick for $^{137}$Cs. Although these estimates should be used only as rough guides, they do demonstrate that for smaller samples $^{241}$Am gives greater sensitivity than $^{137}$Cs; i.e., greater relative change in count rate with change in saturation.

The required source strength also depends upon several factors as mentioned in Subsection 2.3. One important consideration is to maintain good counting statistics. The standard deviation is a function of the total counts, and a measure of the precision of any one count, N, is $N \pm \sqrt{N}$. Thus, it is desirable to balance the geometry of the design with desired counting time and source strength to give high total counts, N.

For $^{137}$Cs, there are few problems in obtaining as large a source as desired. Because of self absorption, $^{241}$Am has a practical limit of source strength. Figure 4, taken from Miller [8], shows the 60 keV photon intensity of $^{241}$Am as a function of source thickness. Of course, for any considerations of source strength, the small effective solid angle resulting from proper collimation must be accounted for in its reduction of the point source strength to the beam strength.
FIG. 6. Schematic drawing of apparatus to control and to measure volumetrically the saturation as a function of capillary pressure.

4. EXPERIMENTAL EQUIPMENT

4.1. Purpose of Experiment

Experiments were set up to compare the saturation of a sample of sand measured volumetrically with the saturation inferred from the absorption of gamma rays from a source of $^{241}$Am. It was desired to maintain uniform capillary pressure within the sample and, hence, insure uniform saturation to provide good comparison of saturation values measured by the two methods. The capillary pressure is defined as the difference between the air pressure and the water pressure across the water-air interfaces within the soil. Therefore, by flowing air upward through the sample at a pressure just sufficient to balance the hydrostatic pressure of the water within the sample, a uniform capillary pressure may be maintained within the sample (Figure 5).

4.2. Detection and Counting Equipment

A thin Harshaw type 2HC1M detector crystal of NaI(Tl) (1 mm thick and 1.27 cm diam.) was coupled to an EMI 9536B photomultiplier tube. The signal from the tube was passed through a special preamplification section with a voltage gain of 20 before being fed to the linear amplifier. Radiation Instrument Development Laboratory (RIDL) Model 30-19. Other components in the system included the high voltage power supply (RIDL Model 40-8B), pulse height analyzer (RIDL Model 33-10B), scaler (RIDL Model 49-26), timer (RIDL Model 54-7), and countrate meter (RIDL Model 35-7).

4.3. Other Laboratory Apparatus

Figure 6 shows the apparatus used to control and to measure volumetrically the saturation of the soil sample as a function of capillary pressure. The compressed air was passed through a presaturator in an attempt to raise the relative humidity sufficiently to prevent drying the sample. The pressure regulators allowed precise control of the air pressure difference across the sample and control of the capillary pressure within the sample. Regulator 3 was set to give the reference pressure above atmospheric. Then Regulator 2
was set to give the desired pressure drop across the sample, which was measured with the Pressure Transducer 5. The difference of pressure between Regulators 3 and 4 controlled the capillary pressure, which was measured with the aid of Transducer 6.

The soil sample was contained in a lucite cylinder of 5.7 cm ID with 6.3 mm wall thickness; the sample was about 3.2 cm high. The water was withdrawn from the sample at both ends through concentric rings of Type M Porvic and measured volumetrically in calibrated horizontal tubes. The air flowed through rings of fine screen concentric with the Porvic rings on both ends of the sample. The design is believed to give fairly uniform distribution of air flow across the face of the sample.

Figure 7 is a photograph of the apparatus, including the counting equipment. The source of $^{241}$Am is located to the right, and the detector with special preamplification section is to the left of the soil sample. The white board contains 6 interconnected horizontal glass tubes which can be read to the nearest 0.01 cm$^2$ of liquid volume. The tubes may be operated individually by teflon stopcocks shown at the left end of the board. The presaturator is shown below the glass outflow tubes.

4.4 Methods of Obtaining Data

The container was packed with air-dry sand, and the bulk density, porosity, and moisture content were determined by the usual gravimetric methods. The sample was set into the gamma ray apparatus and counted to obtain $I_1$ (see Subsection 2.1). Then the sample was placed into a tank
of water and completely saturated under vacuum. The tubing system was also filled to the zero readings on the horizontal glass tubes with the evacuated water from the saturating tank. The sample was again placed in the gamma beam and counted while completely saturated to obtain I₁. The capillary pressure was then increased in small steps to desaturate the sample. After each change of capillary pressure, the system was allowed to come to equilibrium as evidenced by no further movement of the water in the glass tubes. The capillary pressure was recorded together with the volume of water in the glass tubes, and the sample was counted to obtain an I₂ value. Hysteresis was prevented by insuring that any change of saturation was produced by an increase of capillary pressure.

5. RESULTS AND DISCUSSION

Considerable difficulty was experienced in obtaining the desired data, and results to be presented at this time are preliminary. First of all, it was difficult to add enough moisture to the air in the presaturator to prevent drying of the sample. It was determined that fairly good results could be obtained without the air flow through the sample; hence, the data reported here are for no air flow. Figure 8 shows results for two repeated runs under the same conditions. Since the depth of the sample was 3.2 cm, the capillary pressure head was 3.2 cm greater at the top than at the bottom of the sample. Nowhere on the curve would a straight line of 3.2 cm capillary head cause much error. The sample was counted at the midheight, and the volumetric values of saturation—while actually an average over the total sample depth—should correspond very closely with the saturation at midheight. Thus, the volumetric values of saturation are expected to be fairly accurate.

Difficulty with instrument drift when used as a pulse height analyzer prevented data from being collected in this manner. This problem has been traced to the special preamplifier section and has been corrected, but lack of time prevents data from being included. The data shown in Figure 8 for the gamma ray absorption were obtained by counting the entire spectrum with S calculated from Equation (9). Because of a lack of good collimation, it is expected that these results could be in error. Without sufficient collimation, the radiation received at the crystal could include scattered radiation from
outside the desired beam. Such radiation would increase the intensity measured at the detector over that from absorption in the soil and water within the desired beam. Attempts to determine the mass absorption coefficients of water from Equation (9) led to plots that were not straight lines; attempts to explain these results were rather inconclusive.

The count rate as used for Figure 8 was too low for good counting statistics (40,000 to 60,000 counts per 3 minutes). This can be significantly increased by increasing the slit sizes at the source and detector crystal. To confine the beam, good collimation should be used with the increased beam size. The lead shielding the crystal was too thin (about 2 mm) and too close to the crystal (about 1 cm); thus, allowing a good chance for back-scattered radiation from a substantially larger volume.

Even with the poor agreement of these preliminary results, it is believed that the use of $^{241}$Am in a properly designed apparatus will yield good measurements of soil moisture content. After correcting some of the faults of the present experimental apparatus noted above, similar experiments will be run.

6. SUMMARY

The measurement of soil moisture of laboratory samples by attenuation of gamma rays is described with particular reference to the use of $^{241}$Am as a source of photons. The $^{241}$Am is compared with $^{137}$Cs, and some advantages and disadvantages of each are pointed out. The major advantages of $^{241}$Am over $^{137}$Cs are that less biological shielding is required; the apparatus may be made smaller and lighter; there is greater sensitivity for small soil thicknesses (4.5 to 6 cm). Disadvantages of $^{241}$Am are that special preamplification of the 60 keV signal is needed and $^{241}$Am is limited to small columns because of the soft gamma rays emitted. There is a practical limit to strength of source which may be obtained with $^{241}$Am because of self absorption. However, source strengths entirely adequate for most studies should be attainable.

7. REFERENCES


DISCUSSION

D. KIRKHAM: What were the dimensions of your apparatus? If it is as small as it appears, it would obviate some of the hazards associated with the lifting of large lead blocks.

L.G. KING: The cylindrical column containing the soil sample, shown in Fig. 7, has an outside diameter of about 7 cm. The total distance between the radiation source and the detector crystal is about 9.5 cm. The \( {}^{241}\text{Am} \) source is contained in the cube on the right of the soil sample, which is about 5 \( \times 5 \times 5 \) cm. The total weight of the movable source and detector is about 7 lb. The source and detector are moved up and down the column manually and are locked in any desired position by turning a thumbscrew against the plate holding the soil column. I might add that at Colorado State University, where we had a \( {}^{137}\text{Cs} \) source set up to scan a vertical column, we added a 200-lb counter-weight to facilitate the raising of the source and detector.

J.R. McHENRY: Regarding the relative merits of \( {}^{241}\text{Am} \) and \( {}^{137}\text{Cs} \), I would mention that, being of lower energy, \( {}^{241}\text{Am} \) is much more sensitive to changes in the chemical composition of the attenuating medium. Therefore, if he chooses \( {}^{241}\text{Am} \), the researcher should be prepared to establish the detailed composition of the material under investigation. Furthermore, field equipment is usually more rugged than that described, and with this increased ruggedness of equipment much of the energy emitted by a low-energy source such as \( {}^{241}\text{Am} \) will be dissipated in the equipment. These are points to be considered when planning to use \( {}^{241}\text{Am} \) in field measurements.

L.G. KING: Certainly there may be applications of gamma-ray absorption techniques where the soft gamma rays emitted by \( {}^{241}\text{Am} \) are a disadvantage; this is mentioned in the summary of my paper. However, for small sample thicknesses, where it can be used, \( {}^{241}\text{Am} \) has distinct advantages over \( {}^{137}\text{Cs} \), in that the shielding requirements are so much less, and because of the light weight, equipment design problems are greatly simplified.
SCINTILLATION TECHNIQUES IN SOIL-MOISTURE AND DENSITY MEASUREMENTS

P. A. JENSEN AND E. SOMER
DANISH ISOTOPE CENTRE,
COPENHAGEN,
DENMARK

Abstract

SCINTILLATION TECHNIQUES IN SOIL-MOISTURE AND DENSITY MEASUREMENTS. The application and advantages of a neutron-moisture gauge making use of a scintillation detector with a lithium-6-glass scintillator are reported. Based on theoretical calculations and experimental results the influence of source-detector geometry, density effects, soil composition and instrumental instabilities is discussed. With the instrumentation described simultaneous density and moisture measurements can take place by means of a gamma source unit which can be attached to the moisture probe. Backscattered gamma radiation giving information on density and slow-neutron radiation containing moisture information are both detected by the glass scintillator. The two signals are separated in the indicating instrument by means of pulse-height analysis. A technique that permits moisture measurements uninfluenced by density variations is described. The sensitivity to epithermal neutrons of the glass scintillator is made use of in a version of the instrument where the scintillator is shielded by a strong slow-neutron absorber. This results in insensitivity to neutron absorbers in the soil at the cost of a higher density influence and six to seven times longer counting times to reach a given accuracy. Finally a simple method for testing and adjusting the stability of the instrumentation is reported.

1. INTRODUCTION

In the design of soil-moisture and soil-density gauges the choice of detector is important. Most manufacturers of moisture gauges use BF₃-filled proportional counter tubes in their equipment. The main advantages of this detector-type are its simplicity and comparatively low price. The very low sensitivity to gamma radiation is also an advantage in pure moisture gauges. On the other hand this fact makes it impossible to use the BF₃-tube as the common detector in a gauge for simultaneous moisture and density measurement. The main disadvantage is its comparatively low slow-neutron detection efficiency. This problem is to some extent overcome in most commercial instruments by the use of large tubes. However, this limits the free choice of source-detector geometry, necessary for optimizing the performance of the instrument.

Cadmium-covered Geiger-Müller tubes have been suggested as detectors in early reports and are even now used to some extent [1, 2]. A recent paper [2] advocates this detector type because it is also sensitive to capture gammas from slow-neutron capture in the soil. This is claimed to compensate for the effect of neutron absorbers in the soil. The main disadvantage of this detector type is again the low efficiency for slow-neutron detection. Proportional counters filled with ³H have been produced commercially for some time. They are sensitive to epithermal neutrons as well as to thermal neutrons. They have been
suggested for use in neutron-moisture gauges [3]. As far as we know they are not used in commercially available instruments.

The use of scintillation detectors with slow-neutron sensitive scintillators in neutron-moisture gauges has been well known for many years [4, 5, 6], but only a few manufacturers produce such instruments. Work on this type of instrumentation started at our institute in 1958. Instrumentation based on our design has been commercially available since 1962. The early version of our moisture probe made use of a 5-mCi $^{241}$Am-Be source and an Eu-activated lithium-iodide crystal, with $^{6}$Li enriched to 96%. However, this scintillator was found to cause severe troubles after being used several times. Free iodine was formed on the surface of the crystal, most probably because of moisture and air leakage through the encapsulation. This caused a decrease in the light output of the scintillator and the stability of the instrument to deteriorate. Other users of this type of instrument have reported the same trouble [7]. Replacement of the LiI-crystal with a glass scintillator, containing about 9% lithium, enriched in $^{6}$Li to 96%, solved this problem entirely.

The present instrument uses a 30-mCi $^{241}$Am-Be source, which has an even smaller gamma output than the earlier used Am-Be source. A theoretical study of our probe design and comparison with experimental results has been carried out by Ojgaard and Haahr [8]. This work resulted in a computer programme calibrating curves for soils with different compositions and dry-soil bulk densities [9]. Excellent agreement with experimental calibrations has been established. The computer programme can also be used to study the influence of probe parameters, such as source-detector geometry and epithermal neutron sensitivity of the detector on the performance of the instrument. This has been found very useful in perfecting the design for given applications. An example of the computer output is given in Table I. The significance of the terms used in the output sheet is found in Table II.

Our probe design allows for simultaneous moisture and density measurements by the attachment of a gamma-source unit to the moisture probe (see Figs. 1 and 2). The glass scintillator is also used as detector for backscattered gamma radiation from the soil. Pulse-height analysis in the indicating unit is used to separate the large pulses resulting from neutrons giving moisture information and the smaller gamma pulses giving density information. Applications where the use of the gamma-source unit has been found useful will be given later in this report.

2. INFLUENCE OF PROBE GEOMETRY ON THE SHAPE OF THE CALIBRATION CURVE

The main advantage of the enriched $^{6}$Li containing glass scintillators compared with BF$_3$ tubes is their almost 100% slow-neutron detection efficiency. A scintillator thickness of only a few millimetres is practically "black" to slow neutrons and their sensitivity extends well into the epithermal neutron range. Thus, with quite small scintillators the same or higher neutron count-rates can be obtained as with large BF$_3$ tubes. Commercial instruments mainly use BF$_3$ tubes with an

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1 Produced by N.E.A., Copenhagen, Denmark.
### Table I. Example of Computer Output

<table>
<thead>
<tr>
<th>VPY</th>
<th>VPL</th>
<th>VPB</th>
<th>VPC</th>
<th>VPV</th>
<th>VPQ</th>
<th>VPY</th>
<th>VPY</th>
<th>VPY</th>
<th>VPY</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.326</td>
<td>1.0×10^3</td>
<td>3.0×10^3</td>
<td>0.956</td>
<td>0.959</td>
<td>33.50</td>
<td>0.740</td>
<td>1.38</td>
<td>3.79</td>
<td>34.28</td>
</tr>
</tbody>
</table>

### Active Length of 10-20 cm

Our 12-mm-high glass scintillator gives a probe efficiency (count-rate at a given moisture content per unit output of fast neutrons) at least twice as high as that obtained in BF₃-tube probes. In BF₃-tube instruments the source is either placed near the centre of the tube or axially near the end of the tube. Neither of these geometries results in straight-line calibration curves. Centrally placed sources generally give calibration curves with a slope increasing with moisture while end-placed sources give a decreasing slope. Figure 3 shows theoretical and experimental values for different source-scintillator distances with our probe. The agreement between theoretical and experimental results is very good except for the lowest moisture contents. This is because the radius of the calibration drums in this case corresponded to less than infinite volume. The figure demonstrates that a small source-detector distance gives increasing slope while large distances cause decreasing slope. At about 7 cm distance between the centre of source and the centre of the scintillator an almost linear calibration curve is obtained.

A linear calibration curve simplifies calibrations (only calibration at two different moisture levels is needed) and makes it possible to construct indicating instruments directly calibrated in moisture content.
TABLE II. PHYSICAL SIGNIFICANCE OF DATA IN AEK-PROGRAM No. 412 MOPS II-C

**Input Data.**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TM</td>
<td>physical temperature of medium (°C)</td>
</tr>
<tr>
<td>Q</td>
<td>neutron source strength (n/sec)</td>
</tr>
<tr>
<td>VEFF</td>
<td>effective detector volume (cm³)</td>
</tr>
<tr>
<td>SAC</td>
<td>macroscopic 2200 m/s absorption cross-section of detector for process causing pulses (cm⁻¹)</td>
</tr>
<tr>
<td>SD</td>
<td>surface area of the effective detector volume (cm²)</td>
</tr>
<tr>
<td>D</td>
<td>distance from source to detector (cm)</td>
</tr>
<tr>
<td>L</td>
<td>half length of detector (cm)</td>
</tr>
<tr>
<td>C</td>
<td>control parameter</td>
</tr>
<tr>
<td>VPH</td>
<td>weight % H in dry soil</td>
</tr>
<tr>
<td>VPLI</td>
<td>Li - - -</td>
</tr>
<tr>
<td>VPS</td>
<td>B - - -</td>
</tr>
<tr>
<td>VPC</td>
<td>C - - -</td>
</tr>
<tr>
<td>VPN</td>
<td>N - - -</td>
</tr>
<tr>
<td>VPO</td>
<td>O - - -</td>
</tr>
<tr>
<td>VPNA</td>
<td>Na - - -</td>
</tr>
<tr>
<td>VPMG</td>
<td>Mg - - -</td>
</tr>
<tr>
<td>VFAL</td>
<td>Al - - -</td>
</tr>
<tr>
<td>VPI</td>
<td>Si - - -</td>
</tr>
<tr>
<td>VPF</td>
<td>P - - -</td>
</tr>
<tr>
<td>VPS</td>
<td>S - - -</td>
</tr>
<tr>
<td>VPC</td>
<td>Cl - - -</td>
</tr>
<tr>
<td>VPK</td>
<td>K - - -</td>
</tr>
<tr>
<td>VPCA</td>
<td>Ca - - -</td>
</tr>
<tr>
<td>VPTI</td>
<td>Ti - - -</td>
</tr>
<tr>
<td>VPMN</td>
<td>Mn - - -</td>
</tr>
<tr>
<td>VPFE</td>
<td>Fe - - -</td>
</tr>
<tr>
<td>VPCD</td>
<td>Co - - -</td>
</tr>
<tr>
<td>VPCD</td>
<td>Cd - - -</td>
</tr>
<tr>
<td>ROJR</td>
<td>dry soil density or reference medium (g/cm³)</td>
</tr>
<tr>
<td>VR</td>
<td>water volume per cent of reference medium (g/cm³)</td>
</tr>
<tr>
<td>CPMR</td>
<td>count-rate of detector in reference medium (cpm) (to be determined experimentally)</td>
</tr>
<tr>
<td>ROJ</td>
<td>dry-soil density corresponding to calibration curve (g/cm³)</td>
</tr>
</tbody>
</table>

**Correction Factors.**

| C     | computed ratio between the measured and the calculated (C=1) count-rate in reference medium |
| K     | correction factor for depression in detector of epithermal flux (experimentally determined) |

**Output data.**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>water volume per cent in soil (vol, %)</td>
</tr>
<tr>
<td>$\Phi AV$</td>
<td>average thermal flux of detector (n/cm² sec)</td>
</tr>
<tr>
<td>CR(CPM)</td>
<td>count-rate of detector in soil (cpm)</td>
</tr>
<tr>
<td>L</td>
<td>diffusion length of thermal neutrons (cm)</td>
</tr>
<tr>
<td>L1</td>
<td>slowing-down length, first group (cm)</td>
</tr>
<tr>
<td>L2</td>
<td>slowing-down length, second group (cm)</td>
</tr>
<tr>
<td>D</td>
<td>diffusion coefficient of thermal neutrons (cm)</td>
</tr>
<tr>
<td>D2</td>
<td>diffusion coefficient of second fast group (cm)</td>
</tr>
<tr>
<td>$\Phi JD$</td>
<td>epithermal flux at detector centre (n/cm² sec)</td>
</tr>
</tbody>
</table>

$\Phi$ (cpm) does not include count-rate of probe in air. This value must be determined experimentally and should be added to $\Phi$ (cpm) in order to obtain the actual count-rates.
FIG. 1. The BASC instrumentation for soil-moisture and density measurements.
Left to right:
Gamma-source unit in its shield and transport container.
UNBRAKO key for locking gamma-source unit in
its shield container and for connecting and disconnecting
the gamma-source unit and the moisture probe.
Shield and transport container for depth-moisture probe.

Depth-moisture probe.
BASC scaler/count-rate meter.
Gamma-source unit.
Combined shield and transport containers for
moisture probe and gamma-source unit.

There is no doubt that the user will require fully calibrated instruments
in the future just as he is accustomed to from most other instruments
that measure physical or chemical properties.
Numerous theoretical and experimental calibrations with our probe
have shown that change in soil parameters with reasonable accuracy does
not change the linearity of the calibration curve.
A linear calibration curve can be expressed as

\[ w = a \times CR - b \]

where \( w \) = moisture content in vol. \%
\( a \) = slope of the calibration curve \( \frac{dw}{dCR} \)
\( CR \) = count-rate
\( b \) = dry-soil equivalent (\( a \times \) count-rate at 0% moisture)

Both "a" and "b" in the equation can be easily adjusted in a moisture-
reading count-rate meter. An adjustment of "a" corresponds to an
adjustment of the range of the scale while an adjustment of "b" is equi-
valent to a zero suppression. Thus, any calibration curve can be replaced
by two figures giving particular dial settings on the moisture-reading
instrument.
FIG. 2. (a) BASC depth-moisture probe.
(b) BASC depth-moisture probe with density unit.
3. INFLUENCE OF DENSITY ON CALIBRATION CURVE

Variations in dry-soil bulk density affect the calibration curve of a neutron-moisture gauge. Higher densities give higher count-rates for the same moisture content.
By means of the computer programme calibration curves for the same soil type at different dry-soil bulk densities can be established. Again good agreement between experimental and theoretical results has been reported [9]. Figure 4 shows a set of calibration curves for a given soil type at different dry-soil densities. The curves are practically parallel above 25% moisture. They converge slightly towards lower moisture values.

Dry-soil density does not usually change with time and moisture variations when in-situ moisture measurements are being carried out in soil. Often, one is only interested in determining moisture differences as a function of time at a given position and not in the absolute moisture contents. In this case the error in the determination of the moisture difference is not large, even if soil-density corrections have not been carried out.

Let us consider a case, where a calibration curve for the particular soil type at a dry density of 1.5 g/cm³ is known and the actual unknown dry densities vary between 1.0 and 2.0 g/cm³. The maximum errors expressed as ± vol.% H₂O per 1 vol.% H₂O moisture difference in different moisture ranges are tabulated below:

<table>
<thead>
<tr>
<th>Moisture range vol.% H₂O</th>
<th>0-10</th>
<th>10-20</th>
<th>20-30</th>
<th>30-40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. error vol.% H₂O</td>
<td>0.2</td>
<td>0.1</td>
<td>0.05</td>
<td>0</td>
</tr>
<tr>
<td>vol.% H₂O diff.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

If, for instance, a moisture change from 35 to 5 vol.% H₂O has been determined, the maximum error in the difference (30 vol.% H₂O) will be:

\[10 \times 0.05 + 10 \times 0.1 + 5 \times 0.2 = \pm 2.5 \text{ vol.} \% \text{ H}_2\text{O}.

If errors of this size are not acceptable or if absolute moisture values are required, it is necessary to determine the dry-soil density in all measurement positions.

As mentioned before, the dry-soil density does not generally change with time in a given position. Once the dry-soil densities have been established in a profile it is not usually necessary to repeat the dry-density determination.

In our instrumentation the dry-soil density is determined by a moisture probe to which a gamma-source unit containing a 3-mCi ¹³⁷Cs source is attached. By means of an Unbraco screw the gamma source unit is easily fixed to and detached from the moisture probe without any radiation risk (see Figs 1 and 2). Thus, it is not necessary during field work to carry around a heavy gamma source and shield arrangement all the time without using it. On the other hand, it is only necessary to buy a single detector, which can simultaneously perform both moisture and density measurements in a profile.

In density measurements the wet-soil bulk density is determined. This property will, of course, change with moisture. The dry density is obtained from the wet density by subtracting the moisture volume fraction (vol.% H₂O divided by 100). In the simultaneous determination of density and moisture the dry-soil density is not yet known. Therefore, it is necessary to have a set of moisture calibration curves with wet density as parameter. These curves are easily deduced from the calibration curves at different dry densities. Figures 4 and 5 show sets of calibration curves at different dry and wet densities. When the first
FIG. 5. Calibration curves (vol. % H₂O).
Rye soil at different wet densities.

FIG. 6. Calibration curve.
Wet-soil density (g/cm³).

A series of measurements have been finished the dry density can be calculated from the obtained moisture and wet-density results and then these dry densities can be used in later work when moisture measurements are carried out with the pure moisture probe. A typical wet-density calibration curve for our instrumentation is shown in Fig. 6.

The density information is obtained from small light pulses in the scintillator due to backscattered gamma radiation. Figure 7 shows the differential pulse-height spectrum for the combined moisture and density probe. The peak is due to neutrons. Backscattered gamma radiation causes the count-rate at small pulse heights, which is well separated from the neutron peak. The neutron count-rate is determined with an integral discriminator level in the valley between neutron and gamma
FIG. 7. Differential spectrum for BASC depth density/moisture probe No. 2.
Sample: 11 vol.% H₂O at dry density 1.9 g/cm³.

FIG. 8. Illustration of the principle of density-independent moisture measurement with a moisture/density gauge.
The plateau curves represent media with constant moisture content (in vol.% H₂O), but with different densities.

... pulses. The gamma count-rate is determined with a single-channel pulse-height analyser looking at the higher energy part of the gamma spectrum. The upper and lower levels of the pulse-height analyser are set in such a way that the count-rate is almost independent of even considerable pulse-height drifts. A drift in pulse height of ± 25% only causes an error of ± 0.1 g/cm³ density. The stabilization procedure, described later in this report, also automatically stabilizes the density readings.
The density calibration curve shows that the count-rate due to
backscattered gamma radiation decreases with increasing density.
However, as shown earlier, the neutron count-rate at a given moisture
content increases with density. These facts can, in a very simple
manner, be used to compensate the density effect in moisture measure-
ments. Figure 8 demonstrates the principle. The figure shows the
integral pulse-height spectrum from the combined moisture and density
probe for soils with the same moisture content but with different densities.
The dotted curve corresponds to the highest density.

The flat part of the curve is the neutron plateau where only neutrons
are recorded. The increasing count-rate at the lower end contains the
gamma information. It is seen that the two curves intersect. At the
point of intersection the count-rate will be dependent on the moisture
content but independent of the density. Preliminary experiments show
that the discriminator level where intersection takes place is almost
independent of moisture and density. Thus, by discriminating at this
level, density independent moisture readings are obtained. At present,
this method has only been used in the laboratory. The main problem
is that, at this discriminator level, the count-rate is very sensitive
to pulse-height changes.

4. INFLUENCE OF SOIL COMPOSITION ON
CALIBRATION CURVES

Variations in the chemical composition of soil will cause calibration
curve changes. Soil components, with large neutron absorption cross-
section and hydrogen as chemically bound water or in organic matter,
are the influential elements. The effect was studied by Øigaard for five
representative Danish soil types ranging from sand to sandy clay loam[10].

Our instrument calibration curves were calculated for these soil types
by means of the computer programme. The range of the variations is
illustrated in Fig. 9 at three different soil densities. If an average
calibration curve is used for all soils an error is introduced. For the
considered soil types the maximum error in absolute moisture content
because of neglecting soil composition is shown in Table III. The errors,
which will be introduced by the presence of boron, chlorine and iron,
are also listed in the table.

In the determination of moisture differences errors will occur
because of the same reasons. Table IV states the maximum errors
arising from neglect of the soil composition, boron, chlorine and iron
as error in vol.% H₂O per vol.% H₂O difference.

From the tables it can be deduced whether or not the errors for given
soil-type variations and strong neutron absorber contents are acceptable.
If they are not an accurate calibration curve can be calculated by means
of the computer programme or, in the case of strong neutron absorbers,
by plotting a new calibration curve from the error values given or
empirical at two H₂O-contents.

As an alternative we investigated the possibility of using the epithermal
neutron sensitivity of our glass scintillator. Epithermal neutron de-
tection, as a means of decreasing the influence of soil composition on
the calibration curve, has been suggested by several authors [3, 11], but
this facility was not available earlier in commercial soil-moisture gauges.
FIG. 9. Calibration curves (vol.% H₂O).
Five different Danish soils at dry density
(1 g/cm³, 1.6 g/cm³, and 2 g/cm³).

TABLE III. MAXIMUM ERRORS IN VOL.% H₂O IN
ABSOlUTE MOISTURE MEASUREMENTS
(Due to: Neglecting soil composition; boron; chlorine and iron.
At different moisture contents)

<table>
<thead>
<tr>
<th>Moisture (vol. % H₂O):</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil comp. dry density = 1 g/cm³</td>
<td>0.8</td>
<td>0.6</td>
<td>0.5</td>
<td>0.7</td>
<td>0.9</td>
</tr>
<tr>
<td>Soil comp. dry density = 2 g/cm³</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1.5</td>
<td>2</td>
</tr>
<tr>
<td>0.003 wt. % B</td>
<td>0.6</td>
<td>1.2</td>
<td>1.8</td>
<td>2.4</td>
<td>3.1</td>
</tr>
<tr>
<td>1 wt. % Cl</td>
<td>2</td>
<td>5</td>
<td>8</td>
<td>10.5</td>
<td>13</td>
</tr>
<tr>
<td>5 wt. % Fe</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>3.5</td>
<td>4.5</td>
</tr>
</tbody>
</table>

The feasibility of an epithermal neutron detecting probe based on
our instrument was investigated experimentally. Calculations were also
carried out with the computer programme, which gives the epithermal
flux at the detector for given soil parameters and varying moisture
contents as part of the output data (Tables I and II).

Our moisture probe was modified by a shielding arrangement around
the detector. This consisted of a cap of epoxy resin containing boron
carbide. The natural boron content of the material was approximately
50 wt. %. The wall thickness of the boron cap was 1.5 mm. The photo-
multiplier was surrounded by a 0.1-mm cadmium foil in order to prevent
thermal neutrons entering the scintillator through the photomultiplier
cathode. Boron was preferred as an absorbing material around the
detector since cadmium causes gamma-ray emission by neutron capture.
TABLE IV. MAXIMUM ERRORS IN VOL.%/VOL.% MOISTURE DIFFERENCE IN MEASUREMENTS OF MOISTURE DIFFERENCES
(Due to: Neglecting soil composition; boron; chlorine and iron.
At different moisture ranges)

<table>
<thead>
<tr>
<th>Moisture range (vol.% H₂O):</th>
<th>0-10</th>
<th>10-20</th>
<th>20-30</th>
<th>30-40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil comp. dry density = 1 g/cm³</td>
<td>0.04</td>
<td>0.03</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Soil comp. dry density = 2 g/cm³</td>
<td>0.05</td>
<td>0.05</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>0.003 wt. % B</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>1.00 wt. % Cl</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>5.00 wt. % Fe</td>
<td>0.1</td>
<td>0.08</td>
<td>0.08</td>
<td>0.06</td>
</tr>
</tbody>
</table>

TABLE V. EPITHERMAL FLUX (n/cm² sec) AT DETECTOR FOR VARYING MOISTURE CONTENTS IN FIVE DIFFERENT DANISH SOIL TYPES
(Dry soil density 1.60 g/cm³. Flux due to bound H-content subtracted)

<table>
<thead>
<tr>
<th>Moisture (vol.% H₂O)</th>
<th>Sandy clay loam</th>
<th>Sandy loam</th>
<th>Sandy loam</th>
<th>Loamy sand</th>
<th>Sand</th>
<th>Maximum error between the 5 soils (vol.% H₂O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>86</td>
<td>88</td>
<td>88</td>
<td>86</td>
<td>88</td>
<td>± 0.15</td>
</tr>
<tr>
<td>10</td>
<td>149</td>
<td>150</td>
<td>151</td>
<td>149</td>
<td>150</td>
<td>± 0.15</td>
</tr>
<tr>
<td>20</td>
<td>203</td>
<td>204</td>
<td>203</td>
<td>203</td>
<td>204</td>
<td>± 0.1</td>
</tr>
<tr>
<td>30</td>
<td>251</td>
<td>252</td>
<td>251</td>
<td>250</td>
<td>251</td>
<td>± 0.2</td>
</tr>
<tr>
<td>40</td>
<td>291</td>
<td>291</td>
<td>291</td>
<td>291</td>
<td>292</td>
<td>± 0.15</td>
</tr>
<tr>
<td>50</td>
<td>324</td>
<td>326</td>
<td>326</td>
<td>324</td>
<td>326</td>
<td>± 0.3</td>
</tr>
</tbody>
</table>

The limited space around the photomultiplier necessitated the use of cadmium foil here.

From measurements in water it was found that, whereas the addition of 1 wt.% chlorine caused the count-rate for an ordinary probe to decrease by 11%, no measurable decrease could be detected with the modified probe. Computations show that the epithermal flux for five different Danish soils is nearly the same at given moisture contents and constant density. Remaining differences are due to differences in the bound hydrogen content of the soils. Table V shows the epithermal flux after subtraction of the flux due to bound hydrogen. The table also gives the maximum error when using an average calibration curve for these five
soils. Computations of the epithermal flux at the detector for varying moisture contents in a given soil at different densities were carried out (Fig. 10). From these curves the change in flux and the equivalent apparent change in moisture content in vol. % H₂O caused by a change in soil density of 0.1 g/cm³ were found. The values are tabulated below together with the values for the ordinary probe:

<table>
<thead>
<tr>
<th>Moisture content (vol.% H₂O)</th>
<th>0</th>
<th>10</th>
<th>30</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error (vol.% H₂O/0.1 g/cm³)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Epithermal probe</td>
<td>2.2</td>
<td>2.5</td>
<td>2.7</td>
<td>3.0</td>
</tr>
<tr>
<td>Ordinary probe</td>
<td>1.0</td>
<td>1.2</td>
<td>1.4</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Experimental results from measurements in material with different densities showed the same tendency to increased density influence in the epithermal probe compared with the ordinary probe. These measurements also demonstrated that the time necessary to measure the moisture content with a certain accuracy was six to seven times longer for the epithermal probe than for the ordinary probe. Suggestions in literature that the use of an epithermal neutron detector could slightly improve the resolution of the probe were checked experimentally [3]. No significant improvements were obtained in our case.

5. INFLUENCE OF INSTRUMENT INSTABILITY ON CALIBRATION CURVE

Both BF₃ proportional counters and scintillation detectors are energy dependent detectors and give output pulses proportional in height to the energy absorbed in the detector. The height of the output pulses depends on the high voltage supplied to the detector and the pulses must be amplified and must pass a discriminator that only passes pulses over a
certain height to the counter or count-rate meter. By far the largest and most common part of the instrumental instabilities in any neutron-moisture gauge is due to pulse height or discriminator drifts caused by changes in the detector, high voltage, amplifier or discriminator. However, good stability depends not only on the quality of the detector and electronic circuits but also on the pulse-height distribution from the detector. The pulse height from neutron pulses should be well separated from pulses due to other radiation and noise pulses. This will result in a long and flat plateau on the integral pulse-height distribution curve. The pulse-height discrimination usually takes place near the middle of the plateau. Thus, increases or decreases in pulse height or discriminator level will only cause minor changes in count-rate in a given medium.

The generally recommended method to check the stability of a neutron-moisture gauge is to carry out measurements in a standard medium. Mostly the shield container for the probe is used for this purpose. To avoid errors due to instrumental instabilities it is often suggested that the ratio between the count-rate in the standard and count-rate in soil be used as a measure of the moisture content [8]. This method has several drawbacks. The standard does not usually represent an infinite volume so that hydrogenous matter near the standard can cause errors. The count-rate in the standard can be influenced by temperature changes. However, the main problem is that it is so time consuming to take standard count-rates that it is often neglected entirely.

![Figure 11](image_url)

**FIG. 11.** Plateau curve for RASC depth density/moisture probe No. 3 in the transport container. In normal position and in test position.

The method recommended by us for the checking and adjustment of instrumental stability is explained by means of Fig. 11. This figure shows the integral pulse-height distribution curve of our probe ("normal"). When pressing a test push button on the indicating instrument the pulses must pass a fixed attenuator that decreases all pulse heights by a factor of two. This corresponds to the other pulse-height distribution curve in the figure ("test"). It is seen that the discriminator level is now
saturated in the middle of the steep part of the curve. Even a very small drift in pulse height or discriminator level now causes a very significant change in the count-rate. It is only necessary to count for a few seconds in this position in order to detect an instability. The instrument also has a continuously variable attenuator, which is used to restore the original pulse-height distribution. This procedure is usually carried out with the probe in the shield container.

The plateau slope near the discriminator level in our instrument causes a count-rate change of 150 cpm for a 10% change in pulse height. This corresponds to an error of 0.2 vol. % H₂O. In the "test" position a 10% change in pulse height causes a count-rate change of 7000 cpm. It only takes a fraction of a minute to detect such a change and to return the count-rate in the "test" position near its original value. This reduces the instrumental instabilities to a completely insignificant level.

ACKNOWLEDGEMENTS

The authors are grateful to Mr. P. L. Øigaard from the Danish Atomic Energy Commission, who developed the theoretical calculation programme for our neutron-moisture probe; and to Mr. V. Haahr, Danish Atomic Energy Commission, who carried out the majority of the experimental calibrations reported in this paper.

REFERENCES


DISCUSSION

M. DARG: Your diagram showing linearity of calibration with different source-detector distances (Fig. 3) was checked by field observations up to 30% moisture content. In East Africa, we are concerned with moisture contents up to at least 60%. Will it still be linear at such high moisture contents?

E. SOMER: Yes.
M. DE BOOR: If I understood correctly, the error resulting from ignoring the bulk density is only 2.5%, yet the calibration curves in Fig. 4 show a difference of about 100% between densities of 1 and 2.

I also understand that to measure epithermal neutrons, you put a relatively thick cadmium foil round the detector. Would it not be possible to improve these properties by using a thinner cadmium foil (e.g. 0.96 mm)? Our experiments show less dependence on density when using the thinner foil.

E. SOMER: The figure of 2.5% was the error in determining moisture differences, not absolute moisture values.

Actually we used boron round the detector and 0.1-mm cadmium round the photomultiplier. Thinner absorbers produce less density effect, but larger soil composition effects, so each investigator has to decide which compromise to make.

N. AYBERS: In your Fig. 8, for density-independent moisture measurements, two curves for different densities cut one another. This appears to be a function of gamma absorption by the soil, i.e. it depends on the soil composition.

E. SOMER: Our data are not yet complete, but they seem to show that the vertical line of intersection is nearly independent of soil composition, density and moisture content.

M.J. FRISSEL: What language do you use for your computer programme?

E. SOMER: We use ALGOL.

W.K.G. KÜHN: Is the common point for density and moisture of the plateau independent of the water content?

E. SOMER: It is nearly constant.

W.K.G. KÜHN: Why do you not divide the water content value by the density value electronically, as this permits greater accuracy, and what is the temperature dependence of your equipment?

E. SOMER: The method we propose can be applied with an ordinary instrument, without additional circuitry. I have not got the exact figure for temperature with me, but I know that it corresponds to less than 0.5 vol. % H₂O for temperature changes between -10°C and +50°C. Even this small change can be cancelled out by using the standardization method described in the paper.

H.W. SCHARPENSEEL: Regarding epithermal neutron detection, to what extent are the increased errors offset by the lower influences of soil composition and density? Could you comment on some of the practical difficulties?

While measurements in the epithermal region would be of little value under the soil conditions found in areas of semi-humid climate, do you think that epithermal neutron measurements would offer advantages in ground with abruptly changing soil profiles and plenty of free Cl or Fe, such as in saline soils of the semi-arid zone, ferro-allitic soils of the humid tropics or even podsoils of the humid and extremely humid climatic areas?

E. SOMER: The paper indicates the errors due to soil composition, and density changes for the ordinary probe and the epithermal neutron probe. It is therefore possible to evaluate in any specific case which type of measurement is best. My general opinion is that the epithermal
neutron probe should be used only in cases where large variations are expected in the content of strong neutron absorbers. If one does not know which probe to use, it is easy to make comparisons, as the slow neutron absorber shield is easy to apply to the ordinary probe.
EXPLOITATION DES INFORMATIONS CONTENUES DANS UN FLUX DE NEUTRONS THERMALISÉS ET POSSIBILITÉS D'APPLICATION À LA MESURE DE L'HUMIDITÉ ET DE LA DENSITÉ D'UN SOL

E. P. CORROMPT ET P. CALMELS
CEA, CENTRE D'ETUDES NUCLEAIRES DE GRENOBLE, FRANCE

Abstract — Résumé

USE OF INFORMATION OBTAINABLE FROM A THERMALIZED NEUTRON FLUX AND POSSIBLE APPLICATIONS TO SOIL- AND MOISTURE-DENSITY MEASUREMENTS. The deceleration time of a fast neutron of specific initial energy, its "lifetime" in the thermal state and the length of its path through the moderating medium depend solely on the type and number of atomic nuclei which it encounters. The cloud of moderated neutrons surrounding the source contains all the information on the composition of the decelerating medium collected by each neutron, and certain features of this cloud can be used to establish the composition of the medium. This applies particularly to the hydrogen content, dry density and chemical composition of a soil, which act simultaneously on the spatial and energy distributions of the neutron cloud.

Information is normally taken only from the density of the thermal neutron cloud, in order to measure the hydrogen content of the soil. This measurement has to be corrected by measuring the dry-soil density by gamma diffusion, but this method is incomplete since it makes no allowance for the influence of the soil's chemical composition.

A method using three flux density measurements: one of epithermal neutrons close to the source and two of thermal neutrons - one close to the source and the other at a distance of 10 cm - is proposed. Each of these measurements, made with a small-volume detector, provides different information on the hydrogen content, dry density and chemical composition of the soil. Some experimental tests offer hope that a combination of these three results could, after preliminary calibration, be used to establish the water content and dry density of soils of unknown chemical composition. The paper describes a manner of presenting the results. Where the nature of the soil is known, the method can be used, with only one thermal neutron and one epithermal neutron measurement, for determining the dry density and water content of the soil. This process obviates the need for the density correction measurement obtained by gamma diffusion.

EXPLOITATION DES INFORMATIONS CONTENUES DANS UN FLUX DE NEUTRONS THERMALISÉS ET POSSIBILITÉS D'APPLICATION À LA MESURE DE L'HUMIDITÉ ET DE LA DENSITÉ D'UN SOL. La durée du ralentissement d'un neutron rapide ayant une énergie initiale donnée, la durée de sa "vie" à l'état thermique et la longueur de son trajet dans le milieu modérateur dépendent uniquement de la nature et du nombre de noyaux atomiques qu'il rencontre. Le dosage de neutrons ralentis entourant la source renferme finalement toutes les informations sur la composition du milieu ralentisseur collectées par chaque neutron. Certaines caractéristiques de ce dosage permettent d'étudier la composition du milieu. Plus particulièrement, la teneur en hydrogène, la densité sèche et la composition chimique d'un sol agissent simultanément sur la répartition dans l'espace et la distribution énergétique du dosage de neutrons.

Habituellement, on ne retire des informations que de la densité du nuage de neutrons thermiques, en vue de mesurer la teneur en hydrogène du sol. Cette mesure doit être corrigée par une mesure de densité du sol sec, obtenue par diffusion gamma. Cette méthode est incomplète puisque l'influence de la composition chimique du sol est négligée.

Une méthode utilisant trois mesures d'intensité de flux - une de neutrons épithermiques près de la source, deux de neutrons thermiques - l'une près de la source, l'autre à 10 cm - est proposée. Chacune de ces mesures, effectuées avec un détecteur de faible volume, apporte des informations différentes sur la teneur en hydrogène, la densité sèche et la composition chimique du sol. Quelques essais expérimentaux
 permettent d’espérer que la combinaison de ces trois résultats pourrait autoriser la mesure de la teneur en eau et de la densité sèche d’un sol de nature chimique inconnue après un étalement préalable. Un type de représentation des résultats est décrit.

Dans les cas où la nature du sol est connue, il est possible d’employer la méthode présentée en n’utilisant qu’une mesure de neutrons thermiques et une de neutrons épithermiques pour déterminer la densité sèche et la teneur en eau du sol.

Ce procédé permet de supprimer la mesure corrective de densité obtenue par diffusion gamma.

INTRODUCTION


L’influence du sol sec se traduit par la nécessité d’employer une courbe d’étalement adaptée à chaque milieu. Trois solutions ont été étudiées jusqu’à ce jour pour adapter l’utilisation de l’humidimètre à chaque terrain.

- L’étalement en laboratoire dans des échantillons du sol considéré, ou mieux sur le terrain. Ce procédé est long mais assez précis.
- L’étalement à partir d’un calcul de flux neutronique; c’est par exemple la méthode préconisée par Øigaard [1]. Plus légère que la précédente elle nécessite quand même une analyse chimique préalable du sol, ce qui peut entraîner une perte de temps exagérée si la nature du terrain évolue avec la profondeur.

Aucune de ces solutions n’est parfaite. Comme finalement le flux neutronique est conditionné par le terrain, il est intéressant d’examiner si la mesure simultanée de plusieurs paramètres du flux ne permet pas d’identifier le sol et de résoudre ainsi le problème du choix de la courbe d’étalement.

1. RAPPEL SUR LE ROLE DU MILIEU RALENTISSEUR ET DIFFUSEUR

Il faut déterminer quels paramètres du flux sont susceptibles de permettre l’identification du milieu ralentisseur. Pour cela, il est nécessaire de rappeler le mécanisme du ralentissement et de la diffusion des neutrons.

1.1. Action du milieu aux différents niveaux d’énergie

Déjà son apparition le neutron rapide heurte les noyaux environnants et, au cours de sa vie, il entre en contact avec quelques centaines de
noyaux différents. Comme chaque type de noyau a des propriétés particulières de ralentissement et d’absorption, propriétés qui varient avec l’énergie du neutron, la durée de vie et le trajet d’un neutron dépendent entièrement des noyaux qu’il a rencontrés. Certes, il n’est pas possible de recueillir les informations transportées par un seul neutron, puisqu’il n’est pas possible de l’observer mais seulement de le détecter en le détruisant. Par contre, le nuage de neutrons de toutes énergies qui diffuse autour de la source renferme statistiquement les mêmes informations. Il serait intéressant de les déduire de la forme, de la densité de ce nuage et de la répartition énergétique des neutrons qui le constituent.

Pour chiffrer les paramètres déterminant le nuage de neutrons il convient de leur donner une représentation mathématique qui consiste généralement à assimiler le nuage de neutrons à un gaz diffusant dans un milieu poreux. L’action du milieu sur le flux se manifeste par l’intermédiaire de ses sections efficaces de diffusion et de capture. Les sections efficaces traduisent la probabilité d’interaction d’un neutron avec les noyaux; elles varient avec l’énergie du neutron.

L’étude mathématique suppose donc le découpage du nuage neutronique en tranches d’énergie. Les neutrons appartenant à une même tranche d’énergie constituent un groupe [3]. Les sections efficaces sont supposées constantes pour tous les neutrons d’un même groupe puisqu’ils sont supposés avoir tous la même énergie. La représentation mathématique du comportement des neutrons donne des résultats s’accordant d’autant mieux avec la réalité que le domaine d’énergie compris entre 0 et 10 MeV où évoluent les neutrons est découpé en un plus grand nombre de groupes.

L’équation régissant le comportement des neutrons dans un groupe s’écrit [3]

\[ S(x, y, z) + \frac{1}{3 \Sigma_i} \Delta^2 \Phi(x, y, z) - \left( \Sigma_a + \frac{\Sigma_c}{U} \right) \Phi(x, y, z) = 0 \]

\( S(x, y, z) \) est le terme source représentant l’apparition des neutrons dans le groupe considéré. Ils viennent généralement des groupes d’énergies supérieures par ralentissement.

\( (1/3 \Sigma_i) \Delta^2 \Phi(x, y, z) \) représente la disparition des neutrons par diffusion donc éloignement de la source.

\( \Sigma_a \Phi(x, y, z) \) représente l’absorption définitive des neutrons par capture d’un noyau.

\( (\Sigma_c/U) \Phi(x, y, z) \) représente la disparition des neutrons du groupe considéré par ralentissement. Ce ralentissement s’effectue par choc mécanique, auquel cas le neutron passe souvent dans le groupe immédiatement inférieur, ou par diffusion inélastique, auquel cas le neutron peut perdre la plupart de son énergie en une seule interaction. Le premier cas étant le plus fréquent le terme \( (\Sigma_c/U) \) représente la plus grande partie du terme source du groupe immédiatement inférieur.

Dans le groupe thermique les neutrons sont en équilibre énergétique avec les noyaux du milieu ralentisseur. La diffusion entraîne plus de perte d’énergie et le terme \( (\Sigma_c/U) \) disparaît.

Les paramètres caractéristiques du sol interviennent par l’intermédiaire des termes \( \Sigma_a, \Sigma_i, \) et \( \Sigma_c \) qui représentent respectivement les sections efficaces macroscopiques d’absorption, de diffusion et de
### TABLEAU I. INFLUENCE DE LA COMPOSITION DU MILIEU SUR LES PRINCIPAUX PARAMETRES CONDITIONNANT LE FLUX NEUTRONIQUE

<table>
<thead>
<tr>
<th>Nature du sol</th>
<th>SiO₂ 1.6 g/cm³</th>
<th>Al₂O₃ 1.6 g/cm³</th>
<th>SiO₄ 1.35 g/cm³ + C³Na 0.15 g/cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>10%</td>
<td>20%</td>
<td>30%</td>
</tr>
<tr>
<td>1 ≤ E ≤ 2 MeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I₂</td>
<td>0.18</td>
<td>0.22</td>
<td>0.26</td>
</tr>
<tr>
<td>I</td>
<td>0.22</td>
<td>0.30</td>
<td>0.35</td>
</tr>
<tr>
<td>λₐ</td>
<td>17.0</td>
<td>10.6</td>
<td>7.7</td>
</tr>
<tr>
<td>O</td>
<td>1.10⁻⁴</td>
<td>6.10⁻⁴</td>
<td>6.10⁻⁴</td>
</tr>
<tr>
<td>n</td>
<td>0.10⁻⁴</td>
<td>6.10⁻⁴</td>
<td>6.10⁻⁴</td>
</tr>
<tr>
<td>10 ≤ E ≤ 50 keV</td>
<td></td>
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</tr>
<tr>
<td>I₂</td>
<td>0.18</td>
<td>0.30</td>
<td>0.52</td>
</tr>
<tr>
<td>I</td>
<td>0.22</td>
<td>0.66</td>
<td>0.72</td>
</tr>
<tr>
<td>λₐ</td>
<td>5.1</td>
<td>1.7</td>
<td>1.8</td>
</tr>
<tr>
<td>O</td>
<td>4.10⁻⁴</td>
<td>2.10⁻⁴</td>
<td>1.10⁻⁴</td>
</tr>
<tr>
<td>n</td>
<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>2 ≤ E ≤ 3 eV</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>I₂</td>
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<td>0.47</td>
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<tr>
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<tr>
<td>O</td>
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<tr>
<td>n</td>
<td>0.66</td>
<td>0.03</td>
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<td>Thermique</td>
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</tr>
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<td>I₂</td>
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<td>I</td>
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</tr>
<tr>
<td>O</td>
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</tr>
<tr>
<td>n</td>
<td>63</td>
<td>50</td>
<td>52</td>
</tr>
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</table>

I₂ = Section efficace macroscopique de diffusion (cm⁻²)
I = Perte logarithmique moyenne d’énergie à chaque choc
λₐ = Linéaire parcouru moyen d’un neutron dans le groupe avec sa disparition de ce groupe (cm)
O = Temps de vie moyen d’un neutron dans le groupe (b)
α = Pourcentage du flux total dans le groupe.

transport, et par le terme Σ ou perte logarithmique moyenne d’énergie. Les définitions exactes de ces grandeurs et de leurs propriétés se trouvent dans tous les ouvrages consacrés aux neutrons [3-4]. Il suffit de rappeler que si NH, NC, Na, NAl, NSi représentent respectivement les nombres d’atomes des éléments H, C, O, Al, Si présents par centimètre cube de terrain, et σ₂H, σ₂C, σ₂O, σ₂Al, σ₂Si, σ₂H, σ₂C, σ₂O, σ₂Al, σ₂Si les sections efficaces d’absorption et de diffusion de ces mêmes éléments, il vient:

\[ Σ_a = N_H σ_{₂H} + N_C σ_{₂C} + N_O σ_{₂O} + N_{Al} σ_{₂Al} + N_{Si} σ_{₂Si} \]

\[ Σ_l = N_H σ_{₂H} + N_C σ_{₂C} + N_O σ_{₂O} + N_{Al} σ_{₂Al} + N_{Si} σ_{₂Si} \]

\[ Σ = N_H σ_{₂H}(1 - 2/3) + N_C σ_{₂C}(1 - 2/6) + N_O σ_{₂O}(1 - 2/48) + N_{Al} σ_{₂Al}(1 - 2/81) + N_{Si} σ_{₂Si}(1 - 2/84) \]
De même, la perte logarithmique moyenne d'énergie à chaque choc peut se réduire à la composition du milieu par une équation du type [5]

\[ \xi_i = \sum \left( \xi_{i1} \sigma_{d1} N_{i1} \right) = \sum \left[ \left( 1 + \frac{(A_i - 1)^2}{2A_i} \right) \frac{\log A_i - 1}{A_i + 1} \sigma_{d1} N_{i1} \right] \]

\( \xi_i \) représente la perte logarithmique moyenne d'énergie au cours d'un choc contre un des noyaux de masse \( A_i \), de section efficace de diffusion \( \sigma_{d1} \) et présent en nombre \( N_{i1} \) par cm\(^3\).

\( \xi_u \) représente alors le nombre moyen de chocs qu'un neutron arrivant dans un groupe doit subir avant d'en sortir [3].

Dans la mesure où l'équation de diffusion traduit bien le phénomène physique, elle permet d'étudier le comportement des neutrons dans un groupe en fonction de la composition du milieu.

L'équation de diffusion précédente se met, puisque l'on est en géométrie sphérique, sous la forme

\[ \frac{d^2 \phi(r)}{dr^2} + \frac{2}{r} \frac{d \phi(r)}{dr} - \frac{3 \Sigma_{u}}{r} \left( \Sigma_a + \frac{\xi_u}{U} \right) \phi(r) = -3 \Sigma_{u} S(r) \]

\( r \) étant la distance à la source, l'équation s'intègre sous la forme

\[ \phi(r) = A \cdot \exp \left[ -\sqrt{\frac{3 \Sigma_{u}}{\Sigma_a + \frac{\xi_u}{U}} r} \right] + B \cdot S(r) = A \cdot \exp \left[ -\frac{3}{\lambda_u \lambda_a} \right] + B \cdot S(r) \]

\( A \) et \( B \) sont des grandeurs constantes à déterminer par les conditions aux limites.

Le terme \( \lambda_a = 1/(\Sigma_a + \xi_u/U) \) représente alors le libre parcours moyen d'absorption dans le milieu d'un neutron du groupe considéré, c'est-à-dire la longueur de son trajet avant son passage dans un groupe d'énergie inférieure [3-5].

Si \( v = \sqrt{2E/masse\ \text{neutre}} \), représente la vitesse d'un neutron dans un groupe d'énergie \( E \), \( t = \lambda_a/v \) représente son temps de séjour approximatif dans le même groupe [5]. Le tableau I résume les caractéristiques essentielles des divers groupes d'énergie dans quelques milieux.

Ces variations du temps de séjour et du libre parcours moyen d'absorption à l'intérieur de chaque groupe se manifestent sur les répartitions spatiales et énergétiques du nuage de neutrons entourant la source. Il est possible de déterminer théoriquement ces répartitions en calculant les flux neutroniques dans les groupes correspondant aux énergies les plus basses et particulièrement dans le groupe thermique qui contient la majorité des neutrons. Le système d'équation formé par l'ensemble des groupes se résout aisément par récurrence [3].

Le terme source du premier groupe est constitué par la source de neutrons rapides.

**Distribution spatiale du nuage de neutrons**

La méthode présentée ci-dessus aboutit, pour \( n \) groupes d'énergie, à une solution du type

\[ \phi(r) = \sum_{j=1}^{n} f_j(K_1, K_2, ..., K_n) \exp(-K_j r) \]

La méthode présentée ci-dessus aboutit, pour \( n \) groupes d'énergie, à une solution du type
Les termes $K_j$ sont fonction de la composition du milieu \cite{1,3}.

$$K_j = \sqrt{\frac{3}{\lambda_{jj}}}$$

Le flux devient une fonction, variable avec la distance source-détecteur $r$, de la composition du milieu. Cette répartition du flux en
fonction de la distance fournit une première série de paramètres mesurables pouvant être reliés à la nature du terrain. La figure 1 représente quelques distributions spatiales de flux thermique dans divers milieux hydrogénés.

**Distribution en énergie du nuage de neutrons**

Le temps de séjour des neutrons dans chaque groupe d'énergie dépend de la nature du milieu, et le nombre de neutrons présents dans chaque groupe lui est inversement proportionnel puisque la source de neutrons rapides est stable. La répartition du spectre d'énergie du nuage de neutrons constitue la deuxième série de paramètres fonction de la nature du terrain. Des études sur la répartition énergétique des neutrons en fonction de la composition du milieu diffuseur ont été publiées depuis longtemps [3]. La figure 2 représente les variations comparées du spectre énergétique dans différents milieux.

2. **EXPLOITATION DES INFORMATIONS NEUTRONIQUES**

La répartition spatiale et la répartition énergétique du flux neutronique sont pratiquement les deux seules grandeurs accessibles à l'expérimentation. Il faut étudier comment les mesurer expérimentalement et comment les utiliser pour la détermination de l'humidité volumique, de la densité sèche et l'identification du terrain.

2.1. **Méthode de mesure**

Une solution immédiate à ce problème consisterait à effectuer un nombre suffisant de mesures de flux à différents niveaux d'énergie et à différentes distances source-détecteur de façon à pouvoir établir un système d'équations du type

\[ N_i = \beta (r_i, E_i, N_{H}, N_{C}, N_{O}, N_{Al}, N_{Si}) \]
\( N_t \) étant le résultat d'une mesure de flux, à une certaine distance source-détecteur ou à un niveau d'énergie donné \( E_t \). Un système contenant autant d'équations qu'il y a d'inconnues \( N_{HI}, N_{CI}, N_{O}, N_{Al}, N_{Si} \ldots \) etc. permettrait de résoudre entièrement le problème, les conditions de mesures étant choisies pour que le système d'équation admette une solution.

Techniquement une telle solution est irréalisable.

D'une part, les mesures neutroniques sont soumises aux fluctuations statistiques. Les sources isotopiques utilisables sont assez faibles. Pour que les mesures soient possibles, chaque détecteur doit fournir un taux de comptage assez élevé. Les détecteurs doivent avoir un volume d'au moins plusieurs cm\(^3\) pour que leur rendement soit satisfaisant. Enfin, les inhomogénéités du sol viennent perturber les lois rigoureuses de variation du flux avec la distance. Aussi il n'est guère possible d'effectuer des mesures de répartitions de flux pour plus de deux ou trois distances source-détecteur différentes.

D'autre part, la détection des neutrons se fait par une réaction annexe de capture par des noyaux de bore-10, d'hélium-3 ou de cadmium, dont les sections efficaces sont surtout importantes aux faibles énergies. Les études de spectres d'énergie se trouvent par là même restreintes à des mesures de flux effectuées à deux ou trois niveaux d'énergie seulement.

Etant donné ces problèmes, il convient d'envisager une réduction du nombre d'inconnues à déterminer dans le système d'équations cité plus haut. Tous les éléments de sol agissent simultanément sur le flux neutronique et il peut être inutile de représenter l'action du sol sec sur le flux à partir de chacun des paramètres élémentaires \( N_{HI}, N_{CI}, N_{O}, N_{Si}, N_{Al} \). Il vaut mieux établir une classification des sols en fonction de leur comportement devant les neutrons. Des sols ayant par exemple la même courbe de réponse de taux de comptage en fonction de la densité sèche et de la teneur en eau seront regroupés sous un même numéro d'ordre. Des familles de sols seront établies et une des inconnues à déterminer pour effectuer la mesure d'humidité sera le numéro d'ordre du sol dans la classification. Cette inconnue sera appelée \( x \) avant toute évaluation numérique.

Les deux autres inconnues à déterminer seront appelées \( \rho_H \) et \( \rho_S \) et désigneront respectivement, la teneur en hydrogène (ou à un facteur constant près l'humidité du sol), et la densité sèche du sol.

Le problème se ramène à la détermination des trois inconnues. Trois mesures différentes donnant trois équations doivent être suffisantes pour le résoudre. En fonction de ce qui a été dit plus haut ces trois mesures pourront être:
- une mesure de neutrons thermiques effectuée près de la source et donnant une valeur du flux appelée \( N_t \);
- une mesure de neutrons épithermiques effectuée près de la source et donnant une valeur du flux appelée \( N'_t \);
- une mesure de neutrons thermiques effectuée à quelque distance, 10 ou 15 cm, de la source et donnant une valeur du flux appelée \( n \).

Des telles mesures sont compatibles avec la technologie de détection habituelle. Il suffit d'utiliser des compteurs de 2 cm de diamètre et de 2 ou 3 cm de longueur utile dont l'un est convenablement blindé d'indium et de cadmium pour ne détecter que les neutrons épithermiques.
L'interprétation de ces mesures paraît plus complexe puisqu'elle donnerait un système de trois équations à résoudre:

\[ N = f(\rho_H, \rho_S, x) \]
\[ N' = \varphi(\rho_H, \rho_S, x) \]
\[ n = \psi(\rho_H, \rho_S, x) \]

La résolution par abaque d'un tel système exige qu'au moins l'une des variables puisse être mise sous forme séparée des deux autres. Une étude effectuée au laboratoire a permis de vérifier que la forme des fonctions \( N, N', n \) autorise cette séparation.

2.2. Relation linéaire expérimentale obtenue sur des sels dissous

Il convient de travailler en milieu infini pour obtenir des relations applicables dans un sondage sur terrain. Cette condition entraîne la fabrication d'échantillons englobant au moins toute la sphère d'importance des neutrons thermiques. Dans un milieu contenant peu d'hydrogène cette sphère peut avoir jusqu'à 1 m de diamètre ; par contre, elle ne dépasse pas 30 cm dans l'eau.

Pour faciliter la fabrication des échantillons et en limiter le prix, il est possible, pour des essais préliminaires, de travailler sur des milieux fortement hydrogénés dont la composition rappelle celle d'un sol. Les relations trouvées entre flux et nature du milieu peuvent être ainsi extrapolées aux cas réels. C'est un moyen de limiter le nombre d'essais sur les échantillons de terrain de grandes dimensions. Les relations mises au point n'auront plus qu'à être adaptées.

La solution la plus simple consiste à dissoudre des nitrates de calcium, d'aluminium et de silicium dans l'eau. Ils sont peu coûteux et extrêmement solubles, jusqu'à 3 kg/l pour le nitrate de calcium.

Le dosage précis de ces solutions par gravimétrie et densimétrie ne pose pas de grands problèmes.

Les sels sont mis en solution concentrée dans une cuve de 40 cm de diamètre et 50 cm de hauteur qu'un bain thermostaté maintient à 25°C. La source de neutrons de 300 mCi d'Am-Be est placée au centre de la solution, enfermée dans un tube vertical d'acier inoxydable. Le détecteur, dont le milieu de la partie sensible est maintenu au niveau de la source, est placé verticalement dans un tube analogue ; un système de glissières permet de le déplacer latéralement par rapport au tube porte-source. Ce système permet de faire des mesures de flux pour des distances source-détecteur variant de 3 à 19 cm. Les distances sont prises entre les axes verticaux des tubes porte-source et porte-détecteur.

Une cartographie précise exige un détecteur de petites dimensions. Des raisons technologiques ont fait porter le choix sur un compteur au \( BF_3 \) de 3 cm de longueur utile et 1 cm de diamètre pour la détection des neutrons thermiques ; sur un compteur à hélium-3 de 10 cm de longueur utile et 2,5 cm de diamètre blindé par 3 mm de cadmium et 2 mm d'inium pour la détection des neutrons épithermiques.

Les cartographies de flux obtenues par ce procédé permettent de proposer comme relation entre les résultats de comptage en neutrons
FIG. 3. Droites représentatives des résultats obtenus dans les essais sur sels dissous.

FIG. 4. Essais sur sels dissous, variations de $\Delta A/A$ en fonction de la distance source-détecteur.
thermiques et la composition du milieu l'équation

\[ N = A \cdot \rho_H + B \cdot \rho_S \]

Les termes \( \rho_H \) et \( \rho_S \) désignent respectivement les teneurs en hydrogène et en sel, l'oxygène de l'eau étant inclus dans ces derniers. A et B sont deux constantes dépendant de la nature chimique du sel, de la distance source-détecteur et de la durée de comptage ou de l'intensité de la source.

Une relation analogue existe pour les neutrons épithermiques. On convient de la représenter par

\[ N' = A' \cdot \rho_H + B' \cdot \rho_S \]

Ces résultats, mis sous la forme \( N/\rho_S = (A \cdot \rho_H)/\rho_S + B \), sont représentés sur la figure 3.

Une méthode de moindres carrés appliquée aux résultats relatifs à un même sel permet de déterminer A, B, A', B' et leurs écarts type \( \Delta A, \Delta B, \Delta A', \Delta B' \) pour chaque distance source-détecteur. Les figures 4 et 5 montrent que \( \Delta A/A \) et \( \Delta A'/A' \) présentent des minimums très marqués pour certaines distances source-détecteur. Le minimum de 2\% rencontré sur le nitrure d'aluminium correspond à peu près aux erreurs introduites par les fluctuations statistiques pour des comptages
de l’ordre du demi-million d’impulsions et des erreurs de dosage de l’ordre de 0,1%.

Les valeurs A, B, A', B' obtenues ne sont pas proportionnelles. Dans le cas du nitrate de calcium \( A / B = -392, A' / B' = +146 \) pour des distances source-détecteur de 4 et 5 cm. Ces relations linéaires ne sont donc pas une simple approximation due à des incertitudes sur les mesures mais représentent une réalité physique et doivent se rencontrer dans n’importe quel milieu.

3. **ÉTUDE EXPERIMENTALE SUR DES ÉCHANTILLONS DE SOL ET RÉSULTATS**

3.1. **Description des essais sur des échantillons de sols**

Les essais préliminaires donnent des résultats intéressants. Il convient de les confirmer sur des sols réels. En raison des problèmes technologiques soulevés par la réalisation de 10 à 20 échantillons d’étalonnage, ce travail a été entrepris avec la collaboration du Service de radioagronomie du CEN de Cadarache. Celui-ci dispose du matériel de malaxage et de compactage permettant de fabriquer des échantillons homogènes de 400 à 500 kg de terre humidifiée dans des fûts de 80 cm de hauteur et 60 cm de diamètre. Un tube axial vertical de 4,1 cm de diamètre intérieur placé au milieu de chaque fût permet la mise en place de la sonde de mesure.

Pour des raisons technologiques ces essais ont été faits avec une sonde à scintillation. Le scintillateur est constitué par l’assemblage d’un cylindre de plexiglass entouré d’une mince couche d’un mélange de \( \text{SN} \) et de bore enrichi à 90% en \( ^{10} \text{B} \), avec un scintillateur mince au \( ^{10} \text{B} \) et \( \text{SN} \). Le détecteur a ainsi 25 mm de diamètre et 20 mm de hauteur. Il s’approche au maximum d’un détecteur ponctuel essentiel au déroulement de l’étude. Un système de support à crémaillère permet d’approcher ou d’éloigner verticalement le détecteur de la source fixée au centre de l’échantillon.

Au moment de la confection de chaque fût de terre, des prélèvements du mélange eau-sol sont desséchés à l’étuve à 105°C pendant 24 h. La différence de poids après la dessication permet de calculer l’humidité volumique du mélange.

Trois terrains différents ont été étudiés :
- Un limon calcaire contenant en poids sec, l’eau de constitution étant éliminée, 40,5% de silice, 44% de carbonate de calcium, 1,4% de \( \text{K}_2 \text{O} \), 6,9% d’\( \text{Al}_2 \text{O}_3 \), 2,7% de \( \text{Fe}_2 \text{O}_3 \), 2,1% de \( \text{MgO} \), 2,2% de \( \text{CaO} \). Huit échantillons de ce terrain ont été préparés pour vérifier si les relations linéaires précédemment mises en évidence se retrouvait bien.
- Une argile grise contenant en poids sec, l’eau de constitution étant éliminée, 44% de silice, 25,5% de carbonate de calcium, 4,5% de \( \text{Fe}_2 \text{O}_3 \), 12,3% d’\( \text{Al}_2 \text{O}_3 \), 2,5% de \( \text{K}_2 \text{O} \), 2,2% de \( \text{CaO} \), 5% de \( \text{MgO} \). Quatre échantillons ont été préparés.
- Un sable considéré comme formé de silice pure, sans eau de constitution. Deux essais seulement ont été réalisés dans ce milieu.

Le nombre d’essais dans les deux derniers milieux a été limité parce qu’ils n’avaient pour but que d’apprécier le contraste apparaissant sur les mesures dans des sols de natures différentes.
3.2. Résultats et mode de représentation

La mise sous forme linéaire des résultats expérimentaux s'effectue sans difficulté. Les coefficients A, B, A', B' des relations obtenues pour le limon calcaire présentent des dispersions faibles $\Delta A/A < 3\%$ (voir fig. 6). Cette dispersion peut être expliquée par les fluctuations statistiques, les dérives ou les erreurs de mesures de densité et d'humidité. Pour les autres sols, les mesures sont trop peu nombreuses pour que la dispersion des résultats ait un sens.

Les mesures de flux sont bien toutes trois différentes: pour le limon calcaire $A/A' = 25.3, B/B' = 2.65, A/a = 3.46, B/b = 0.7$ avec des distances source-détecteur de 2, 4 cm et 14 cm pour les neutrons thermiques et de 3, 2 cm pour les neutrons épithermiques. $a$ et $b$ sont des coefficients analogues à $A$ et $B$, mais relatifs à la troisième relation obtenue avec les neutrons thermiques à 10 ou 15 cm de la source.

D'autre part la représentation des courbes $N = f(n)$ et $N = \gamma(N')$ obtenues avec les trois milieux différents montre bien la variation de ces fonctions avec la nature du terrain (voir fig. 7). Il faut constater l'influence de la densité sèche du sol qui explique la dispersion des points d'un même milieu autour de la courbe représentative.

A partir de ces résultats linéaires il est possible de traiter le problème d'un sol inconnu. Les trois relations obtenues se mettent
FIG. 7. Influence de la composition du sol sur les relations $N = f(a)$, $N = \psi(N)$.

FIG. 8. Abaque graphique donnant $X$ et $F(X)$. 
FIG. 3. Variations des coefficients $a(x)$, $b(x)$, $a'(x)$, $b'(x)$ en fonction de la nature du terrain.

sous la forme:

$$N = A(x) \cdot \rho_H + B(x) \cdot \rho_S$$

$$N' = A'(x) \cdot \rho_H + B'(x) \cdot \rho_S$$

$$n = a(x) \cdot \rho_H + b(x) \cdot \rho_S$$

Le système se ramène à l'équation unique ne dépendant pas de $\rho_H$ et $\rho_S$

$$N = \frac{aB - Ab}{aB' - A'b} \cdot N' + \frac{AB' - BA'}{aB' - A'b} \cdot n$$

$$N = \psi(x) \cdot N' + \phi(x) \cdot n$$

En posant $\phi(x) = X$ et $\psi(x) = F(X)$ il vient

$$F(X) = -\frac{n}{N'} \cdot X + \frac{N}{N'}$$

Si un étalement préalable fait sur plusieurs terrains a permis de construire la courbe $Y = F(X)$ (fig. 8) la résolution de l'équation se
ramène à la construction de la droite

\[ Y = -\frac{n}{N} X + \frac{N}{N'} \]

La valeur de \( X \) ainsi déterminée permet d’obtenir \( x \) (voir fig. 9). La détermination de \( x \) permet, soit d’obtenir \( A, B, A', B' \), soit plus directement (fig. 9) \( \rho_H \) et \( \rho_S \) par des relations du type suivant:

\[ \rho_H = a(x) \cdot N + \beta(x) \cdot N' \]

\[ \rho_S = a'(x) \cdot N + \beta'(x) \cdot N' \]

3.3. Etalonnage et précision

Il faut construire les courbes \( \gamma(x), \psi(x), F(x), a(x), \beta(x), a'(x), \beta'(x) \).
A partir de plusieurs essais effectués pour des humidités et des densités différentes d’un même sol, on obtient la détermination d’un point de chacune de ces courbes. Les mêmes essais repris dans plusieurs milieux permettent la construction complète de ces courbes.

Bien que trois terrains différents seulement aient été traités lors de nos essais, les figures 8 et 9 donnent les formes des fonctions \( a(x), \beta(x), a'(x), \beta'(x), \gamma(x), F(X) \). En supposant que les deux premières mesures donnant \( N \) et \( n \) aient eu lieu pour des distances source-détecteur de neutrons thermiques de 3,4 cm et 9,4 cm et que la mesure de neutrons épithermiques ait eu lieu à la distance 3,4 cm, il vient dans le cas d’un limon calcaire de densité sèche \( \rho_S = 1336 \text{ g/dm}^3 \) et de teneur en hydrogène \( \rho_H = 38,4 \text{ g/dm}^3 \):

\[ N/N' = 8,47, n/N' = 6,34. \]

Les figures 8 et 9 donnent \( X = 2,02, x = 1,9, a = 0,075, \beta = -0,20, \]
\( a' = -1,35, \beta' = 32,8. \) Il vient alors:

\[ \rho_H = 0,075 \times 733 \times 337 - 0,2 \times 86 \times 500 = 37,7 \text{ g/dm}^3 \]

\[ \rho_S = -1,35 \times 733 \times 337 + 32,8 \times 86 \times 500 = 1845 \text{ g/dm}^3 \]

Les écarts entre grandeurs réelles et mesurées sont:

\[ \Delta \rho_H = 0,4 \text{ g/dm}^3 \quad \Delta \rho_S = 9 \text{ g/dm}^3 \]

Dans le cas d’un limon calcaire de densité sèche \( \rho_S = 1874 \text{ g/dm}^3 \) et de teneur en hydrogène \( \rho_H = 55,9 \text{ g/dm}^3 \) il vient \( N/N' = 10,34, n/N' = 7,30 \) et

\[ \rho_H = 55,5 \text{ g/dm}^3, \rho_S = 1847 \text{ g/dm}^3. \]

La précision moyenne tirée de ces deux exemples paraît devoir s’établir autour du point d’humidité volumique et de 1% sur la densité sèche.

3.4. Essais de représentation théorique

L’expérimentation étant complexe et chère, il paraît intéressant de la compléter par des calculs de flux de neutrons. Ceux-ci doivent permettre, d’abord de retrouver les résultats expérimentaux, ensuite d’intrapoler à des densités et teneurs en eau intermédiaires, puis d’extrapoler à d’autres compositions chimiques.
La méthode de calcul présentée par Oigaard [1] a été essayée. Diverses modifications ont été apportées pour que les calculs soient valables dans des milieux calcaires, telle l’adjonction des sections efficaces de diffusion du carbone et du calcium dans les deux premiers groupes. La longueur du compteur et sa position ont été adaptées pour être compatibles avec notre détecteur. Mais les résultats théoriques obtenus n’ont pas correspondu à nos résultats expérimentaux. En particulier, nous n’avons pu les mettre sous forme de relations linéaires. Un essai destiné à calculer le flux épithermique n’a pas abouti non plus. Ne sachant dans quelle mesure ce désaccord constaté provient d’une mauvaise interprétation de la méthode de calcul proposée par Oigaard, nous n’avons pas poursuivi nos essais.

4. UTILISATION PRATIQUE DE LA MÉTHODE

L’application du principe de mesure que nous proposons conduirait à un appareil formé d’une source d’Am-Be pouvant se déplacer entre deux compteurs de petites dimensions. L’un des compteurs est destiné aux mesures de neutrons thermiques, l’autre, recouvert d’un blindage de 3 mm de cadmium + 2 mm d’indium, est destiné aux mesures de neutrons épithermiques. Le déplacement de la source est réalisé à l’aide d’un micromoteur électrique; l’ensemble est représenté sur la figure 10. Dans la position 2 la source est près du détecteur de neutrons épithermiques et loin du détecteur de neutrons thermiques. Les mesures \( N' \) et \( n \) sont effectuées. La source vient s’appliquer contre le détecteur de neutrons thermiques et la mesure \( N \) est effectuée à son tour. Il est possible de n’utiliser qu’une seule échelle de comptage, les mesures \( N' \) et \( n \) ayant lieu l’une après l’autre.

Les essais qui ont été effectués avec une source de 300 mCi d’Am-Be et de petits compteurs proportionnels remplis d’hélium-3 sous 15 atm ont donné les taux de comptage dans l’eau suivants:

\[
N = 2000 \text{ coups/s}, \quad N' = 150 \text{ coups/s}, \quad n = 1000 \text{ coups/s}.
\]

Une précision statistique convenable exigerait des temps de comptage de l’ordre de 10 min pour \( n \) et \( N \) et de plus du double pour \( N' \) avec une source de 100 mCi d’Am-Be dans un sol contenant 10% d’eau.

La durée d’une mesure en sol inconnu sera de l’ordre de la demi-heure. Aussi il y aurait avantage, pour des mesures de bilans hygiéiques, à n’effectuer les mesures complètes qu’une seule fois en chaque point pour déterminer \( x \) et \( \rho_2 \). Ces paramètres étant établis, une seule mesure \( N \) permettrait d’obtenir, soit en passant par le système d’abaque complet, soit en passant par des courbes classiques, \( H_v = K(N/A - B\rho_2) \).
CONCLUSION

La méthode présentée ci-dessus pourrait être, malgré un prix vraisemblablement élevé de l'appareil et sa complexité technologique, un apport intéressant. Mais elle demande encore un complément d'étude. Il convient de vérifier, sur un nombre élevé de points expérimentaux, le bien-fondé de son principe, ses possibilités, et tout particulièrement la précision qu'elle autorise. Il reste en particulier à déterminer l'origine du désaccord constaté entre les résultats expérimentaux et théoriques.

REFERENCES


DISCUSSION

M. DE BOODT: Use of 3-mm cadmium shielding lowers the numbers of counts from 2000 to 150. Would it affect your method if you used 0.06-mm cadmium shielding so as to obtain a much larger count?

E. P. COROMPT: If thin cadmium shielding is used, the count-rate increases, thus reducing statistical fluctuations, but the energy zones in which one is working then fall very close together, so that measurements of thermal and epithermal neutrons become very similar and the contrast disappears. This could result, in particular, in confusion between the curve F(X) and the straight line -(n/N)X + N/N' in Fig. 8, whose slopes are already very similar.
DETERMINATION DE LA COURBE D’ETALONNAGE DE L’HUMIDIMETRE A NEUTRONS A PARTIR DE L’ANALYSE CHIMIQUE DES SOLS

P. COUCHAT
CEA, CENTRE D’ETUDES NUCLEAIRES DE CADARACHE,
FRANCE

Abstract — Résumé

DETERMINATION OF THE CALIBRATION CURVE FOR THE NEUTRON-MOISTURE METER BY CHEMICAL ANALYSIS OF SOILS. The main difficulty at present in using the neutron moisture meter in agronomy lies in the establishment of a calibration curve. The normal gravimetric method, whether carried out in the laboratory or in the field, involves a long and costly operation; moreover, it provides little information on the cause of the variations observed in terms of either the dry density or the type of soil. Theoretical investigations conducted in parallel with experiments seem to offer a good approach to determining the influence of the measuring parameters on the response of the moisture meter.

The author used the three-group theory of neutron diffusion to construct a mathematical model representing the moisture meter and the medium studied (defined by its over-all chemical composition). This model is applied using a Fortran IV computer programme, by which it can be adapted in the light of experimental studies on the influence of geometry and the nature of the measuring system. Allowance has already been made for thermal flux depression and spread due to the presence of tubing, the emission spectrum of the source, and the yield and the energy level of detection of the counters. Particular reference must be made to the importance of epithermal neutrons (energy above 0.4 eV).

To compare the theoretical and experimental data, the author defines a method of representation by which it is possible to assess the ability of the model to account for the results obtained with seven different media (siliceous sand, alumina, limestone, dolomite, kaolinite, chalky clay and silt) defined by their over-all chemical composition. In the range of utilization in agronomy, the response of the moisture meter coincides with the calculated figures to roughly ± 5%. Study of the effect of dry density suggests a general equation for the calibration curves of the form \( N = \beta_1 + \beta_2 \rho + \beta_3 N_s, \) where \( N_s \) = moisture content per volume, \( \rho_d \) = dry density, and \( \beta_1, \beta_2, \beta_3 \) are constants obtained from calculations based on chemical analysis of the soils.

DETERMINATION DE LA COURBE D’ETALONNAGE DE L’HUMIDIMETRE A NEUTRONS A PARTIR DE L’ANALYSE CHIMIQUE DES SOLS. A l’heure actuelle, le problème majeur posé par l’utilisation de l’humidimètre à neutrons en agronomie est l’établissement de la courbe d’étalonnage. La méthode classique par gravimétrie, conduite en laboratoire ou au champ, reste une opération longue et coûteuse; au surplus, elle apporte peu d’informations sur la cause des variations observées, tant en fonction de la densité sèche que de la nature du sol. Une recherche théorique menée de pair avec l’expérience semble être le mode d’approche adapté pour déterminer l’influence des paramètres de mesure sur la réponse de l’humidimètre.

Un modèle mathématique de représentation de l’humidimètre et du milieu étudié (défini par sa composition chimique totale) a été constitué à partir de la théorie à trois groupes de diffusion des neutrons; un programme de calcul utilisant le code Fortran IV exploite ce modèle et permet son adaptation d’après les résultats d’études expérimentales portant sur l’influence de la géométrie et de la nature du système de mesure. C’est ainsi qu’ont été pris en compte la dépression et l’étalonnage du flux thermique, la présence de tube, le spectre d’émission de la source, le rendement et le niveau d’énergie de détection des compteurs; il faut noter en particulier l’importance des neutrons épithermaux (énergie supérieure à 0.4 eV).

En vue de comparer les données théoriques et expérimentales, un mode de représentation a été défini, qui permet d’apprécier l’aptitude du modèle à rendre compte des résultats obtenus sur sept milieux différents (sable siliceux, argile, calcaire, dolomie, kaolinite, argile caillouteuse, limon) définis par leur composition chimique totale. Dans la zone d’utilisation agronomique, la réponse de l’humidimètre
collece avec les previsions du calcul a ± 5% environ. L'etude de l'influence de la densite seche amene a proposer pour equation generale des courbes d'etalonnage une fonction de la forme \( N = f(H_v, \rho_s, \alpha, \beta, \gamma, \delta) \), avec \( H_v \) humidite volumique, \( \rho_s \) densite seche, \( \alpha, \beta, \gamma, \delta \) et \( \delta \) etant des constantes fournies par le calcul a partir de l'analyse chimique des sols.

1. INTRODUCTION

L'agronome et l'hydrogeologue qui veulent etablir le bilan hydrique d'un sol, tant pour la conduite d'une irrigation que pour l'etude des reserves en eau disponibles, doivent pouvoir mesurer avec precision l'humidite volumique du milieu. Habituellement, cette valeur est obtenue a partir de mesures fournissant la densite apparente seche et l'humidite pondereale, ce qui necessite une instrumentation lourde et souvent imprécise (tailiere, etuve, densitometres ...).

La determination directe de l'humidite volumique est devenue possible avec l'humidimetre a neutrons, qui utilise le principe du ralentissement et de la diffusion des neutrons dans les moderateurs hydrogenes. Introduit dans un sol humide, l'appareil permet une mesure representative de la densite en atomes des elements rencontrés, en particulier de l'hydrogene present sous forme d'eau. La courbe d'etalonnage de l'appareil fournit en pratique la relation entre la vitesse de comptage et la teneur en eau volumique exprimee en pourcent; ses parametres sont la nature chimique et la densite du sol.

Le present travail repond a un double objectif: determiner le comptage theorique obtenu avec l'humidimetre pour un sol defini par sa composition chimique, connaissant l'humidite et la densite; etablir l'influence du parametre densite seche sur la courbe d'etalonnage.

2. CALCUL DU RALENTEISSEMENT ET DE LA DIFFUSION DES NEUTRONS

a) La theorie a trois groupes.

A l'heure actuelle, plusieurs modes theoriques sont utilises pour determiner la courbe d'etalonnage de l'humidimetre. En 1955, Holmes [1], appliquant la theorie de l'age, proposait une equation liant la vitesse de comptage de l'humidimetre a la teneur en eau volumique. Cette equation est a l'origine de plusieurs developpements qui ont pour auteurs Semmler [2], Ijima et al. [3] et, plus recemment, en 1965, Majerczyk et Zuber [4]. Bien que la simplicité de son emploi la rende interessante, la theorie de l'age ne permet pas de prendre en compte tous les parametres de la mesure d'humidite.


1 Nous proposons les notations suivantes: \( \rho_s \) densite apparente seche; \( \rho_1 \), poids specifique du sol; \( H_{P_s} \), humidite pondereale seche; \( H_v = \rho_s \cdot H_{P_s} \), humidite volumique.
Le sol humide étant défini par la composition pondérale de ses éléments (onze éléments sont actuellement pris en compte), le flux thermique $\phi_{th}(r)$ autour d'une source ponctuelle est donné par l'équation (1) où les trois groupes, indiqués 1, 2 et 3, figurent de façon homogène. Les groupes 1 et 2 sont les groupes rapides, le groupe 3 est le groupe thermique.

$$\phi_{th}(r) = \frac{Q}{4\pi D_3 r} \left[ \frac{L_1^2 \exp(-r/L_1)}{(L_1^2 - L_2^2)(L_2^2 - L_3^2) + (L_2^2 - L_3^2)(L_3^2 - L_0^2)} \right]$$

Dans cette formule la variable est la distance $r$ à la source; $Q_0$ est le taux d'émission de neutrons rapides; $L_1$, $L_2$, $L_3$ et $D_3$ sont des constantes calculées à partir de la composition chimique élémentaire du sol humide.

Les groupes rapides comprennent les neutrons dont l'énergie se situe entre l'énergie moyenne d'émission de la source (4,5 MeV dans le cas du radium-béryllium) et l'énergie thermique. On calcule les longueurs de ralentissement $L_1$ et $L_2$ en divisant les groupes en sous-groupes d'énergie pour lesquels les sections efficaces sont fournies par le tableau des constantes de Bondarenko [7]. Une correction de premier et dernier choc est effectuée suivant les formules données par Wigner [8]. On trouve pour l'eau pure une valeur de l'énergie égale à 50,8 cm², valeur voisine de celle fournie par l'expérience [9].

À l'intérieur du groupe thermique on définit, en adoptant la description de Cohen [10], un spectre de distribution des vitesses qui tient compte de la présence des absorbants. Cela revient à calculer une température $T_0$, différente de la température du modérateur.

b) Représentation de l'humidimètre et du sol

L'appareil, fabriqué par la compagnie française CGEI, est équipé d'une source d'américium-béryllium de 50 mCi placée au milieu d'un compteur à BF₃ de 12 cm. Pour les calculs, l'humidimètre est assimilé à un ensemble source ponctuelle-détecteur linéaire de neutrons thermiques. La vitesse de compte à fournir par un tel ensemble introduit dans un sol humide est proportionnelle au flux thermique moyen le long du détecteur, un coefficient de proportionnalité rendant compte du rendement.

Le sol est défini par sa composition chimique totale en pourcentage des constituants (SiO₂, Al₂O₃, Fe₂O₃, CO₂Ca, ...). A partir de ce critère on calcule les courbes d'étalonnage du sol; paramétrées en densité sèche, elles expriment la relation qui existe entre la vitesse de compte et l'humidité volumique. Le facteur granulométrique a été volontairement négligé. Dans le tableau 1 sont rassemblés les résultats exprimés en pourcent des analyses chimiques des milieux étudiés.

c) Exploitation des équations du modèle mathématique

Un programme de calcul numérique, écrit en code Fortran IV [11] et exploité sur machine IBM 360, résout les équations du modèle; deux types de résultats sont obtenus pour un sol humide déterminé: la valeur du flux thermique en fonction de la distance $r$ à la source,
TABLEAU I. ANALYSES CHIMIQUES DES SOLS UTILISES (%)

<table>
<thead>
<tr>
<th>Composants a</th>
<th>Alumine</th>
<th>Calcaire</th>
<th>Dolomie</th>
<th>Kao lin</th>
<th>Limon b</th>
<th>Argile calcaire</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O c</td>
<td>0,25</td>
<td>0,62</td>
<td>0</td>
<td>0</td>
<td>1,13</td>
<td>0,29</td>
</tr>
<tr>
<td>SiO₂</td>
<td>0,20</td>
<td>3,03</td>
<td>0,89</td>
<td>44,18</td>
<td>49,43</td>
<td>42,23</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>98,02</td>
<td>1,21</td>
<td>0,25</td>
<td>33,09</td>
<td>7,48</td>
<td>12,81</td>
</tr>
<tr>
<td>CO₂</td>
<td>0,10</td>
<td>41,83</td>
<td>45,97</td>
<td>0,51</td>
<td>16,06</td>
<td>17,51</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>0,05</td>
<td>0,17</td>
<td>0,03</td>
<td>17,80</td>
<td>3,38</td>
<td>4,07</td>
</tr>
<tr>
<td>CaO</td>
<td>0,13</td>
<td>52,90</td>
<td>33,53</td>
<td>0,34</td>
<td>18,44</td>
<td>17,46</td>
</tr>
<tr>
<td>MgO</td>
<td>0</td>
<td>0,30</td>
<td>17,58</td>
<td>0,21</td>
<td>1,45</td>
<td>2,23</td>
</tr>
<tr>
<td>K₂O</td>
<td>0,02</td>
<td>0,08</td>
<td>0,09</td>
<td>0,12</td>
<td>0,90</td>
<td>1,76</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0,32</td>
<td>0,04</td>
<td>0,09</td>
<td>0,02</td>
<td>0,67</td>
<td>0,49</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0,21</td>
<td>0,02</td>
<td>0</td>
<td>3,42</td>
<td>0,61</td>
<td>0,79</td>
</tr>
</tbody>
</table>

a Teneur en pourcentage.
b Terre de Cadarache.
c Eau de constitution (sous forme symbolique H₂O).

- La vitesse de comptage fournie par l'ensemble source-détecteur en fonction de l'humidité volumique.
Par une option de calcul on détermine les variations de la courbe de répartition du flux thermique et de la vitesse de comptage lorsqu'un des constituants du sol varie, toutes choses étant égales par ailleurs. L'utilisation d'un grand nombre de données permet d'étudier la plupart des paramètres du système de mesure et du milieu.
A l'aide de ce programme, on a pu donner la courbe d'étalonnage théorique du sol de Cadarache (limon sableux) pour une densité sèche de 1,5 g/cm³. On constate (fig. 1) qu'une divergence existe entre les résultats expérimentaux obtenus avec l'humidimètre CGEI et la courbe théorique.

3. ADAPTATION DU MODELE MATHEMATIQUE

Afin d'expliquer puis de corriger les divergences entre la théorie et l'expérience, on a précisée l'influence des paramètres de mesure importants (système de mesure et sol) en comparant les observations expérimentales et les données du calcul théorique.
a) Paramètres du système de mesure

Tubage: On observe que le tubage servant à introduire la sonde dans le sol crée un vide qui engendre une dépression et un étalement du flux de neutrons thermiques autour de la source (fig. 2). L’analyse des expérimentations de Tittle [12] dans le cas des sondages pétroliers montre que, pour calculer la dépression du flux thermique, il est possible d’assimiler le milieu hétérogène à un milieu homogène à condition d’augmenter d’une quantité constante les longueurs de diffusion.

D’autre part, pour représenter l’étalement du flux, on propose de remplacer la variable r de l’équation (1) par la variable r' telle que

\[ r' = ar + \beta. \]

L’équation (1) est alors modifiée en remplaçant \( L_1 \), \( L_2 \) et \( L_3 \) par \( L'_1 \), \( L'_2 \) et \( L'_3 \) tels que

\[ L'^2 = L^2 + a^2. \]

Les figures 2 et 3 montrent dans le cas de l’eau pure et de l’hydrargillite la transformation introduite dans la courbe de répartition du flux lorsque \( a = 2,6, \alpha = 0,8 \) et \( \beta = -1 \).

Spectre énergétique des neutrons. Le spectre des neutrons émis par la source est un autre paramètre important à considérer car il intervient directement sur le calcul des longueurs de ralentissement.
FIG. 2. Répartition du flux thermique dans l'eau pure.
Diamètre extérieur du tuyage: 45 mm.

FIG. 3. Répartition du flux thermique dans l'hydrazilitite
sèche (AlF₃, 3H₂O) d'équivalent eau 54%.
TABLEAU II. HYPOTHESES CONCERNANT LE SPECTRE ENERGETIQUE D’EMISSION DES NEUTRONS POUR LES SOURCES D’AMERICIUM-BERYLLIUM ET DE RADIIUM-BERYLLIUM

<table>
<thead>
<tr>
<th>Source</th>
<th>1ère hypothèse</th>
<th>2ème hypothèse</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Energie</td>
<td>Pourcentage</td>
</tr>
<tr>
<td></td>
<td>de neutrons</td>
<td></td>
</tr>
<tr>
<td>Ra-Be</td>
<td>4,5 MeV</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Am-Be</td>
<td>5,5 MeV</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Dans ce but on a comparé les sources Ra-Be et Am-Be; deux hypothèses concernant leur spectre d’émission (fig. 4) sont retenues dans le tableau II.

Les comptages obtenus pour les deux sources avec l’humidimètre dans différents milieux humides montrent (fig. 5) que l’on passe de l’une à l’autre source par le simple rapport des mesures dans l’eau pure; le spectre à deux raies approche mieux la réalité expérimentale. La source Ra-Be, la moins énergique, fournit la répartition de flux.
moins étalée (fig.6); elle est plus efficace que la source d’Am-Be pour l’humidimètre à neutrons, à même taux d’émission. On voit l’intérêt d’une source dont le spectre énergétique s’étend le plus bas possible, tant pour le rendement que pour la focalisation. Dans la recherche des courbes d’étalonnage théoriques, on assimilera le spectre d’émission à une raie moyenne à condition de se référer aux mesures obtenues dans l’eau pure.

Compteur. Dans le cas de l’humidimètre CGEI, on assimile le compteur à une droite parallèle à l’axe du tubage et située à 2 cm de la source. Le comptage est une fonction du flux moyen de neutrons thermiques traversant le compteur pendant l’unité de temps.

\[ N = \frac{1}{u^i - u} \int_{u}^{u^i} \eta \cdot \varphi(r) \, dr \]

u et u’ sont les distances de la source à l’extrémité et au centre du compteur. Le rendement \( \eta \) dépend du comportement électronique \( \eta_e \) du détecteur et du rendement \( \eta_r \) de la réaction nucléaire d’absorption des neutrons par le bore ou l’hélium. La valeur de \( \eta_r \) varie le long du compteur comme l’indique la figure 7. Une étude menée à l’aide du programme de calcul a montré que les comptages obtenus avec rendement réel et avec rendement fictif constant étaient liés par le rapport des valeurs « eau ». Dans la suite des calculs, \( \eta_r \) est considéré...
comme indépendant de $r$. Le rendement $\eta$ de la réaction nucléaire suit la loi de variation de la section efficace d'absorption du gaz BF$_3$ ou $^3$He. Par suite, les neutrons détectés sont thermiques mais aussi épithermiques. On constate d'ailleurs expérimentalement que le rapport de la mesure des neutrons épithermiques (énergie égale ou supérieure à 0.4 eV) à celle des neutrons thermiques varie avec le taux d'humidité et, pour un sol donné, semble indépendant de la densité sèche (fig. 8). Le paragraphe suivant montre l'intervention du niveau énergétique de détection des neutrons dans les mesures.

b) Paramètres du milieu étudié

Présence d'éléments absorbeurs de neutrons. Les éléments comme le fer, le potassium, le titane et le chlore se caractérisent par une valeur importante de leur section efficace macroscopique d'absorption au niveau d'énergie thermique. On a étudié expérimentalement et théoriquement à l'aide du programme de calcul l'effet sur la vitesse de comptage d'une adjonction de chlore (sous forme de ClNa) à de l'eau pure ainsi qu'à un limon sableux humide. Dans les deux cas le modèle théorique
FIG. 7. Étude du rendement électronique du compteur BE2 (12 cm) soumis à un flux thermique constant focalisé.

FIG. 8. Rapport des comptages épicadmiques (0, 4 eV) sur thermiques dans le cas d'un limon sabloïque d'humidité volumique variable.
prévoit des baisses de comptage plus importantes que celles fournies par l'expérience. En effet, le programme calcule le flux de neutrons thermiques et, par suite, donne une fausse idée du flux des neutrons détectés dans le cas de sols absorbants. Admettant [13] que le flux des neutrons épithermiques n'est pas perturbé par la présence du chlore, on corrige les valeurs théoriques en tenant compte du rapport (comptages épithermiques/comptages thermiques) (fig. 9 et 10).

![Diagram](image)

**FIG. 9.** Evolution des comptages obtenus dans l'eau salée rapportés aux comptages obtenus dans l'eau pure.

Eau de constitution. La présence d'eau de constitution dans la matière sèche des sols pose le problème de la liaison chimique des éléments entre eux. On sait qu'elle influe sur la valeur de la section efficace de diffusion des éléments au niveau thermique, spécialement dans le cas de l'hydrogène. L'eau liée sous forme d'ion oxhydrile pourrait avoir un effet différent de l'eau libre sur la diffusion des neutrons thermiques. En appliquant la prescription de Radkowsky [14] on a déterminé à l'aide du programme la variation de la courbe d'étalonnage du kaolin consécutive à une variation de la section efficace de diffusion de l'hydrogène présent sous forme OH⁻ (fig. 11). Une étude

---

2 Un programme en cours d'exploitation doit fournir le flux épithermique et permettre d'appliquer les corrections nécessaires au cas des sols fortement absorbants de neutrons.

4. RESULTATS OBTENUS

Validité du modèle. La détermination in situ des courbes d'étalonnage de l'humidimètre revient à comparer en un point d'un sol humide la vitesse de comptage et l'humidité volumique du sol obtenue par la méthode gravimétrique. Le même processus est employé au laboratoire. On a opéré sur sept sols ou milieux divers définis par leur composition chimique totale (tableau 1). Les résultats théoriques et expérimentaux sont portés sur la figure 12. Ce mode de représentation permet d'inclure les paramètres composition chimique et densité sèche et de faire ressortir la corrélation qui existe entre la théorie et l'expérience. Une campagne de mesure est en cours à l'heure actuelle sur plusieurs sols français.
FIG. 11. Variation de la courbe théorique d'étalonnage du kaolin lorsque la section efficace de diffusion de l'hydrogène ($\alpha_{H}$) varie de 30 à 50 b.

en vue de juger sur un large échantillonnage de sols l'aptitude du modèle à rendre compte de la réponse expérimentale de l'humidimètre.

Influence de la densité sèche. La composition chimique définit donc pour un sol un faisceau de courbes d'étalonnage théoriques ayant pour paramètre la densité sèche. Le comptage $N$ est donné par la fonction $N = f(\rho_s, H_v)$. Le calcul théorique montre que la dérivée partielle de $N$ par rapport à $\rho_s$ est indépendante de $\rho_s$ et réciproquement. On peut alors explicitier la fonction $N$ de la manière suivante:

$$N = (\alpha \rho_s + \beta) H_v + \gamma \rho_s + \delta$$

$\alpha, \beta, \gamma$ et $\delta$ sont des constantes définies par la composition chimique du milieu. Un lissage des points théoriques des courbes d'étalonnage a été effectué pour les ajuster à la fonction $N$ et $\alpha, \beta, \gamma, \delta$ ont été déterminés pour chaque type de sol (tableau III). La valeur $\alpha$ est généralement faible devant $\beta$, ce qui se traduit par un déplacement parallèlement à elle-même de la courbe d'étalonnage lorsque $\rho_s$ varie peu. En pratique, pour le sol de Cadarache, si $\rho_s$ varie de 12,5% (soit de 1,4 à 1,6 g/cm$^3$), la pente varie de 1,8%.
Par contre, une même variation de \( \rho \) entraîne une variation de comptage qui se traduit par une erreur de deux points pour une humidité volumique de 30%.

5. CONCLUSION

Une approche théorique et expérimentale a été proposée pour expliquer et prévoir le comportement de l'humidimètre à neutrons dans un sol humide. On est parti d'un programme de calcul numérique exploitant les formules qui décrivent le ralentissement et la diffusion des neutrons en vue de généraliser les données de l'expérience et déterminer l'influence des paramètres de la mesure. Les résultats obtenus ont permis d'adapter le modèle mathématique simulant la mesure neutronique de l'humidité. Au stade actuel celui-ci prévient la réponse expérimentale pour sept milieux différents (sols et constituants).

On détermine la courbe d'étalonnage de l'humidimètre relative à une parcelle d'expérimentation donnée (irrigation du maïs par exemple) en effectuant l'analyse chimique d'un ou plusieurs échantillons représentatifs de la zone étudiée. Le faisceau des courbes d'étalonnage (paramétrées en densité sèche) est calculé à partir de la
<table>
<thead>
<tr>
<th>Corps</th>
<th>α</th>
<th>β</th>
<th>γ</th>
<th>δ</th>
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<tbody>
<tr>
<td>Alumine</td>
<td>0,54</td>
<td>4,77</td>
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<td>53,20</td>
<td>-69,03</td>
</tr>
<tr>
<td>Sable</td>
<td>0,77</td>
<td>4,70</td>
<td>39,99</td>
<td>-64,47</td>
</tr>
<tr>
<td>Kaolin</td>
<td>0,45</td>
<td>4,74</td>
<td>105,01</td>
<td>-58,667</td>
</tr>
<tr>
<td>Argile</td>
<td>0,43</td>
<td>4,82</td>
<td>35,23</td>
<td>-61,67</td>
</tr>
<tr>
<td>calcaire</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limon</td>
<td>0,43</td>
<td>4,74</td>
<td>42,52</td>
<td>-65,27</td>
</tr>
</tbody>
</table>

N.B. Les valeurs des constantes sont données dans le cas d'une humidité exprimée en pourcentage et pour un humidimètre équipé d'une source Ra-228 de taux d'émission \(7,5 \cdot 10^5 \) μCi.

La connaissance approchée de la densité sèche à 10% près est suffisante pour définir la pente et par suite donner accès à l'étude des consommations de la culture, des réserves hydriques du mouvement de l'eau. Si l'on recherche la valeur absolue de l'humidité volumique, il sera par contre nécessaire d'associer à la mesure neutronique une mesure de densité sèche (densimètre à photons par exemple).

REFERENCES

O. TEODORU: Were there large differences in the grain size of your samples and would your method be suitable for studying saline and alkaline soils, which have quite different physical and chemical properties?

P. COUCHAT: The grain size was fairly even (<2 mm). If the theoretical studies were extended to heterogeneous soils, a suitable heterogeneity criterion would have to be defined.

The method would be suitable for saline and alkaline soils, since the criterion adopted at present is chemical composition. We still have to determine the divergencies due to physical properties, to which brief reference is made in the paper.

H. KICK: Did you also study organic soils? I am asking this because such soils have not, hitherto, been considered in models used to test theoretical calculations.

P. COUCHAT: This has not been done experimentally, but some authors, such as Yemel, Yanat and Churayev, have shown that the hydrogens of the water of formation and of organic material have the same influence on neutron scatter. I believe that, in accordance with Melkonian's results (Ref. [15] of the paper), we can identify the hydrogens of free water and organic material, and we have shown that bound and free water have the same effect. This leaves only the soils which we have studied.

E. P. COROMPT: As the spectral differences between Am-Be and Ra-Be are not very large, it is difficult to understand why Fig. 6 shows a very large difference in the thermal neutron distribution of these two sources.

P. COUCHAT: This is caused mainly by the fact that most of the value for the deceleration length $L_1$ is provided by the energy sub-groups close to 5 MeV, a small variation in the initial energy producing a large change in $L_1$.

M. DE BOODT: With reference to the fact that the Am-Be source behaves differently from the Ra-Be source, can you explain why the sensitivity is higher when Am-Be is used with 0.06-mm cadmium shielding than when Ra-Be is used, other conditions remaining the same in the neutron gauge?

P. COUCHAT: The sensitivity increases as the lengths $L_1 L_2 L_3$ in the equation $\phi = (r)$ decrease, i.e. if the source is weaker, or if the captured neutrons have greater energy. Surprisingly, this is not the case when we use Am-Be (for preference) or Ra-Be with a cadmium foil round the source. One CEA report shows the results obtained with an Sb-Be source (26-keV monoenergetic neutrons).
THE INFLUENCE OF BULK DENSITY, SLOW NEUTRON ABSORBERS, AND TIME ON THE CALIBRATION OF NEUTRON-MOISTURE PROBES

J.R. McHENRY AND ANGELA C. GILL
UNITED STATES DEPARTMENT OF AGRICULTURE,
AGRICULTURAL RESEARCH SERVICE,
OXFORD, MISS.,
UNITED STATES OF AMERICA

Abstract

THE INFLUENCE OF BULK DENSITY, SLOW NEUTRON ABSORBERS, AND TIME ON THE CALIBRATION OF NEUTRON-MOISTURE PROBES. The flux of slow neutrons in a soil measured by the neutron-moisture probe is a function of the hydrogen atom content of the soil. Most of the hydrogen atoms in soil are associated with soil moisture but some non-water hydrogen is found in organic matter and in the lattice structure of clay minerals. A change in bulk density of a soil will affect significantly the neutron calibration curve only when the change per unit volume of this non-water hydrogen atom content is equivalent to or greater than the minimum detectable volume percentage of soil moisture. Measurements of the slow neutron flux in a block of Grenada silt-loam soil at differing bulk densities substantiated these conclusions. A system capable of simulating soil of varying moisture content was developed and evaluated for measuring the long-term effect of instrument-component variation on reproducibility of a neutron-calibration curve. The effect of differing concentrations of neutron absorbers was also simulated. Elements which are neutron absorbers exist in some soils but will seldom be in quantities sufficient to affect significantly the neutron-calibration curve. Three types of neutron probes were evaluated. While characteristics of the respective calibration curves varied, the reliability with time of all neutron probes tested was satisfactory.

1. INTRODUCTION

The determination of soil moisture by neutron scattering has been practiced since the early 1950's (1). The method is one of the most reliable yet developed for use in plant-soil-water relationships. The development of the neutron scatter method of measuring soil moisture is reviewed by Cope and Trickett (2) and van Bavel (3), and the methods of measurement in use today are detailed by van Bavel, Nixon, and Hauser (4). The advantages and disadvantages of the neutron scatter method are succinctly presented by Barrada (5).

The neutron scatter method is based on the fact that hydrogen atoms are very effective in slowing down fast neutrons. As most of the hydrogen atoms found in soils are associated with oxygen as water, the method is calibrated to yield moisture content as a function of the slow neutron flux. Such calibration curves are furnished by the manufacturer but most research workers caution that calibration of the instrument with the material in which it is to be used is essential (3, 5, 6, 7). Van Bavel and co-workers (4, 6) and Holmes (7) emphasize the need for precision in determining the calibration curve under laboratory conditions. Some workers (8, 9) have attempted field calibration with varying success.

The calibration of neutron probes is influenced by several factors. The volume of soil, or other material used (6), the density of the material (10), and the presence of slow neutron absorbers in the soil (11, 12) are parameters which may affect the validity of the calibration.
In a previous paper, McHenry (13) considered the effective sensitive length of two neutron probes, the Nuclear-Chicago P-19 1/ and the Troxler 102. Additional studies were conducted with these two types of probes to determine the effect of bulk density, time and neutron absorbers on the calibration curves. This paper describes these studies and presents the experimental data obtained in a series of laboratory experiments.

2. MATERIALS AND METHODS

2.1 Instrumentation

Two types of neutron moisture probes were used; those with center placement of the radioactive source (Nuclear-Chicago P-19) and those with end placement of the radioactive source (Troxler models). Both radium-beryllium and americium-beryllium sources were used in the end-placement probes. A Nuclear-Chicago Model 2800 scaler was used with both the Nuclear-Chicago and Troxler probes. The various instrument systems used in this study are described in Table 1.

2.2 Soil

A metal container, 1 x 1 x 1 m, was filled with a Grenada silt loam soil and was used as a calibration standard. A 5-cm diameter aluminum access tube was centered in the container. Initially oven-dried (1050 C) soil was placed in the container in increments equal to a 5-cm depth at the required bulk density and was compacted to volume. Successive additions of soil were made and each was packed to volume. This was repeated until 45 to 50 cm of soil had been added. After standing 24 to 48 hours, density measurements were made at 5-cm intervals with the Nuclear-Chicago P-20 depth density probe. If the density was uniform, measurements then were taken with each neutron probe. If the density was not uniform, the soil was removed and repacked. The mean of two 5-minute readings was used as the measurement of the slow neutron flux.

The soil was then removed, screened, and about 5% by weight of water was added to each soil increment. The wetted soil was mixed and then compacted to volume in the container in increments as before and the necessary measurements were made. After all measurements were completed, core samples were taken for gravimetric moisture determinations. This procedure was repeated until the soil became too wet for further handling. The soil in the container was next saturated and a final set of measurements made. The soil was then removed, screened, oven dried, and the sequence repeated at another dry bulk density value.

2.3 Soil simulation

The problems of varying the soil parameters in order to study the factors affecting neutron-probe response are many. Each soil is somewhat different. An infinite soil mass (for neutron travel) is massive. Conditions within the soil mass cannot be readily changed. Once a soil mass is conditioned it is difficult to use this particular soil for other tests.

1/ Company names and trade names are provided for the benefit of the reader only and do not imply any endorsement or preferential treatment by the United States Department of Agriculture.
<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>PROBE</th>
<th>SCALER</th>
<th>SOURCE AND NOMINAL STRENGTH</th>
<th>OPERATING VOLTAGE</th>
<th>STANDARD READING c.p.m.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Troxler 104</td>
<td>Nuclear-Chicago 2800, No. 277</td>
<td>Ra - Be 3 mCi</td>
<td>1,350</td>
<td>12,716*</td>
</tr>
<tr>
<td>B</td>
<td>Troxler 102</td>
<td>Nuclear-Chicago 2800, No. 373</td>
<td>Ra - Be 3 mCi</td>
<td>1,400</td>
<td>10,662</td>
</tr>
<tr>
<td>C</td>
<td>End Placement (USDA Sed. Lab.)</td>
<td>Nuclear-Chicago 2800, No. 277</td>
<td>Am - Be 100 mCi</td>
<td>1,350</td>
<td>51,034</td>
</tr>
<tr>
<td>E</td>
<td>Nuclear-Chicago P-19, No. 175</td>
<td>Nuclear-Chicago 2800, No. 277</td>
<td>Ra - Be 5 mCi</td>
<td>1,450</td>
<td>5,441**</td>
</tr>
<tr>
<td>F</td>
<td>Nuclear-Chicago P-19, No. 238</td>
<td>Nuclear-Chicago 2800, No. 115</td>
<td>Ra - Be 5 mCi</td>
<td>1,400</td>
<td>5,300</td>
</tr>
<tr>
<td>G</td>
<td>Nuclear-Chicago P-20</td>
<td>Nuclear-Chicago 2800, No. 277</td>
<td>Cs-137 3 mCi</td>
<td>1,000</td>
<td>14,223</td>
</tr>
</tbody>
</table>

* For Troxler-type probes the standard reading is for a standard-water pail (van Bavel (4)).

** For Nuclear-Chicago-type probes the standard reading is for the paraffin shield.

The production and detection of slow neutrons in a soil can be simulated by using a hydrogenous medium (water) and neutron absorbers. Cadmium, in solution (6) and as a shield about the access tube (13), has been used as the neutron absorber. Gadolinium is superior to cadmium in its efficiency as a slow neutron absorber. (The microscopic absorption cross section for 2200 m/sec neutrons is: Gd, $\sigma_a = 46,000$ barns; Gd, $\sigma_a = 2550$ barns (14)). Because Gd(NO$_3$)$_3$ was available, control rods containing a saturated solution of Gd(NO$_3$)$_3$ over excess salt at room temperature were prepared.

A 208-liter steel drum was filled with water. A 5-cm diameter aluminum access tube was placed in the center. Two aluminum rings, 5-cm i.d. and containing sixteen 8-mm holes, were fastened to the access tube. Sixteen pyrex glass tubes, 7 mm in diameter and 60 cm in length, containing
saturated Gd(NO₃)₃ solution, were used as control rods. These rods were placed in the holes in the aluminum rings so they were next to the wall of the access tube in a vertical position. The rods rested on a third, solid aluminum ring. The neutron probe was placed in the access tube near the middle of the control rods. The observed slow neutron flux measured by the neutron detector was a function of the number of rods in position.

### Table II

| MODERATOR | ATOMIC (MOLECULAR) WEIGHT | $\xi^*$ | N | $\sigma_g$ | $\sigma_a$ | $\xi_g\sigma_g$ | $\xi_a\sigma_a$ |
|-----------|---------------------------|--------|---|----------|----------|----------------|----------------|}
| H₂O       | 18                        | 0.93   | - | 49       | 0.66     |                | 70             |
| D₂O (99.75%) | 20                       | 0.51   | - | 10.5     | 0.0026   |                | 21,000         |
| H         | 1                         | 1      | 18| 38       | 0.33     |                | 115            |
| Li        | 7                         | 0.261  | 69| 1.4      | 71       | $5 \times 10^{-3}$ |                |
| Be        | 9                         | 0.207  | 87| 7        | 0.01     |                | 145            |
| B         | 11                        | 0.171  | 105| 4        | 755      | $9 \times 10^{-4}$ |                |
| C         | 12                        | 0.158  | 114| 4.8      | 0.003    |                | 253            |
| N         | 14                        | 0.136  | 132| 10       | 1.88     |                | 0.72           |
| O         | 16                        | 0.120  | 150| 4.2      | 2 x $10^{-4}$ |                | 2,520          |
| Na        | 23                        | 0.0845 | 213| 4.0      | 0.505    |                | 0.67           |
| Mg        | 24                        | 0.0811 | 222| 3.6      | 0.063    |                | 4.6            |
| Al        | 27                        | 0.0723 | 249| 1.4      | 0.23     |                | 0.44           |
| Si        | 28                        | 0.0698 | 258| 1.7      | 0.16     |                | 0.74           |
| P         | 31                        | 0.0632 | 285| 5        | 0.20     |                | 1.58           |
| S         | 32                        | 0.0612 | 294| 1.1      | 0.52     |                | 0.13           |
| Cl        | 35.5                      | 0.0554 | 325| 16       | 33.6     |                | 0.026          |
| K         | 39                        | 0.0504 | 357| 1.5      | 2.1      |                | 0.04           |
| Ca        | 40                        | 0.0492 | 366|          | 0.44     |                |                |
| Sc        | 45                        | 0.0438 | 411| 24       | 24       |                | 0.04           |
| Tl        | 48                        | 0.0411 | 438| 4        | 5.8      |                | 0.03           |
| Cr        | 52                        | 0.0380 | 474| 3        | 3.1      |                | 0.04           |
TABLE II. -- CONTINUED

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Mn</td>
<td>55</td>
<td>0.0359</td>
<td>501</td>
<td>2.3</td>
</tr>
<tr>
<td>Fe</td>
<td>56</td>
<td>0.0353</td>
<td>510</td>
<td>11</td>
</tr>
<tr>
<td>Co</td>
<td>59</td>
<td>0.0335</td>
<td>537</td>
<td>7</td>
</tr>
</tbody>
</table>

* $\xi$ = Average value of logarithmic energy decrease per collision.

* $N$ = Average number of collisions to reduce neutron energy to thermal levels (2 Mev to 0.025 ev).

* $\sigma_s$ = Mean scattering cross section (barns).

* $\sigma_a$ = Mean absorption cross section for thermal neutrons (barns).

Each control rod acted as a slow neutron "sink". Thus a neutron probe response equivalent to that obtained in a soil of any given moisture content could be duplicated. This relationship could be extended to 100% water in one continuous system.

3. EXPERIMENTAL

3.1 Effect of bulk density on calibration of neutron probes

The flux of slow neutrons measured by the neutron probe in a soil should be a function of only the hydrogen-atom content of the soil. The elemental composition of most soils is such that the moderating effect of the soil mass is related directly to its moisture content. The moderating effect, i.e., conversion of fast neutrons to thermal neutrons, of elements commonly occurring in soils is summarized in Table II. The data, calculated from handbook tables (15, 16), show that H2O, H, Be, O, and C are excellent moderators. The values for H and O are for the gaseous phase and, hence, are not applicable in soils. Beryllium is seldom found in soils in significant amounts. Because the migration length for C (54 cm) is much greater than that for water (6.4 cm), its moderating effect in a small volume is much less than that of water. (Migration length is defined as the average (vector) distance a neutron travels between its birth and ultimate absorption (17)). Effectively the slow neutron flux in soils is a unique function of the moisture content increasing as the water content increases.

In calibrating neutron probes the question arises as to the effect the dry bulk density of the soil under test will have on the observed neutron flux measurements.

Moisture measurements were made with several detection systems (Table I) over a range of moisture contents (oven-dry to saturation) on a Grenada silt loam soil at dry bulk densities of 1.2, 1.3, and 1.4 g/cc. The results are summarized in Figures 1 through 3.
FIG. 1. Calibration of Troxler-type neutron probes in a Grenada silt loam soil at differing dry bulk densities.

FIG. 2. Calibration of a neutron probe using an Am-Be source in a Grenada silt-loam soil at differing dry bulk densities.
FIG. 3. Calibration of Nuclear-Chicago neutron probes in a Grenada silt-loam soil at differing dry bulk densities.

The results show:

1. No significant differences in the calibration curves were obtained with changes in dry bulk density from 1.2 to 1.4.

2. The calibration curves for the Nuclear-Chicago probes were more nearly linear than those of the Troxler type and the difference between the Nuclear-Chicago probes was slight.

3. There was a difference in response of the various Troxler-type probes and the observed curves were less linear than those obtained with the Nuclear-Chicago units.

4. There was no observable difference in the detection or measurement of neutrons from Am-Be or Ra-Be sources.

Various workers (5, 7, 10, 18, 19), have indicated that the count rate recorded by the neutron detector is a function of the apparent density of the soil. It is also stated that there is a general tendency to high densities at large water contents and vice versa. It is not always clear whether dry bulk density or total bulk density of the soil is involved. Several workers (7, 10, 18) indicate the observed effect of bulk density is that which would be expected if the measurements were affected by hydrogen in forms other than free water, i.e., bound water and organic matter.

The results of this study are based on dry bulk density of the test soil. Only one soil is involved and the range in dry bulk density is limited by the physical characteristics of the soil. Insofar as this one soil, Grenada silt-loam, is concerned, changes in dry bulk density from 1.2 to 1.4 do not significantly affect the measurement of volume percentages of soil moisture for any of the instrument systems tested.
### TABLE III
THE STABILITY OF RESPONSE OF FIVE NEUTRON PROBES TESTED MARCH 1965, TO JUNE 1966

<table>
<thead>
<tr>
<th>NEUTRON PROBE</th>
<th>NO. OF TRIALS</th>
<th>MEAN READING IN WATER c.p.m.</th>
<th>MEAN MOISTURE EQUIVALENT PERCENTAGE</th>
</tr>
</thead>
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<tr>
<td></td>
<td></td>
<td>4 rods</td>
<td>6 rods</td>
</tr>
<tr>
<td>A</td>
<td>12</td>
<td>16,513</td>
<td>(305)*</td>
</tr>
<tr>
<td>B</td>
<td>12</td>
<td>13,942</td>
<td>(358)</td>
</tr>
<tr>
<td>C</td>
<td>11</td>
<td>67,279</td>
<td>(1,392)</td>
</tr>
<tr>
<td>E</td>
<td>12</td>
<td>17,283</td>
<td>(315)</td>
</tr>
<tr>
<td>F</td>
<td>12</td>
<td>17,028</td>
<td>(269)</td>
</tr>
</tbody>
</table>

* Figures in parentheses are standard deviations, 1σ, for the mean values reported for the indicated number of trials.
Because this soil contains considerable amounts of expanding lattice-type clays, some bound water will exist. For a soil with 10% montmorillonitic clay, this is about 0.0016 g/cc. The organic matter content is low, 0.71%. The data do not indicate any significant difference in observed counts for the oven-dry soil at bulk densities of 1.2, 1.3, and 1.4 g/cc.

Bulk density, per se, did not affect the observed slow neutron flux in a Grenada silt loam soil under the limited test conditions. Other workers (7, 10) have confounded hydrogen content with bulk density. The differences they ascribe to variations in bulk density are in fact accountable for by the differences in hydrogen content (other than free-water hydrogen) of the soil tested. Assuming that a neutron probe can detect > 0.005 g/cc water it can be shown that this is the approximate equivalent of 0.01 g/cc organic matter. Therefore, increases in bulk density will be significant where changes in the organic matter content exceed 0.01 g/cc. If a lower detection limit is attributed to the neutron flux measurement, a lesser change in organic matter content per unit volume of soil would be significant. At a dry bulk density of 1.4, the Grenada silt loam has less than 0.01 g/cc organic matter. Hence changes in dry bulk densities of this soil from 1.2 to 1.4 do not significantly affect the calibration curve of the neutron probe.

3.2 Stability of neutron probe calibration with time

A number of factors affect the validity of a calibration curve for a given neutron probe. One of these variables is the change in component characteristics of the probe with time. To overcome these generally unpredictable variations, the observed readings are reported usually as a ratio, i.e., as a percentage of a standard reading. Should the operating characteristics of the system change, the observed values of both the test and standard measurements would, hopefully, change in a similar manner. The ratio of the two observations should not change.

It was of interest to consider the effect of changes in the operating characteristics of the various systems with time on the entire calibration curve. The usual ratio value relates only one point and it is of considerable interest to evaluate the entire calibration curve.

For over a year calibration measurements were made approximately monthly with a number of neutron probes. At each measurement, a check was made of the performance of the probe over the entire calibration range by comparing the observed measurements made under similar conditions. Six measurements were made each trial—a reading in water and readings with 4, 6, 8, 12, and 16 Gd(NO₃)₃ absorption rods in position. Each measurement was a mean of two 5-minute readings. The equivalent moisture contents for a Grenada soil were obtained from the calibration curves prepared for each neutron probe from soil block data.

The results are summarised in Table III. The mean moisture equivalent values and standard deviations are given for each neutron probe tested. The standard deviations for the mean readings in water are a measure of the dispersion, or range of values, with time. The mean moisture equivalent percentages are corrected for dispersion and the standard deviations indicate the degree of precision of the duplicate measurements of equivalent moisture. The data summarised are for the period from March 1965, through May 1966. Collection of the data is continuing.
All of the neutron probes performed well during the trial period recorded. The results obtained with the two Troxler probes were similar as were those obtained with the Nuclear-Chicago Probes. The differences in equivalent moisture percentages observed between the two probe types for like conditions are due to differing characteristics of the source location and electronic detection components of the two probes. Because of the differing source location, the geometric arrangement of the neutron absorber rods in space undoubtedly affects the observed neutron flux. This difference has been previously noted (13, 19).

Under the existing laboratory conditions -- which are undoubtedly near optimum for neutron probe performance -- all of the neutron probes tested performed very satisfactorily for a period exceeding 14 months. The variations with time in the response to a given uniform neutron flux were minor. The variations, as expressed by the standard deviations, are less than one per cent of the mean equivalent moisture values. There seems to be little to choose between the two types of probes based on their performance in these tests. The neutron probe using 100 mCi of americium-241 gave slightly better statistical values because of the greater count rate. This, together with the decreased radiological hazards of the americium source would make this neutron probe slightly more advantageous.

3.3 Effect of neutron absorbers, frequently found in soils, on the measurement of slow neutron flux

Many investigators have noted that the presence in a soil of elements with a high capture cross section for slow neutrons will affect measurements of soil moisture by the neutron scatter method (2, 5, 11, 12). These elements do not, fortunately, occur in significant amounts in most soils. Two elements, boron and chlorine, which occur in some soils in measurable quantities, have significant neutron capture cross sections (Table II). Iron, although having a small absorption cross section, occurs in most soils in appreciable amounts and the total absorption of thermal neutrons per unit volume may be significant (9).

![Graph](image-url)

FIG. 4. The effect of boron concentration on the slow neutron flux measured by a Troxler neutron probe at differing moisture percentages.
FIG. 5. The effect of different neutron absorbers on the slow neutron flux measured by a Troxler neutron probe at differing moisture percentages.

FIG. 6. The effect of boron concentration on the slow neutron flux measured by a USDA Sedimentation Laboratory neutron probe at differing moisture percentages.

The effect of B, Cl, Mn, Co, and Fe on slow neutron flux determinations was evaluated. Boron was added as H$_3$BO$_3$; Cl as MgCl$_2$; Fe as Fe$_2$(SO$_4$)$_3$; Co as CoSO$_4$·7H$_2$O; and Mn as MnSO$_4$·H$_2$O. The concentration ranges studied were: B, 10-250 ppm; Cl, 10-1,000 ppm; Mn, 100-2,500 ppm; Co, 10-750 ppm; and Fe, 100-10,000 ppm. Slow neutron flux readings were taken in water, in solutions of the above salts, and with 4 to 16 absorption rods in position. The equivalent mean moisture percentage for each system (instrument x absorption rods) are shown in Table III. The results, reported as a percentage of the water reading (the maximum slow neutron flux), are summarized in Figures 4 through 8.
FIG. 7. The effect of boron concentration on the slow neutron flux measured by a Nuclear-Chicago neutron probe at differing moisture percentages.

FIG. 8. The effect of different neutron absorbers on the slow neutron flux measured by a Nuclear-Chicago neutron probe at differing moisture percentages.

The effect of increasingly greater concentrations of boron on slow neutron flux are summarized in Figures 4, 6, and 7 for the three types of neutron probes. At 10 ppm B there is little effect from the neutron absorber at the lower simulated moisture values. For concentrations of 50 ppm B and greater there is a measurable reduction in slow neutron flux, even at the lower moisture values.
There is a marked difference in the shape of the curves for the Nuclear-Chicago and Troxler probes. The linear response of the Nuclear-Chicago probe is in contrast to the curvilinear response of the Troxler and USDA Sedimentation Laboratory probes. This difference in response has been noted (13, 19), but it is interesting that the family of curves, corresponding to increasingly greater concentrations of slow neutron absorbers, are of the same pattern as the soil moisture response.

A measure of the effectiveness of various slow neutron absorbers is presented in Figures 5 and 8. Similar data for the USDA Sedimentation Laboratory probe were essentially the same as that shown for the Troxler probe in Figure 5. The effect of most of these slow neutron absorbers is negligible in the lower soil moisture range. Even at high simulated moisture contents, the effects of the maximum concentrations of neutron absorbers used were less than that for 25 ppm B. Effectively, 10 ppm B are equivalent roughly to 200 ppm of Cl or Co, 600 ppm of Mn, and 3,000 ppm of iron. This is based on the relative microscopic absorption cross sections of these elements. These concentrations of elements are relatively insignificant at the lower moisture percentages, which are equivalent to field moisture conditions.

In Figure 6, data for the USDA Sedimentation Laboratory probe are plotted as curvilinear. In Figure 2, the data appear linear. In fact the data for this probe are curvilinear over the entire moisture range but approach a linear relationship at lower equivalent moisture values as plotted in Figure 2.

One feature of the differing response to changes in relative neutron flux for the Nuclear-Chicago and Troxler probes is the greater response or sensitivity of the Troxler probe in the lower moisture range. This is in the range of field soil moisture. The greater sensitivity of the Nuclear-Chicago probe at higher moisture values is of no particular advantage in measurements of soil moisture. There is a lesser effect of the neutron absorbers on the response of the Troxler probe as compared to that of the Nuclear-Chicago probe (compare the spread of values in Figures 5 and 8 at 40% moisture). The response to boron is approximately the same for all the probes examined.

4. DISCUSSION

It is generally agreed (3, 7, 10) that for precise work it is necessary to know the (dry) bulk density of the soil in addition to the slow neutron flux. For general field work the need is less demanding. Accuracy of individual field measurements of soil moisture content is seldom better than 0.5 per cent by volume (3). As indicated for most north Mississippi conditions, this accuracy is unaffected by probable changes in the bulk density of the soil because of the low organic matter content. For most conditions the probable effect of changing bulk density of soils will depend on the organic matter content. With the exception of peat and muck soils and surface horizons, the organic matter level of most soils will be less than that which, with probable changes in bulk density, would affect a change in the observable slow neutron flux.

Any change in slow neutron flux due to bulk density changes within a given soil series from place to place is offset by the fact that changes in moisture content are usually sought. Variations in bulk density would have no appreciable effect when only soil moisture changes were calculated, because the bulk density is immaterial if successive measurements at one
location are made. However if the bulk density of a soil at a given site and depth changes, the possibility of its affecting the validity of a calibration would depend largely on the non-water (mineral and organic matter) hydrogen content of the soil. As long as this organic matter content is less than 0.01 g/cc the probability that the calibration curve for the given soil will vary with possible bulk density changes of that soil is indeed small.

The applicability and accuracy of a neutron probe calibration curve over an extended period of time will depend, among other factors, on the stability of the detection system. To verify this stability, calibration standards are necessary. Many standards have been suggested (3). Simplicity of construction, ease of use, and reliability of repeated performance are essential to such standards. As van Bavel (3) indicates, soil moisture simulating standards are useful to verify the continuing behavior of a slow neutron detecting system with a minimum of difficulty. Such a system has been described and its performance over a period of time evaluated. The standards are easy to fabricate, the geometry is readily changed and/or duplicated, and conversion of simulated soil moisture data to individual soils is readily accomplished for any desired neutron probe. Temperature changes and time do not affect the standard. Furthermore the presence of neutron absorbers such as boron or chlorine in a soil, can readily be included in the simulated model.

The influence of neutron absorbers in a soil on the measured slow neutron flux has been extensively discussed (2, 5, 11, 12), and calculated (18). The problem concerning this influence was to measure the effect of various neutron absorbers on the calibration of neutron probes. This information was obtained using a simulated soil. These findings can, in turn, be applied to any soil whose neutron moisture calibration curve is correlated with the simulated standard. As with bulk density changes, the probable concentration of most neutron absorbers was shown to cause negligible effects. This is because the elements do not generally occur in concentrations large enough to significantly reduce the slow neutron flux. The results of this study indicate that suitable corrections for known Cl and B content can be made, either by calculations, or by inclusion of the element in the simulated standard. The results so obtained agree with those attributed to Holmes and Jenkinson by van Bavel (3).

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N. AYBERS: What do you consider to be the potentialities of the Nuclear Chicago moisture probe?

J. R. McHENRY: From a strictly theoretical viewpoint, the linearity of response of the probe makes it very useful. For deep soil-moisture measurements, it is excellent. I expect that lower prices for both the probe and the scaler will result in wider use of this method.

E. SOMER: How did you assign the various moisture contents to the neutron absorber standards?

J. R. McHENRY: We assigned the moisture equivalent values obtained with the Grenada silt loam soil calibration. For a certain value with the neutron absorbers, we assigned the moisture content (density = 1.3 g/cm³) corresponding to that count-rate (flux).

E. SOMER: Did you assign the same moisture content to the same solution for all probes?

J. R. McHENRY: No, the values were assigned to each probe from the corresponding calibration curve obtained with the Granada silt loam soil. Of course, we could assign values obtained for any soil for which we possess a calibration curve. In this way, we feel able to assign the potential effect of adsorbers to any soil and for each neutron probe.

E. SOMER: While it is safe to use the neutron absorber standard technique for studying the effect of time on the stability of measurements, I doubt if it is correct to use it to check the effect of neutron absorbers. The slow-neutron flux distribution in the standard is different from the distribution in soil with the same moisture as assigned to the standard. In fact, we have found much larger values than you for the boron effect in one of the probes which you checked.

J. R. McHENRY: Our original objective was to find a cheap, easily duplicated standard with which the performance of neutron moisture gauges could be checked periodically. We wanted to check the probe response over the entire soil-moisture range, not just at one point. From this we progressed to the neutron absorber studies. Now whether or not the individual neutron probes respond to our neutron absorber systems as they would to similar conditions in the soil has still to be checked by experimentation and I believe we shall be doing this. It would be extremely interesting to check your computer programme against our experimental data.

E. SOMER: I have one further comment. It seems to me that only a small part of the density effect can be attributed to the compaction of hydrogenous material. Most of the effect is caused by fast-neutron scatter by ordinary soil components other than hydrogen.

J. R. McHENRY: You are referring to the gross calculated effects, but if you examine the data given in Table II, you will see that the moderating ability of most elements is small compared with that of the elements we discuss as possible neutron moderators. The moderating effect of molecules, such as H₂O and D₂O, is not necessarily the sum of the elemental moderating effects. Our aim was to consider those factors which were of sufficient magnitude to influence the measurement of soil moisture, which could be assumed to be determined with an accuracy of 0.5% by volume. Within the limits of our experimental data, we did not find changes in soil bulk density to be statistically significant.
as regards response of the neutron probes. Our density variations are small compared with those calculated in your computer programme. However, it was physically impossible to achieve a greater range in soil bulk density and still have data for a moisture range of practical magnitude. Using our experimental data, we did not obtain a response of the magnitude which your computer programme predicted for any of our neutron probes.

W.K.G. KUHN: Generally speaking, iron is not an absorber, but an element which produces inelastic scattering of epithermal neutrons, so that the presence of iron causes more intense thermal neutron activity. I think it should therefore be borne in mind that the iron content of the soil can influence measurements in this way.

J.R. McHENRY: Iron has the property of being both an adsorber and a moderator of thermal neutrons, but the values in each case are small, so that the effect of iron would be negligible, except where it occurs in high concentrations.

L.E. DANFORS: How did you analyse the effects of soil density on count-rate? From Figs. 1-3, the count-rates for soils with a density of 1.2 g/cm³ appear to be lower than those for soils with higher densities.

J.R. McHENRY: We determined the statistical significance of the least squares equation for each set of data. There was no significant difference at 95% confidence limits.

D. KIRKHAM (Chairman): Would you comment on the significance of the centre source in the Nuclear Chicago probe, compared with the end source in the Troxler probe, in connection with your comparisons of these two instruments?

J.R. McHENRY: The relative positions of the radioactive sources in the two probes in question is undoubtedly responsible for most of, if not all, the discrepancy. In one case, the flux distribution from the source radiates in two directions, being strongest in the centre and diminishing uniformly in two directions. With the source in the end position, the flux variation is much greater from one end of the detector to the other. This geometric difference may well magnify discrepancies caused by instrument sensitivity to neutron energy.

Y. BARRADA: There are other probes that perform in the same way as the Nuclear Chicago probe, for example the Nuclear Enterprise probe and that of the CGEI (France); they all give a straight-line calibration curve over a very wide range of soil moisture.

J.R. McHENRY: I assume that these probes also have provision for a central positioning of the radiation source. I believe A. Zuber and J.P. Cameron also discussed this point in their recent paper on neutron gauges (Atom. Energy Rev., IV 4 (1966) 143).
GAMMA-RAY AND NEUTRON ATTENUATION IN MEASUREMENT OF SOIL BULK DENSITY AND WATER CONTENT*

W. H. GARDNER AND C. CALISSENDORFF**
WASHINGTON STATE UNIVERSITY,
FULLMAN, WASH.
UNITED STATES OF AMERICA

Abstract

GAMMA-RAY AND NEUTRON ATTENUATION IN MEASUREMENT OF SOIL BULK DENSITY AND WATER CONTENT. Use of gamma-ray attenuation measurements for obtaining non-destructive water-content and bulk-density measurements with high resolution and precision in experimental laboratory columns has long been possible. Thermal neutrons used in place of gamma-rays at fluxes available at a nuclear reactor make possible about tenfold improvement in the precision of water-content measurements for the same count-rate. Concurrent measurements using two different gamma-ray energies or gamma-rays and thermal neutrons make it possible to infer both soil bulk-density and water-content, thus increasing flexibility in experimental studies of water flow as affected by various soil factors. The limiting factor in both bulk-density and water-content measurement is the random emission of gammas or neutrons. Standard deviation for both types of radioactive emission is the square root of the number of disintegrations. Based upon random emission only, the precision (standard deviation) for both water content and bulk density is about 0.006 g/cm³ for an experimental set-up with 10⁶ counts through air at the position where the soil column would be placed. For a 10-cm soil column with the measurement being made in a lamina 1 mm x 3 cm and for 1-min counting a gamma-ray source of about 300 mCi is required. At the Washington State University Nuclear Reactor Facility this count is achieved in about 0.5 min. Precision may be increased by increasing the counting rate, the increase being proportional to the square root of the ratio of the old to new counting rate. For example, increasing the counting rate by a factor of 4 by increasing slit size or lengthening counting time increases the precision by a factor of 1/\sqrt{4} = 1/2. Other factors involved in precision and resolution are column width, collimator slit width, variation in mass attenuation coefficients of the mineral substances involved, and undetected changes in bulk density.

The attenuation of gamma radiation in matter involves both the chemical composition and concentration of matter and varies with gamma-ray energy. For soil of unchanging chemical composition it is possible to infer overall density from attenuation measurements where the mass attenuation coefficient is known for the gamma energy used. If the soil is dry then the density inferred is the bulk density of the soil [1]. If, on the other hand, the bulk density remains constant and attenuation is known for dry soil at this bulk density, then water content may be inferred from attenuation measurements [2-7]. If the chemical properties, apart from changes in water content and soil bulk density, remain constant then through concurrent measurement at two different gamma energies, where the relationship between the attenuation coefficients for soil and water differs appreciably at the two gamma energies, it is possible to infer both bulk density and water content. Or, thermal neutrons may be combined with gamma rays with the same result.

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** Professor and Senior Experimental Aide, Department of Agronomy (Soils)
Theory of attenuation methods

At the gamma energies generally used in measurement of soil bulk density or water content (<1.5 MeV) the absorption of gamma rays largely is by photoelectric interaction and Compton scattering. Absorption of neutrons is by a combination of scattering and capture. The attenuation of a collimated monoenergetic beam of gammas or neutrons in passing through an absorber depends upon absorber thickness, \( S \) (cm.), and is proportional to the intensity of the interacting beam, \( N \) (number of counts), the bulk density, \( \rho \) (g./cm.\(^3\)), and mass attenuation coefficient \( \mu \) (cm.\(^2\)/g.), of the absorber, thus

\[
-dN = \rho \mu N dS
\]

Integration of this equation between \( N \), the intensity of the emergent gamma beam, and \( N_0 \), the intensity of the incident beam, and between \( S_0 = 0 \) and \( S \) the thickness of the soil column, gives the standard attenuation equation,

\[
\ln \frac{N}{N_0} = -\rho \mu S
\]

The term on the right may be expanded to include a combination of absorbers, for example soil, water and the walls of the container. Rewritten in exponential form this becomes

\[
N = N_0 \exp \left[ -S(\mu_s \rho_s + \mu_w \theta) - S' \mu_c \rho_c \right]
\]

where the subscripts \( s \), \( w \) and \( c \) denote soil, water and the container material, \( S' \) is the combined thickness of the container walls and \( \theta \) is water content in g./cm.\(^3\). The intensity of the emergent gamma or neutron beam can be measured by interception with a detector in which each gamma photon or neutron interacts with an absorber in the detector to produce an electrical pulse. One of the most efficient counters for gamma photons is a thallium activated sodium iodide crystal in which the absorption of a gamma photon gives rise to a light pulse which may be picked up by a sensitive photo multiplier with the resultant electrical pulse being amplified and counted by a scaler or rate meter. The intensity of the light pulse is a function of gamma photon energy, and the potential of the resulting electrical pulse therefore is determined by photon energy. An emergent gamma beam will contain gamma photons of a variety of energies as a result of interactions with the absorber, but it is possible by means of electronic selection to identify and measure the quantity of gamma photons which pass through the absorber essentially unchanged. The ratio of the incident to emergent intensity of this beam is a measure of the attenuation which takes place.

Thermal neutrons passing through the absorber are detected with good efficiency by a detector consisting of a gas-filled metal tube which acts as one electrode and containing a central wire forming a second electrode. The gas in the tube is boron fluoride enriched with the \(^{10}\)B isotope of boron. When a thermal neutron encounters a \(^{10}\)B nucleus and is absorbed an alpha particle is produced and attracted to the charged wire electrode creating an electrical pulse. This pulse is amplified and picked up with a conventional scaler or rate meter.
For the determination of bulk density of dry soil, or the water content of wet soil having a known density, it is possible using gamma ray attenuation to measure the intensity of the emergent gamma beam cumulatively for the entire energy range. The attenuation coefficient under such conditions differs from the coefficient determined for a particular energy range. However, for good resolution it is necessary to restrict measurements to the energy of the highest energy peak of the gamma source so as to eliminate the influence of gamma photons scattered into the soil outside of the collimated beam path, many of which would be scattered back into the beam so as to reach the detector. This necessitates use of an electronic discriminator in the counting circuit which excludes all energies below the peak energy used in the measurement.

Comparable discrimination has not been obtained with neutrons. The experimentally determined resolution using a collimated neutron beam has proved to be slightly greater than twice the width of the collimated beam, indicating that neutrons are scattered outside of the beam path.

Equations for bulk density and water content and statistical considerations.

To apply gamma attenuation theory to the determination of bulk density equation (2) is written for the empty soil container and for the container with dry soil in place, thus

\[
\ln \frac{N_c}{N_o} = -\rho_c \mu_c S_c \tag{4}
\]

and

\[
\ln \frac{N_s}{N_o} = -\rho_c \mu_c S_c - \rho_s \mu_s S_s \tag{5}
\]

where the subscripts, c and s, have been added to designate the container and the dry soil and \( N_o \) represents the count obtained with only air in the beam path. Subtracting equation (4) from equation (5) to eliminate \( N_o \) and the parameters pertaining to the container wall, and solving the resulting equation explicitly for the bulk density, gives

\[
\rho_s = -\frac{\mu_s S}{\mu_s S} \ln \frac{N_s}{N_c} = -\frac{2.3}{\mu_s S} \log \frac{N_s}{N_c} \tag{6}
\]

In a like manner equation (5) may be rewritten to include water concentration, \( \theta_w \) with the subscript w being used to designate water and \( N_w \) the count in wet soil, thus,

\[
\ln \frac{N_w}{N_o} = -\rho_c \mu_c S_c - \rho_s \mu_s S_s - \theta_w \mu_w S_s \tag{7}
\]

Subtracting equation (5) from equation (7) to eliminate \( N_o \) and the parameters pertaining to the container and dry soil, which are presumed to remain constant, and solving the resulting equation explicitly for water
concentration, gives

\[ \theta = \frac{-1}{\mu_w S} \ln \frac{N_w}{N_s} = -2.3 \frac{S}{\mu_S} \log \frac{N_w}{N_s} \quad (8) \]

Equations (6) and (8) are widely used for dry bulk density measurements and for measurements of water content in systems where bulk density may be presumed to remain constant.

Using equation (4) to eliminate the parameters associated with the soil container from equation (7), replacing them with the gamma count through the container, yields an equation for water content, \( \theta \), for a system in which soil bulk density is included as a parameter, thus,

\[ \theta = \frac{-1}{(\mu_w S)} \left[ \ln (N_w/N_c) + \rho_s \mu_s S \right]. \quad (9) \]

The precision of the method for measurement of water content is limited by the random emission of gamma photons from the radioactive source. Under many conditions the parameters in the equation can be measured with sufficient precision that their variance becomes negligible compared to the variance in \( N_w \). However, the precision required to make their contribution negligible is of importance. And, in some instances unanticipated variation in the bulk density \( \rho_s \), the thickness of the column \( S \), and the chemical composition which governs the mass attenuation coefficient \( \mu_s \) will contribute to variance in water content measurements. The variance in water content is made up of the sum of the individual variances, thus,

\[ V_\theta = V_\theta(\text{counting}) + V_\theta(\mu_w) + V_\theta(S) + V_\theta(\rho_s) + V_\theta(\mu_s) \quad (10) \]

where the subscript notation indicates the contribution to variance in water content measurements which would result from variance in the component indicated in parenthesis. Equations for variances due to variation in \( \rho_s \) and \( \mu_s \) are of identical form.

The first term on the right hand side in equation (10), as obtained from equation (9) is

\[ V_\theta(\text{counting}) = \frac{1}{(\mu_w S)^2} \ln \frac{N_w}{N_c} \quad (11) \]

where \( N_c \) has been replaced by \( N'_c/n \) on the right hand side where \( n \) is the ratio of counting times used for each count, \( N'_c/N_c \). With reasonable assumptions it may be shown that

\[ V_\ln \frac{N_w}{N'_c} = \left( \frac{N'_c/n}{N_w} \right)^2 \frac{V_{N_w}}{N'_c/n} \quad (12) \]
\[ V_{N_c}/n = \frac{(1/N_c/n)^2 \left( V_{N_w} + (N_w/N_c/n)^2 V_{N_c}/n \right)}{1 + N_w/nN_c}. \]  

(13)

Gamma ray and neutron emission are known to have Poisson distributions for which variance is the count itself so that \( V_{N_w} \) may be replaced by \( N_w \) and \( V_{N_c}/n \) by \( 1/n^2 N_c \). Applying equations (12) and (13) and replacing variances with their count equivalents gives the equation for the variance in water content due solely to random emission of radiation, thus,

\[ V_{\bar{\theta}}(\text{counting}) = \frac{1}{\mu_w S^2 N_w} \left[ 1 + \frac{N_w}{nN_c} \right]. \]  

(14)

Where the count through the soil container is 3 or 4 times as long as the count through soil the second term in the bracket becomes negligibly small for most purposes and equation (14) becomes

\[ V_{\bar{\theta}}(\text{counting}) = \frac{1}{\mu_w S^2 N_w} \]  

(15)

or, when \( N_w \) is replaced by its equivalent from equation (9) written in exponential form, the variance becomes

\[ V_{\bar{\theta}}(\text{counting}) = \frac{\exp \left[ S(\mu_w S + \mu_w \theta) \right]}{\mu_w S^2 N_c}. \]  

(16)

Plots of standard deviation in water content as influenced only by random emission, \( \left[ V_{\bar{\theta}}(\text{counting}) \right]^{1/2} \), as a function of column thickness, \( S \), are shown in Figure 1 for four different gamma ray energies, Am-241, Cs-137, Ce-144 and Co-60 as well as for 0.5 ev neutrons where mid-range values of water content and bulk density, 0.15 and 1.2 g./cm.\(^3\), have been used. Standard deviations for some other values of water content and bulk density are shown in Fig. 2 where each of these variables is held constant at a mid-range value while the other becomes the independent variable. Comparable curves to those shown in Fig. 1 for water content are shown for bulk density in Fig. 3.

It may be noted in equation (16) that standard deviation, the square root of the variance, is inversely related to the square root of the count. Hence, for a particular gamma energy, reduction of standard deviation by a factor of 1/2 may be accomplished by increasing the count by a factor of 4 which requires increasing the collimating slit area or source strength by a factor of 4.

The remaining terms in equation (10) are not limited by random emission of the gamma source, except as gamma counting is involved as a limiting factor in determining \( \mu_w \) and \( \mu_s \). However, since long counting
FIG. 1. Standard deviation in water-content measurements using various gamma sources as a function of soil-column thickness where variation is due solely to random gamma emission. $N_0 = 10^8$ counts and bulk density is 1.2 g/cm$^3$.

FIG. 2. Standard deviation in water-content measurements as a function of water content at a mid-range value of bulk density and as a function of bulk density at a mid-range value of water content for $^{241}$Am and $^{137}$Cs. $N_0 = 10^8$ counts and soil-column thickness is 10 cm.

FIG. 3. Standard deviation in bulk-density measurements using various gamma sources as a function of soil-column thickness where variation is due solely to random gamma emission. $N_0 = 10^8$ counts and soil is air dry.
times are possible the effect of random emission may be minimized. The magnitude of these contributions to variance is important in establishing the precision required in measurements of the parameters as well as in evaluating the effect of unanticipated variation in the parameters. These contributions to variance are:

\[
V_{\theta}(\mu_w) = 1/S^2 \left( \ln N_w/N_c + \rho_s \mu_s S \right)^2 / \mu_w V_{\mu_w} \tag{17}
\]

\[
V_{\theta}(S) = 1/(\mu_w^2 S^4) (\ln N_w/N_c)^2 V_S \tag{18}
\]

\[
V_{\theta}(\mu_s) = (\mu_s/\mu_w)^2 V_{\mu_s} \tag{19}
\]

\[
V_{\theta}(\rho_s) = (\rho_s/\mu_w)^2 V_{\rho_s} \tag{20}
\]

Curves relating contribution to variance, \(V_\theta\), of each of the variables given in equations (17), (18), (19), and (20) to standard deviation for each of the parameters, expressed as a percentage of a nominal value, are shown in Figure 4. For a system involving liquid flow, changes in composition of the soil at the point of measurement due to influx or efflux of soluble components would be regarded as influencing the values of \(\mu_s\) and \(\rho_s\).

Although the neutron-matter interaction is different from the gamma ray-matter interaction the mathematical equations governing its use in attenuation measurements are the same. However, because of the much greater difference in attenuation of thermal neutrons in water than in soil for the same radiation intensity, neutrons are much more sensitive to water content and less sensitive to mineral matter normally found in soil. This difference may be noted in the curves for neutrons in Figures 1 and 3.

Mass attenuation coefficients vary with gamma energy so that the variances associated with gamma counting and the effect of variation in the various parameters should depend upon the gamma energy used. Of particular interest is the thicknesses of soil columns which can be used at acceptable precision. By computing the change in variance with column thickness, \(\partial V_S/\partial s\) from equation (16) and setting it to zero it is possible to infer that minimum variance occurs at

\[
S_{\text{opt.}} = \frac{2}{\mu_s \rho_s + \mu_w} \tag{21}
\]

From this equation it may be observed that column thickness for optimum precision increases as bulk density and water content decrease and as the mass attenuation coefficients decrease. Since mass attenuation coefficients generally decrease as gamma energy increases this means that the optimum column thickness \(S\) increases with increasing gamma energy.
Equations for bulk density $\rho_s$ corresponding to equations (8) and (9) and equations (16) through (20) for water content may be obtained by interchanging $\rho_s$ and $\theta$ and $\mu_w$ and $\mu_w'$. If water content is zero the gamma count $N_w$ becomes the count for dry soil $N_s$, equations corresponding to equations (19) and (20) vanish, and equations (9), (10), (16) and (17) become somewhat simpler.

![Graph showing contribution to variance in water content of errors in measurement or unknown change in column thickness $S$, bulk density $\rho_p$, mass-attenuation coefficients for soil and water $\mu_s$ and $\mu_w$, for $^{241}$Am and $^{137}$Cs at mid-range values of bulk density, 0.5 g/cm$^3$, water content 0.15 g/cm$^3$, and for optimum $S = 5$ cm for $^{241}$Am and 19.3 cm for $^{137}$Cs.]

**Resolution in attenuation measurements of bulk density and water content**

Collimation of gamma rays may be accomplished efficiently using lead or tungsten. Collimator length required for tungsten is about $2/3$ that for lead because of the higher density of tungsten. For maximum resolution collimation is required on both source and detector sides and collimating slits or holes should be parallel and of the same size. The thickness of the source-side collimator is determined in part by radiation safety requirements. Shield thickness to meet U. S. Atomic Energy Commission laboratory tolerance requirements (2.5 mrad/hr. at surface of a device) is about 7.9 cm. of lead for 100 mc. and 8.7 cm. for 300 mc. for Cs-137 and about 0.17 cm. for 100 mc. and 0.19 cm. for 300 mc. Am-241 as inferred from equations given by Blizard[8]. Over the range from 0 to 500 mc. the shield thickness varies almost linearly with source strength. Collimator length required for resolution depends upon resolution criteria. Assume that the effect of a sharp change in water content in soil adjacent to the collimated beam (say a change from 0 to 50% water content) is not to affect the measurement of water in the beam path by more than 0.0001 g./cm. $^3$ (1/100 of a water content percent). On this basis both the source-side and detector-side collimators should be about 8.5 cm. long for Cs-137 and 0.15 cm. long for Am-241. Increased count can be obtained by use of tapered slits which increase the area of the active face of the source with direct-line access to the face of the detector. However, for simple collimator slits this reduces the resolution.

Collimation of neutrons supplied by the Washington State University atomic reactor is achieved by use of an air slit tapered in two directions [9, 10]. The slit is about 80 cm. in length and is formed in an epoxy-boron plug placed in the beam port. The slit is designed to produce a beam
of thermal neutrons 1.0 x 0.1 cm. in cross section at a distance of about 80 cm. from the exit of the beam port. Measured resolution is about 1.2 x 0.25 cm. The neutrons from the reactor core pass through a graphite plug about 26 cm. thick placed just ahead of the collimator slit in the reactor core. The neutron count in air is about 2.4 x 10^6 counts/min. and in about 1.5 cm. of dry soil about 3.0 x 10^5 counts/min. About 94% of the neutrons in the beam have energies below 0.5 ev. as determined by a cadmium cut-off measurement.

**Concurrent measurement of bulk density and water content**

To measure both soil bulk density and water content concurrently it is necessary to make independent attenuation measurements at two different gamma energies or at one gamma energy and with thermal neutrons. If equation (3) in logarithmic form is written twice, once for each gamma energy (or for a single gamma energy and thermal neutrons), and the two equations solved simultaneously to eliminate water content, \( \theta \), the following equation results:

\[
\rho_s = \frac{\left( \mu_{wa}/\mu_{wb} \right) \ln \left( N_b / N_{ob} \right) - \ln \left( N_a / N_{oa} \right) + S' \rho_c \left( \mu_{cb} \mu_{wa} / \mu_{wb} \right)}{S' \left( \mu_{sa} - \mu_{sb} \mu_{wa} / \mu_{wb} \right)}
\]

(22)

where subscripts a and b have been added to designate two different gamma energies or one gamma energy and neutrons. With the parameters all determined for a particular system the working equation becomes

\[
\rho_s = 1/S \left[ k_1 \log \left( N_b / N_{ob} \right) - k_2 \log \left( N_a / N_{oa} \right) + k_3 \right]
\]

(23)

The limiting precision in \( \rho_s \), assuming that the parameters may be measured with any needed precision, depends upon random emission. Variance in \( \rho_s \) associated with variance in counting is

\[
V_{\rho_s} (\text{counting}) = 1/S^2 \left[ k_1^2 V_{\log \left( N_b / N_{ob} \right)} + k_2^2 V_{\log \left( N_a / N_{oa} \right)} \right]
\]

(24)

Using the same assumptions as were made in arriving at equation (14) for variance in water content due solely to random emission, and counting \( N_{ob} \) and \( N_{oa} \) long enough so that their contribution to variance is negligible, it is possible to write the comparable equations for variance of soil bulk density, thus

\[
V_{\rho_s} (\text{counting}) = 1/S^2 \left( k_1^2 / N_b + k_2^2 / N_a \right)
\]

(25)

A more useful equation results when \( N_b \) and \( N_a \) are replaced by their exponential equivalents as was done in arriving at equation (16) for water content, thus

\[
V_{\rho_s} (\text{counting}) = 1/S^2 \left\{ \left( k_1^2 / N_{ob} \right) \exp \left[ S' \mu_{sb} \rho_s + \mu_{wb} \theta \right] + S' \mu_{cb} \rho_c \right\} + \left( k_2^2 / N_{oa} \right) \exp \left[ S' \mu_{sa} \rho_s + \mu_{wa} \theta \right] + S' \mu_{ca} \rho_c \right\}
\]

(26)
Standard deviations, \((\sqrt{\text{counting}})^{1/2}\), where only counting variation is considered, for various combinations of gamma energies and for a particular gamma energy and thermal neutrons are shown in Fig. 5 as a function of soil column thickness where \(N_{oa} = N_{ob} = \text{ca. } 10^6\) counts.

**FIG. 5.** Standard deviation in bulk-density measurements made in wet soil using two gamma energies or a single gamma energy and thermal neutrons as a function of soil-column thickness \(s\). \(N_t = 10^6\) counts for both measurements.

**FIG. 6.** Mass-attenuation coefficients for water and concrete as a function of energy. Concrete and soil have similar values, some typical values for soil in \(\text{cm}^2/\text{g}\) for 0.060 and 0.661-MeV gammas being as follows: Palouse silt loam 0.307 and 0.094, Salcia silty clay loam 0.311 and 0.076, Everett gravelly loam 0.310 and 0.076, Astotin Bt clay 0.223 and 0.076. It may be observed that certain combinations are better than others for particular column thicknesses. In choosing the most ideal combination of gamma energies values should be picked where the attenuation coefficients differ the most markedly between the two energies. Mass attenuation coefficients as a function of gamma energy for water and concrete are shown in Fig. 6 [11]. Values for soil are reasonably close to those for concrete. It may be noted that the ideal energy combination would be one where the difference between soil and water to the left of the cross-over point is greatest with the second energy being one where the difference is greatest to the right of the cross-over point. Actually the number of choices is extremely limited by other considerations such as the excessively
short half life of an isotope, presence of interfering high energies which scatter down and are counted erroneously with the desired energy, expense of source material, and self absorption. Self absorption is a severe limitation at low energies and the maximum useful source strength often is quite low. For Am-241 for a source with cross-section of 1 x 0.1 cm. the maximum useful source strength is of the order of 230 mc. because of self absorption. Considering all of the many factors the most useful sources appear to be Am-241 and Cs-137. Using these sources (229 mc. Am-241 and 300 mc. Cs-137) and counting to get 10^6 counts through an empty container, bulk density was inferred for a simulated soil system where both bulk density and water content were changed. In place of soil thin glass plates and water-filled glass cells were used so as to permit precise computation of bulk density from thickness and density measurements made independently. The curve shown in Fig. 7 represents the double-gamma inferred bulk density as a function of the bulk density obtained from independent measurements. Bulk density and water content were varied by adding glass plates and filling cells with water.

For \( N_{oa} = N_{ob} = ca. 10^6 \) counts the variance for the measurement of bulk density, due solely to random gamma emission, was about \( 9 \times 10^{-6} \text{ g/cm}^3 \). With bulk density known to this precision it then is possible to infer, with the aid of the curves in Fig. 4, that the contribution to error in water content measurement due to such variation in bulk density measurements is about \( 8 \times 10^{-6} \text{ g/cm}^3 \). Adding these two variances together and taking the square root gives the standard deviation in water content to be expected by a combination of the error due to counting and the error due to uncertainty of bulk density as measured using double-gamma techniques.

For the conditions specified this standard deviation is 0.004 g/cm^3.

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DISCUSSION

P. COUCHAT: Why do you consider that a reactor or accelerator must be used for thermal neutron transmission studies? Studies have been made without such neutron sources.

W. H. GARDNER: My conclusion that a nuclear reactor is normally necessary for effective use of neutron attenuation measurements of water content is a practical one based on the need for a large count to reduce the error from random radiation emission. Certainly, the answer to the question whether or not a sub-critical reactor or other type of neutron source can be used depends largely upon the criteria specified by the investigator. In our work, we required spatial resolution of a few millimetres. The Washington State University 100-kW nuclear reactor (now being modified to go up to 1000 kW) provided a thermal neutron beam...
with a $0.1 \times 1$-cm ($0.1$ cm$^2$) cross-section in air, of strength $2 \times 10^6$ thermal neutrons per minute. The neutrons were thermalized by graphite in the beam-port access tube, so that only a small percentage (less than 5%) of the emergent neutrons had energies greater than 0.5 eV as inferred from cadmium cut-off measurement.

If experimental conditions permit the use of a larger neutron beam cross-section, or long counting times, the neutron count can be considerably increased with the same neutron source. On the other hand, if less precision is acceptable, a smaller count may be tolerated. Hence, a lower flux source may be used under certain conditions. The limiting precision in water-content measurements (standard deviation), considering only random emissions, is given for $10^6$ counts in Fig. 1 of the paper, from which it is possible to find the precision obtainable for $10^6$ counts at a desired soil column thickness. The square root of the ratio of this precision to a desired precision is the factor by which $10^6$ counts must be multiplied to get the required count (or Eq.(16) may be used directly). This count can then be used to decide whether a given neutron generator or source would be adequate. One has to consider whether the neutron flux is reported as a solid-angle flux, or a flux per unit area. Moreover, if the flux reported is for fast neutrons, the slow-neutron flux will be less by a factor of about 100, depending on particular conditions.

On the whole question of attenuation techniques for this work, however, I should like to make it clear that, as may be inferred from the curves in Fig. 1, the advantages offered by thermal neutrons, owing to the much larger mass-attenuation coefficient for water, compared with soil, are usually more than balanced by the difficulties associated with the production of a high thermal neutron flux. When a reactor is handy and an experiment may conveniently be run at a beam port adjacent to the reactor core, one may as well use the advantages offered by thermal neutrons. Where that is not the case, gamma sources — which can usually be obtained at any desired source strength, thus compensating for less favourable soil and water mass-attenuation coefficients — are not only far more convenient than low-flux neutron sources or generators but sufficiently accurate for most water-content measurements.
SECTION II
SOIL-MOISTURE STUDIES
COMPARISON OF THREE METHODS OF MEASURING SOIL MOISTURE

M. HAJDUKOVIĆ, M. JAKOVLJEVIĆ AND V. VAJGAND,
DEPARTMENT OF PLANT PHYSIOLOGY AND SOIL CHEMISTRY,
INSTITUTE FOR THE APPLICATION OF NUCLEAR ENERGY
IN AGRICULTURE, VETERINARY MEDICINE AND FORESTRY,
BELGRADE, YUGOSLAVIA

Abstract

COMPARISON OF THREE METHODS OF MEASURING SOIL MOISTURE. In field conditions on pseudo-gley soil, by applying intensive liming and deep ploughing, the soil moisture was measured continuously by the following methods: (a) gypsum-block electrical resistance, (b) neutron-scattering, (c) fibre-glass electrical resistance, and (d) the gravimetric method as a control. The gypsum blocks used were made by the authors. The neutron-scattering method was carried out by using a Nuclear Chicago Moisture Meter, model 2000A, together with the model P-19 probe including one 5-mCi radium-beryllium source and one 90Y detector tube. The thermistor method was carried with fibre-glass blocks made by Soiltest Incorporated, Chicago.

The results obtained indicated the advantages as well as the disadvantages of each of the methods used. The gypsum-block resistance method was found to be quick, relatively cheap and suitable for the reclamation systems. However, it appeared to be very sensitive to the composition of the soil solution. The results obtained by this method were accurate only within field capacity and wilting point of the aforementioned soil. The appearance of hysteresis during the rapid soil-drying was also noticed. The neutron-scattering method was very accurate, applicable to all soil types as well as to the degree of soil moisture; but the equipment is rather expensive. The thermistor method served only as a correction for the electrical resistances in gypsum blocks.

INTRODUCTION

An earlier paper [1] described the continuous measuring of soil moisture by the electrometrical method with gypsum blocks, made by the authors. However, as is known, despite its positive characteristics [2], this method is not applicable to all soil types. Hence, on parapodsolic soils in an experimental field at Varna in Sabac, soil moisture was continuously measured by the neutron-scattering, gypsum blocks, and thermistor methods, and the gravimetric method was used as a control. This soil had been improved by modern agricultural techniques through liming with deep ploughing, which rendered this field favourable for the observation and comparison of different methods for determining soil moisture. Thus, it was possible to obtain fair estimations regarding the value of several methods under our field conditions.

METHOD OF WORK

The investigations to evaluate these various methods of determining soil moisture were carried out in 1965 and 1966, in an experiment where the parapodsolic soil was subjected to intensive liming and deep ploughing.

It is a parapodsolic type of soil, with marked evidence of leaching. The differentiation of the horizons is considerable. The acidity of the
soil in the top horizon is low – the pH in the potassium chloride being 4.78. Horizon A has 2.83% of humus, and this percentage rapidly decreases with depth. According to its granulometric content horizon A belongs to dusty loam, and horizon B_g to the clay-gley.

The different experiments on the measurements and observations of soil moisture were as follows:

(1) Ploughing on 20 cm without liming, with normal nitrogen, phosphorus and potassium fertilizing;
(2) Ploughing on 20 cm with liming (8000 kg CaO/ha) with normal NPK fertilizing;
(3) Ploughing on 60 cm, with liming (8000 kg CaO/ha) with normal NPK fertilizing;
(4) Ploughing on 60 cm with liming (16 000 kg CaO/ha) with normal NPK fertilizing;
(5) Ploughing on 60 cm with liming (24 000 kg CaO/ha) with normal NPK fertilizing.

The moisture of the experimental soils was measured at 20-, 40-, 60- and 100-cm depths while all three investigated methods (gravimetric, gypsum blocks, and neutron scattering) were simultaneously applied. Moisture measurements with thermistors was only done at one place, and at the same depths, so that it was therefore possible to correct the electro-resistances on the gypsum blocks.

The gravimetric method was applied in a standard manner. Two samples from the same depth were taken separately beside the gypsum blocks, and separately beside the probe of the neutron-moisture meter. The soil moisture was expressed in weight percentages.

The gypsum-block method was applied to blocks made by the authors [1], and the measurement of the resistance of the gypsum blocks was performed by a battery ohm-meter, Model MC-300 (Soiltest Incorporated-Chicago). Five blocks were put down at each of the four depths. Field calibration of the gypsum blocks was done during the vegetation period, as it has been proved to be far more reliable than laboratory calibrations. This was even more justifiable, when it appeared that the soil had two different horizons – loam and clay-gley. Thus, two calibration curves were obtained – one for 20- and 40-cm depths, and the other for 80- and 100-cm depths (Fig. 2). From a total of 200 dug blocks on the experimental field there were only five failures.

For the neutron-scattering method we used the Nuclear Chicago neutron-moisture meter, which comprises a portable counting-assembly Model 2800A, and probes with a safety-plate Model P-18. The probe has a source of 5-mCi neutrons (Ra-Be), and one detector tube ($^{10}$BF$_3$), which is sensitive only to slow neutrons.

This method is based on the physical laws of dispersion and the slowing down of fast neutrons. In the soil the fast neutrons strike the nuclei of the surrounding atoms and disperse in all directions. At each slow the neutron incurs a loss of kinetic energy. This process of dispersion and energy reduction of the neutron continues until a state is achieved where the neutrons have the same kinetic energy as the surrounding atoms. The neutrons with this level of kinetic energy are called slow or thermal neutrons.

Fast neutrons lose much more energy at the collision point with the atoms of the small mass numbers. The neutron probes for measuring
soil moisture are so constructed that they possess special detectors that do not register fast neutrons, but detect only the slow ones. As nitrogen is the only element of small atomic weight in non-organic soils, the number of slow neutrons is detected in a time-unit measurer for the atom concentration in the soil. The greatest number of hydrogen atoms in non-organic soils comes from water molecules, which is why the number of detected neutrons in a unit of time is proportional to the amount of water.

The sensitive volume depends primarily on the soil moisture [8]. In high moisture the radius of this sphere is 20 cm, and in very low moisture conditions it goes up to 40 cm. The physical and chemical characteristics of the soil frequently do not influence neutron measurements. According to Gardner and Kirkham [9] and Stewart and Taylor [10], for all soils with a small or medium percentage of humus (1 to 5%), it is possible to use only one calibration curve, the exact measurement to be ± 1.5 vol.%. However, in as much as each soil is separately calibrated, the accuracy of the measurement can increase considerably.

To lower the probes into the soil we used 50-mm-diam. steel seamless tubes, which, closed at the bottom, were pressed into soil holes of the same diameter. Field calibration was also applied in this method. For 40-, 80- and 100-cm depths, one calibration curve was obtained. Therefore, this method is independent of the granulometric soil composition. For a 20-cm depth a special calibration was needed owing to the proximity of the soil surface and, as a result, one part of the fast neutrons was lost in the air. The results were statistically elaborated in linear regression. For a 20-cm depth the following equation of the line is obtained:

$$Y_1 = 764 + 171.87 \times$$  \hspace{1cm} (1)

For depths of 40, 80 and 100 cm the following line is obtained:

$$Y_2 = 18 + 293.87 \times$$  \hspace{1cm} (2)

The thermistor method was applied to a far smaller degree. With the same ohm-meter with which resistance was measured in the gypsum blocks, the resistance in United States fibre-glass blocks (Soiltest Incorporated - Chicago) was also measured. However, this served only to correct the resistance obtained in the gypsum blocks and the correction referred to the temperature of the soil during measuring, as was done by Slater and Beryant [5] and Stokhause [7]. It was for this reason that the blocks were placed at the same depths as the gypsum blocks.

**RESULTS AND DISCUSSION**

As can be seen from the calibration curves for gypsum blocks (Fig.1), the soil-moisture measurement by this method is limited in value. The measurement range of the gypsum blocks at 20- and 40-cm depths is between 14 and 28% in each case (curve 1 on Fig.1), and for 80- and 100-cm depths the measurement ranges from 18 to 32%. In other words, this method enables a satisfactory correct measurement for only those moistures of
soils that lie between the wilting point and the retention capacity of the soil. This is certainly a drawback, but this disadvantage is to a certain point compensated by the fact that it is especially that range of soil moisture that is of greatest interest for agricultural production, and this justifies the application of the method.

The calibration of the neutron-moisture meter, as can be seen from Fig. 2, shows that this method can be applied with the same exactness from absolutely dry to the completely saturated state of the soil. (lines Y₁ and Y₂ on Fig. 2), as the calibration curves are linear.

The exactness of the methods was tested during numerous observations. There were 168 observations for the gypsum blocks, and 157 for the neutron-moisture meter. The standard error of determination was used as a comparison — the difference between data obtained from other methods was calculated. The standard error of determination for the gypsum blocks was 0.83%, in the neutron method it was 0.70%, whereas the standard deviation in the gravimetric method was from 0.65 to 0.67%. Hence one can deduce that the neutron method is considerably more exact than that of the gypsum blocks. The increased inaccuracy of this latter method had
FIG. 2. Two calibration curves—one for 20- and 40-cm depths, and the second for 80- and 100-cm depths.

two sources for errors. The first lay in the structure changes of the soil during different moistures, followed by changes in the temperature and electrolytes concentration, i.e., soil solution, and also in the phenomenon of hysteresis. The second error source arose from interrelated individual changes between some gypsum blocks. The neutron method is practically independent of all these.

During continuous observation of soil moisture in the vegetation period it was noticed, as can be seen from Figs. 3 and 4, that both the neutron and the gypsum-blocks methods more or less conform to that of the gravimetric method, but in the gypsum blocks (Fig. 3), during
FIG. 3. Measurement of gypsum blocks.

FIG. 4. Moisture measurement by the nuclear method.
intense and rapid drying that occurred around 1 August, the phenomenon of hysteresis appeared. In the neutron-scattering method (Fig. 4) this phenomenon did not take place.

CONCLUSIONS

In 1965 and 1966 under field conditions experiments on parapodolsic soil, which was subjected to liming and deep ploughing, were carried out on soil moisture by three methods: gypsum blocks (electroconductivity), neutron-scattering (dispersing and slowing down of fast neutrons), and the gravimetric method (drying at 105°C).

The disadvantages and advantages of certain methods are noted, viz. the gypsum-block method does not enable the soil moisture to be measured below the wilting point or above retention capacity. Besides, this method is very sensitive to a quick soil drying, which results in hysteresis. To also obtain more accurate results by this method in the full moisture range where it can be applied, it is necessary to correct the electrical resistances with the temperature. Apart from these minor disadvantages, the gypsum-block method can be usefully applied in non-alkalai soils under irrigation, especially since the blocks are cheap, and their accuracy for this purpose is satisfactory.

The neutron-scattering method enables the soil moisture from full water saturation up to absolutely dry conditions to be observed. This method permits one calibration for all mineral soils, and it is independent of the mineral composition of the soil. The measurement of soil moisture by this method is relatively fast, and the accuracy very near to the gravimetric means of determination. By comparison with the gypsum-block method of measurement, moisture measurement by neutron scattering is independent of hysteresis, as the equilibrium state in the latter is restored within one minute. Furthermore, the disadvantages are that, for the surface-layer dry soil (from 0 to 20 cm), a surface measurement with a special additional apparatus must be made, or a special calibration must be done. In addition, the portable measurement equipment plus the probe are very expensive.

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DISCUSSION

J. MARCESSE: You give two calibration curves for the neutron moisture meter, one valid for a depth of 20 cm and the other for lower levels, and you attribute the difference between them to a surface effect, but I do not believe that this effect alone can explain such a large variation. In an earlier publication, Mr. Maertens showed that the surface effect at 20 cm does not cause an error of more than 1% humidity. Could the dry density have had some influence?

M. HAJDUKOVIC: The two horizons in our soil were quite distinct, so it is possible that density differences were partially responsible for the variation in the two calibration curves.

J. MARCESSE: I might point out that the Radio-Agronomy Service in Cadarache has developed a light and simple neutron reflector with which measurements can be made up to 10 cm below the soil surface.

M. Ş. YEŞİLSOY: Having in mind the hysteresis that occurs in soil and gypsum blocks, the results you obtain for the blocks are excellent. Did you carry out any preselection before using them in the field and how were calibration curves drawn for the blocks, by calculations or by hand, using the scattering points?

Do you always make temperature corrections when you use the blocks in the field for practical purposes?

M. HAJDUKOVIC: Yes, the blocks were selected in the laboratory and the calibration curves were based on the scattering points. Temperature corrections were made at one place only, using thermistors in the soil at the same depths as the gypsum blocks.

H. W. SCHAFFENSEEL: Your parapodsol appears to be what we call pseudogleys. In our institute at Bonn, the moisture contents of these pseudogleys in particular have been measured at different levels for several years. In the course of this work, my colleagues had great difficulty in using a single calibration curve for different levels, especially the $g_1$ (water-table fluctuation) and $g_2$ (water-carrying, argillaceous and dense), apparently because of the considerable variation in the density and iron content of the various layers.

M. HAJDUKOVIC: Parapodsol is the same as pseudogley, except that aluminium predominates instead of iron in the Bg layer.

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1 See also discussion on MARCESSE, J., «Determination in situ de la capacité de rétention d'un sol au moyen de l'humidimètre à neutrons», these Proceedings.
EVOLUTION DE L'HUMIDITE D'UN SOL SOUMIS A UN APPORT CONTINU D'EAU SUR UNE PETITE SURFACE

D. RANÇON
CEA, CENTRE D'ETUDES NUCLEAIRES DE CADARACHE, FRANCE

Abstract — Résumé

CHANGES IN THE MOISTURE OF A SOIL CONTINUOUSLY IRRIGATED OVER A SMALL SURFACE.

The paper contains a description of water movements in the soil when the irrigated surface is restricted by a 40-cm-diam. hollow dug in the soil. Vertical and lateral water movements have been followed with a neutron-moisture meter designed for deep measurements.

Several tubes, 1 m apart and extending to a depth of 3 m, are placed in a brown, clay-limestone soil on the site of the Cadarache Nuclear Research Centre. The hollow is dug around the central tube and a constant water level maintained in it. Water profiles taken at regular intervals of time over a period of several months show the infiltration on the central tube and diffusion on the outer tubes.

On the central profile, the rate of advance of the infiltration front decreases with time. After some days, equilibrium is established between the water supply and the diffusion and evapotranspiration losses, and the soil moisture tends towards a constant value.

Examination of the other profiles indicates vertical and lateral water movements and gives qualitative and quantitative information on the volume of moistened soil and the moisture limit.

The phenomena observed can be explained by competition between gravity and suction forces and by the fact that the central profile, which is constantly under water, is not subject to evaporation, whereas in the others evaporation causes a rising movement of moisture.

These investigations form part of the studies on the radiological safety of sites, for which purpose it is important to know the water movements in the first few metres of soils likely to be contaminated by the spilling of radioactive liquids.

EVOLUTION DE L'HUMIDITÉ D'UN SOL SOUMIS A UN APPORT CONTINU D'EAU SUR UNE PETITE SURFACE. Cette étude présente une description des mouvements de l'eau dans un sol lorsque la surface arrosée est limitée par une une cuvette de 40 cm de diamètre creusée dans le sol. On a suivi les mouvements verticaux et latéraux de l'eau à l'aide d'un humidimètre à neutrons de profondeur.

Dans un sol brun argilo-calcaire, situé sur le site du Centre d'études nucléaires de Cadarache, plusieurs tubages ont été implantés : ils sont distants de 1 m les uns des autres et atteignent 3 m de profondeur. Autour du tube central est creusée la cuvette dans laquelle on maintient une charge constante d'eau. Les profils hydriques, relevés à intervalles de temps réguliers pendant une durée de plusieurs mois, permettent de suivre l'infiltration sur le tube central et la diffusion sur les tubes périphériques.

Dans les profils centraux, la vitesse d'avancement du front d'infiltration décroit avec le temps. Après un certain nombre de jours, un équilibre s'établit entre l'apport d'eau d'une part et les pertes par diffusion et évapotranspiration d'autre part ; l'humidité du sol tend vers une valeur constante.

L'examen des autres profils donne les mouvements d'eau verticaux et latéraux, la connaissance qualitative et quantitative du volume de sol mouillé et la limite d'humidification.

Les phénomènes observés peuvent être expliqués par la concurrence entre les forces de gravité et les forces de succion, ainsi que par le fait que le profil central, constamment sous l'eau, n'est pas soumis à l'évaporation, alors que dans les autres l'évaporation provoque un mouvement ascendant d'humidité.

Ces expériences se situent dans le cadre d'études de sûreté radiologique des sites ; dans ce domaine, il est important de connaître les mouvements de l'eau dans les premiers mètres de sols susceptibles d'être contaminés par un épanchement de liquides radioactifs.

I. INTRODUCTION

Dans un milieu poreux soumis à un apport d'eau affectant seulement une petite surface, l'humidité évolue dans un volume limité ; l'infiltration s'effectue alors sous l'influence principale de deux potentiels (forces de
gravité et forces de succion ou de capillarité) qui déterminent la forme du volume mouillé ainsi que la vitesse d'avancement du front d'humidité.

L'étude de ces phénomènes a été entreprise en laboratoire sur des milieux poreux de natures et de formes variées maintenus dans des modèles réduits.

Ce mémoire décrit des expériences effectuées sur le terrain où les mesures d'humidité n'ont pu être réalisées qu'au moyen de la méthode neutronique.

Dans le cadre des études de sûreté radiologique, ces expériences sont destinées à mettre au point un procédé pour évaluer l'enveloppe maximale de l'humidification après l'épandage accidentel d'une eau radioactive à la surface du sol.

II. DISPOSITIF EXPERIMENTAL

L'appareil de mesure utilisé est un humidimètre à neutrons de profondeur, du type HP 310 (source Am-Be), associé à un dispositif de comptage EC 310. Les expériences ont été conduites sur un terrain du Centre d'études nucléaires de Cadarache, dans un sol brun argilo-calcaire.

Une série de tubages ont été implantés. Ils sont distants de 1 m les uns des autres et atteignent 3,40 m de profondeur. A leur base, ils butent sur un conglomérat imperméable. Autour d'un tube (tube C) est creusée une cuvette de 5 cm de profondeur et de 6250 cm² de surface. Dans cette cuvette on maintient une hauteur constante d'eau de 5 cm, le débit d'alimentation étant égal au débit d'infiltration. Un tube témoin hors de portée d'influence de l'eau rejettée est destiné au contrôle de l'évolution de l'humidité naturelle sous l'influence de la pluviométrie.

III. MODE OPERATOIRE

Les profils hydriques sont mesurés sur le tube à cuvette (C) et sur les tubages périphériques P₁, P₂ et P₃ distants respectivement de 1, 2 et 3 m de C. On relève le profil hydrique sur chaque tube avant le rejet; après le début de l'arrosage, les mesures sont faites à intervalles de temps réguliers sur chaque tube; on obtient ainsi sur chaque profil l'évolution de l'humidité en fonction du temps (on désigne l'humidité volumique par Hᵥ et par Hₒ l'humidité volumique avant rejet).

Afin de mieux apprécier le mouvement de l'eau rejetée, on peut tracer les profils d'accroissement d'humidité volumique au lieu de les tracer en fonction de Hᵥ. De chaque profil hydrique Hᵥ au temps t on retrace la valeur Hₒ du profil initial avant arrosage et on établit les profils en fonction de Hᵥ - Hₒ (fig. 1 et 2).

L'apport d'eau a été continu pendant 150 j. Le débit de l'infiltration dans la cuvette est de 40 litres/j le premier jour, 30 litres/j jusqu'au dixième jour; il se stabilise ensuite à 25 litres/j jusqu'au 150° jour. Le débit de 25 litres/j correspond à la vitesse apparente d'infiltration de 4 cm/j (hauteur d'eau de la cuvette infiltrée en 1 j).
IV. EXAMEN DES PROFILS HYDRRIQUES DU TUBE CENTRAL

Les profils hydriques variant en fonction du temps ont été tracés sur un même graphique (fig.1). Sur la figure 2, on a tracé les profils d'accroissement d'humidité volumique $H_v - H_0$.

a) Valeur limite d'humidité

Les figures 1 et 2 montrent que l'eau ne se répartit pas uniformément dans le sol. Chaque profil possède une branche subverticale qui est super-...
posée à celle du profil précédent; à partir d'une certaine profondeur, ces courbes s'incurvent et chaque portion de courbe évolue parallèlement à la précédente.

Il s'établit un équilibre entre l'apport d'eau et les pertes par infiltration ou diffusion, l'eau commence à assurer la capacité de rétention du sol avant de progresser vers le bas.

Les branches verticales se situent autour de 28% en humidité volumique. Cette valeur correspond à la capacité de rétention du sol.

b) Vitesse d'avancement du front d'humidité

Les différents profils (fig. 2 et 3) ont tous des portions de courbes sensiblement parallèles qui correspondent au front d'humidité. Ces parallèles ne sont pas horizontales; compte tenu de la sphère d'influence neutronique, cela prouve l'existence d'un gradient d'humidité; il y a donc une frange capillaire en avant du front d'infiltration.

En mesurant l'intervalle entre ces parallèles au niveau du point d'inflexion, on obtient les valeurs de la vitesse d'avancement du front d'humidité. Ces diverses valeurs sont indiquées sur le tableau I. Les vitesses d'avancement diminuent avec le temps ou avec la profondeur. Le front s'est déplacé de 50 cm/j le premier jour, à partir du 50e jour (profondeur 180 cm) sa vitesse se stabilise à 1 cm/j.

Remarque. Dans le tableau I sont portées les valeurs du coefficient de perméabilité K établi en appliquant la loi de Darcy par la formule 

\[ Q = K S \text{ grad } P \]

Le gradient de pression est voisin de 1, Q est connu, 

\[ S = \pi R^2 + 2 \pi R h \] (R = rayon, h = hauteur d'eau dans la cuvette). On constate que K, très différent de la vitesse du front pendant les 30 premiers jours de l'expérience, est du même ordre de grandeur par la suite.
V. EXAMEN DES PROFILS PÉRIPHERIQUES

L’examen des profils périphériques permet d’évaluer les mouvements d’humidité à 1, 2 et 3 m du tube central. Les branches verticales à 28% en $H_v$ ne s’observent que sur les profils $P_1$ et seulement jusqu’à 100 cm de profondeur (fig. 3); sur les profils à 2 et 3 m, l’apport d’eau n’est pas suffisant pour assurer la capacité de rétention du sol (fig. 4).

On constate par ailleurs que les profils évoluent avec des pentes bien plus élevées que dans les profils $C$; les gradients d’humidité sont beaucoup plus faibles (0,05% $H_v$/cm).

Il convient de noter que le profil $C$ constamment sous l’eau n’est pas soumis à l’évaporation, alors que dans les profils $P$ l’évaporation provoque un mouvement ascendant de l’humidité.

VI. EVOLUTION DU VOLUME DE SOL MOUILLE


Les graphiques de volume après 4, 10, 20, 100 et 140 j sont représentés sur les figures 5 à 9.

Variation du volume mouillé en fonction du temps

Les coupes de volume mouillé établies après 4 et 10 j d’arrosage ont une forme sensiblement elliptique (fig. 5 et 6). On constate que la progression latérale de l’eau est importante, avec cependant un faible gradient d’humidité. L’infiltération le long du tube central est caractérisée par le réseau serré des courbes d’égal accroissement de $H_v$.

Le gradient d’humidité élevé dénote la présence d’un front d’humidité avec une frange de diffusion. Ce gradient d’humidité associé au front d’infiltération a la valeur $d(H_v - H_{v0})/dx = 0,2(H_v - H_{v0})$% /cm pendant toute la durée des 150 j de l’expérience. Le gradient d’humidité de la diffusion latérale est 20 fois plus faible.

A partir du 20e jour, l’expérience a été perturbée par des pluies abondantes; l’apport d’eau de pluie se répercute sur la construction des graphiques. On note donc sur le profil $H + 20$ que les courbes d’augmentation de $H_v$ sur les tubes $P + 2$ et $P + 3$ m sont sensiblement parallèles et correspondent à l’humidification par la pluie (pluies de 60 mm). Par la suite, les profils évoluent régulièrement mais la forme elliptique tend à disparaître.

Les gradients du front d’infiltération sur les profils $C$ et $P + 1$ sont sensiblement égaux; au-dessus du front, la variation d’humidité est plus faible, l’eau tend à remplir les pores du milieu.

Une faible partie de l’eau de rejet atteint le profil $P_3$ (analogie du profil $P_3$ et du profil terrain des eaux naturelles).

La partie inférieure accuse une augmentation de 2 à 4% de $H_v$ (sur la figure 10, le profil terrain à 100 j a été superposé au profil $P_3$).
<table>
<thead>
<tr>
<th>Profondeur du front d'humidité (cm)</th>
<th>Intervalle de temps écoulé (j)</th>
<th>Débit d'alimentation (litres)</th>
<th>Vitesse d'avancement du front (cm/j)</th>
<th>K (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 à 60</td>
<td>0 à 1</td>
<td>40</td>
<td>60</td>
<td>7 · 10⁻⁴</td>
</tr>
<tr>
<td>60 à 100</td>
<td>1 à 10</td>
<td>30</td>
<td>8,8</td>
<td>10⁻⁴</td>
</tr>
<tr>
<td>100 à 120</td>
<td>10 à 15</td>
<td>25</td>
<td>4,4</td>
<td>5,1 · 10⁻⁵</td>
</tr>
<tr>
<td>120 à 140</td>
<td>15 à 20</td>
<td>25</td>
<td>4,0</td>
<td>4,6 · 10⁻⁵</td>
</tr>
<tr>
<td>140 à 165</td>
<td>20 à 35</td>
<td>10 (gel)</td>
<td>1,5</td>
<td>1,7 · 10⁻⁵</td>
</tr>
<tr>
<td>165 à 180</td>
<td>35 à 50</td>
<td>20</td>
<td>1,2</td>
<td>1,4 · 10⁻⁵</td>
</tr>
<tr>
<td>180 à 200</td>
<td>50 à 65</td>
<td>25</td>
<td>1,1</td>
<td>1,3 · 10⁻⁴</td>
</tr>
<tr>
<td>200 à 230</td>
<td>65 à 100</td>
<td>25</td>
<td>1,0</td>
<td>1,15 · 10⁻⁵</td>
</tr>
<tr>
<td>230 à 255</td>
<td>100 à 140</td>
<td>25</td>
<td>1,0</td>
<td>1,15 · 10⁻⁵</td>
</tr>
</tbody>
</table>

**TABLEAU I. VITESSE D'AVANCEMENT DU FRONT D'HUMIDITE EN FONCTION DU TEMPS ET DE LA PROFONDEUR**
VII. AVANCEMENT DE LA LIMITE D'HUMIDIFICATION

Les profils hydriques et les graphiques permettent de déterminer la limite d'humidification en profondeur; ces valeurs sont résumées dans le tableau II.

Latéralement, la limite d'humidification ne peut être repérée avec précision, car l'apport de la pluie a masqué les faibles augmentations d'humidité; toutefois, en comparant les profils P₃ au profil témoin, on peut déduire que la limite de l'apport latéral d'eau se situe entre 3 et 4 m du profil C.
VIII. REJETS LIMITES D'EAU SUR UNE PETITE SURFACE

Ces expériences ont été menées dans un but pratique afin de mesurer la profondeur maximale atteinte par l'eau après un rejet instantané sur une petite surface. Comme dans l'expérience précédente, l'eau a été versée dans une cuvette creusée autour du tube de forage afin d'éviter le ruissellement. La quantité rejetée est évaluée en hauteur d'eau, compte tenu de la surface de la cuvette. Les hauteurs d'eau versée ont varié de 4 à 20 cm.

Dans chaque essai, la limite atteinte par l'infiltration ne dépasse pas la profondeur de 60 cm, seule varie l'augmentation de $H_0$; d'autre part,
FIG. 8. Courbes d'égal accroissement d'humidité après 100 j de rejet.

FIG. 9. Courbes d'égal accroissement d'humidité après 140 j de rejet.

L'eau n'a jamais atteint les tubes voisins situés à 1 m du tube axé sur la cuvette.

IX. CONCLUSION

Les résultats que nous venons d'exposer sont un nouvel exemple de l'intérêt de la méthode neutronique pour les mesures de l'humidité dans le sol.

Les expériences décrites n'auraient pu être réalisées par d'autres méthodes non nucléaires; seul l'humidimètre à neutrons, qui peut effectuer
TABLEAU II. PROFONDEUR LIMITE DE L'HUMIDIFICATION EN FONCTION DU TEMPS

<table>
<thead>
<tr>
<th>Temps (j)</th>
<th>Profondeur limite d'humidification (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
</tr>
<tr>
<td>4</td>
<td>140</td>
</tr>
<tr>
<td>10</td>
<td>140</td>
</tr>
<tr>
<td>20</td>
<td>190</td>
</tr>
<tr>
<td>50</td>
<td>230</td>
</tr>
<tr>
<td>100</td>
<td>340</td>
</tr>
<tr>
<td>120</td>
<td>&lt;340</td>
</tr>
<tr>
<td>140</td>
<td>&lt;340</td>
</tr>
</tbody>
</table>

Les mesures non destructives répétées dans le temps au même endroit, permet l'étude efficace du mouvement de l'eau dans le sol. Les mesures sont aisées, rapides et précises car les causes d'erreurs dues aux petites hétérogénéités du sol sont réduites. Enfin, l'appareil est particulièrement fidèle; dans un milieu qui n'évolue pas, les mesures sont parfaitement reproduites; on peut ainsi déceler avec précision de faibles variations d'humidité.

L'humidimètre à neutrons est donc particulièrement bien adapté aux études que nous poursuivons sur l'évolution de l'humidité dans le sol.
REMERCIEMENTS

Nous tenons à remercier le Service de radio-agronomie du Centre d'études nucléaires de Cadarache, et spécialement M. J. Marcesse pour les conseils qu'il a bien voulu nous donner au sujet de l'utilisation de l'humidimètre à neutrons.

DISCUSSION

H. KICK: You point out in your paper that Cadarache has an undifferentiated, brown, chalky soil. Did you analyze grain size?

D. RANÇON: We analysed the grain size of the soil with which we were working, in addition to making chemical and mineralogical analyses. I have not got the results here, but can send them to you if you so wish.

F. GERA: Do you know the permeability of the soil used in your experiments?

D. RANÇON: Permeability measurements carried out in the laboratory with a saturated medium gave K values varying around $10^{-5}$ cm/s. We plan to make more detailed measurements in the laboratory, to supplement the field trials and obtain permeability values for non-saturated media.
DETERMINATION IN SITU DE LA CAPACITÉ DE RETENTION D'UN SOL AU MOYEN DE L'HUMIDIMÈTRE À NEUTRONS

J. MARCESSE
CEA, CENTRE D'ETUDES NUCLEAIRES DE CADARACHE, FRANCE

Abstract — Résumé

DETERMINATION IN SITU DETERMINATION OF SOIL-RETENTION CAPACITY, USING A NEUTRON-MOISTURE METER.
The neutron-moisture meter provides a means of making in-situ measurements of soil-water reserves to ± 1%, and of carrying out repeated and non-destructive measurements at a given point. These advantages are exploited in a study of the development of the water profile in homogenous ground after irrigation.

The results provide a clear interpretation of the phenomenon of drying. Analysis of water movement as a function of time at a given level demonstrates the existence of two exponential kinetic processes. One is associated with rapid run-off by gravity and the other, which is much slower, reflects the capillary forces and tends towards equilibrium which, in the work to which this paper relates, occurred at about zero. From this the author deduces a value for the retention capacity, considered as the amount of soil moisture causing the slow kinetic process. This value corresponds quite well to the generally accepted definition for retention capacity, i.e. the maximum level of moisture causing only a slow infiltration or, from an agronomical point of view, the maximum volume of water which can be stored in the soil and which is available to plants. This method has the advantage of not involving a pre-determined value for capillary potential and of taking the structure of the soil into account.

By making similar calculations at each depth, the author constructs a profile for retention capacity, which can be used at any time to estimate a moisture deficit or the amount of irrigation required.

DETERMINATION IN SITU DE LA CAPACITÉ DE RETENTION D'UN SOL AU MOYEN DE L'HUMIDIMÈTRE À NEUTRONS. L'humidimètre à neutrons offre la possibilité de déterminer in situ, à 1 point, les teneurs en eau volumique des sols et de réaliser en un même lieu des mesures répétées et non-destructives. Ces avantages sont mis à profit dans l'étude de l'évolution du profil hydrique d'un terrain homogène après apport d'une dose d'arrosage.

Les résultats obtenus traduisent clairement le phénomène du resserrement. À un niveau donné l'analyse du mouvement de l'eau en fonction du temps fait apparaître la superposition de deux cinétiques de forme exponentielle. La première est liée à l'écoulement rapide par gravité. La seconde, beaucoup plus lente, rend compte des forces capillaires et tend vers un équilibre qui, dans le cas de l'expérimentation, se situe au volatilage de zéro. On en déduit une mesure de la capacité de rétention, considérée comme le taux d'humidité volumique du sol à l'origine de la cinétique lente. Cette valeur répond bien à la définition généralement admise pour la capacité de rétention, à savoir le taux d'humidité maximal s'entraînant qu'une cinétique d'infiltration lente ou bien, au point de vue agronomique, la limite supérieure du volume d'eau pouvant être mis en réserve dans le sol et utilisable par les plantes. Cette méthode présente l'intérêt de ne pas utiliser une valeur prédéterminée du potentiel capillaire et de tenir compte de l'état structural du sol.

En effectuant des calculs analogues à chaque niveau de profondeur, on construit le profil à la capacité de rétention, dont la connaissance permet à tout moment d'évaluer un déficit en eau ou une dose d'arrosage.

1. Introduction

Les diverses méthodes de détermination en laboratoire de la capacité de rétention d'un sol se heurtent à certaines difficultés qui rendent les résultats imprécis. La structure du sol est le plus souvent détruite au cours des essais et il existe en général une incertitude sur la valeur de la force de succion à laquelle doit être soumis l'échantillon. Une nouvelle façon d'aborder le problème consiste à tirer parti des qualités de l'humidimètre à neutrons de profondeur, appareil qui permet de suivre en un même
lieu et avec une précision supérieure à 1 point d'humidité volumique l'évolution du profil hydrique. La méthode est fondée sur l'analyse in situ de la cinétique de l'eau au cours d'un ressuyage après apport d'une dose d'arrosage sur un sol qui est au départ relativement sec et bien drainé.

2. Expérimentation

Un tubage (Ø 41-45 mm) de 2,5 m est mis en place verticalement dans le sol à proximité d'un arroseur. La sonde de l'humidimètre à neutrons\(^1\) est introduite jusqu'au fond du tubage où a lieu une première mesure. Elle est ensuite remontée de 10 en 10 cm jusqu'à 20 cm de la surface. Chaque arrêt de 1 à 3 minutes est l'occasion d'une lecture sur l'échelle de comptage ou sur l'intégrateur. Les résultats sont ensuite traduits en humidité volumique à partir de la courbe d'étalonnage spécifique du sol considéré. L'ensemble des valeurs obtenues permet d'établir un profil hydrique.

![Diagram](figure1.png)

**FIG.1.** Evolution des profils neutériques pendant la première expérimentation (août).

\(^1\) Type HP 110 CGEI-LEPAUTE.
Le terrain de Cadarache est un sol brun calcaire non différencié, limono-sableux de densité sèche moyenne 1,6. L'humidité équivalente, exprimée en eau résiduelle après centrifugation à 1000 g, se situe vers 17%.

Deux expérimentations ont été réalisées, l'une au mois d'aôut avec une dose d'arrosage de 226 mm en 20 h, l'autre en novembre avec apport de 93 mm d'eau. Quelques uns des profils successivement relevés dans le temps sont représentés sur les figures 1 et 2.

FIG. 2. Évolution des profils neutroniques pendant la deuxième expérimentation (novembre).

3. Capacité de rétention

Un rapide examen des profils montre que dans les horizons supérieurs fortement réhumectés le taux d'humidité décroît très rapidement pendant les premières heures puis évolue beaucoup plus lentement jusqu'à tendre vers une valeur d'équilibre. On retrouve ainsi deux cinétiques de l'eau bien connues qui correspondent à l'intervention, pour la première des forces de gravité, pour la seconde des forces capillaires.
La courbe $H = f(t)$, où $H$ est l'humidité volumique et $t$ le temps, peut être tracée pour chaque horizon à partir des données expérimentales et montre bien ce phénomène (figure 3). L'analyse est facilitée lorsqu'on exprime les résultats en coordonnées semi-logarithmiques (figure 4).
Au bout de quelques jours les points représentatifs de la courbe sont alignés, ce qui implique une décroissance exponentielle de la teneur en eau vers une valeur d'équilibre voisine de zéro. L'évolution est de type $H_v = H_0 e^{-\lambda_2 t}$, où $H_2$ représente le taux d'humidité à l'origine et $\lambda_2$ la constante de ressuyage. En prolongeant la droite vers l'origine et en portant graphiquement les écarts avec la courbe initiale on obtient une seconde droite correspondant à l'équation $H_v = H_1 e^{-\lambda_1 t}$. Ce traitement classique montre que, pendant la période qui suit de quelques heures à une quinzaine de jours l'arrêt de l'irrigation, le processus de ressuyage est la juxtaposition de deux cinétiques de forme exponentielle, chacune d'elles correspondant à un compartiment d'eau différent.

Par analogie avec le phénomène de décroissance d'une source radioactive on caractérise chaque droite, c'est-à-dire chaque cinétique de ressuyage par sa période $T_1$, celle-ci étant définie comme le temps nécessaire pour que la quantité d'eau d'un compartiment donné diminue de moitié. A la profondeur de 1 m on relève les valeurs suivantes : $T_1 = 0,4$ jour pour la cinétique rapide, $T_2 = 100$ jours pour la cinétique lente. Ainsi la moitié de l'eau du premier compartiment aura disparu au bout de 0,4 jour et pratiquement il ne subsistera que $3\%$ de la quantité initiale après 5 périodes c'est-à-dire 48 h. Les équations des 2 droites sont $H_v = 4,6 e^{-1,6 t}$ et $H_v = 29,7 e^{-0,10 t}$ ce qui donne pour la valeur initiale des deux compartiments d'eau : $H_1 = 4,6\%$, $H_2 = 29,7\%$.

Nous proposons d'identifier la capacité de rétention à la valeur du compartiment d'eau correspondant à la cinétique lente définie par l'ordonnée à l'origine de la seconde droite (soit 29,7\% dans l'exemple précédent).

Cette valeur répond bien à la définition qui est le plus généralement admise de la capacité de rétention à savoir : les taux d'humidité maximaux n'entraînant qu'un mouvement d'infiltration lent, ou bien, vue sous l'angle agronomique, la limite supérieure du volume d'eau pouvant être mis en réserve dans le sol et utilisable avec profit par les plantes.

Pour chaque horizon, dans la mesure où il a été fortement mouillé, on peut tracer la courbe $H_v = f(t)$, construire la droite $\lambda_2$ représentant la cinétique lente et définir graphiquement la capacité de rétention. Les tableaux ci-après donnent pour les deux expérimentations la valeur des périodes de ressuyage $T_1$ et $T_2$ ainsi que la capacité de rétention.

Les périodes $T_2$, variables suivant la profondeur, témoignent d'une certaine hétérogénéité du sol; de plus aux horizons proches de la surface (-29 et -39 cm) les faibles valeurs obtenues sur la première expérimentation qui a eu lieu au mois d'août sont consécutives au phénomène d'évaporation. Il est intéressant de constater que les variations de $T_1$ et $T_2$ ont peu d'incidence sur la valeur de la capacité de rétention.

Compte tenu de la durée des observations limitées à une quinzaine de jours et de la précision des mesures il est difficile d'analyser avec exactitude la phase "cinétique lente". On pourra dans certains cas mettre en évidence une valeur d'équilibre $H_2$ groupant les mouvements d'eau, sous forme de liquide.
<table>
<thead>
<tr>
<th>Periodes (mm)</th>
<th>$T_{1}$ exp.</th>
<th>$T_{1}$ exp.</th>
<th>$T_{1}$ exp.</th>
<th>$T_{1}$ exp.</th>
<th>$T_{2}$ exp.</th>
<th>$T_{2}$ exp.</th>
<th>$T_{2}$ exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>29</td>
<td>0.4</td>
<td>0.4</td>
<td>25</td>
<td>86</td>
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<td>108</td>
<td>119</td>
</tr>
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<td>99</td>
<td>99</td>
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<td>100</td>
</tr>
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<td>0.6</td>
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<td>99</td>
<td>99</td>
<td>99</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>69</td>
<td>0.6</td>
<td>0.6</td>
<td>99</td>
<td>99</td>
<td>99</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Profondeur (cm)</td>
<td>29</td>
<td>39</td>
<td>49</td>
<td>59</td>
<td>69</td>
<td>79</td>
<td>89</td>
</tr>
<tr>
<td>---------------</td>
<td>----</td>
<td>----</td>
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<td>----</td>
<td>----</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>1&lt;sup&gt;ère&lt;/sup&gt; exp.</td>
<td>30</td>
<td>30,8</td>
<td>30,2</td>
<td>30,6</td>
<td>31,2</td>
<td>31,6</td>
<td>30,8</td>
</tr>
<tr>
<td>2&lt;sup&gt;ème&lt;/sup&gt; exp.</td>
<td>31,1</td>
<td>31,7</td>
<td>31,1</td>
<td>31,3</td>
<td>31,5</td>
<td>31,5</td>
<td>31,4</td>
</tr>
<tr>
<td>A</td>
<td>30</td>
<td>31,5</td>
<td>32</td>
<td>31,7</td>
<td>31,8</td>
<td>32,0</td>
<td>31,4</td>
</tr>
</tbody>
</table>
ou de vapeur, extrêmement lents. De toute façon la capacité de rétention restera définie comme la somme des compartiments d'eau caractérisés par une cinétique lente.

Remarques : D'une façon générale les profils hydriques évoluent parallèlement à eux-mêmes en fonction du temps dans la zone située au-dessus du front d'infiltration initial. Cette constation est normale dans le cas d'un sol homogène fortement et uniformément humidifié et semble prouver que le ressuyage de chaque horizon de sol s'effectue indépendamment des apports d'eau qui lui parviennent des couches voisines en cours d'assèchement.

Dans le cas fréquent de sols à horizons pédologiques différenciés les valeurs de la capacité de rétention mesurées à chaque niveau risquent d'être très différentes de celles qui seraient théoriquement obtenues en milieu homogène. Ainsi une couche perméable aura une capacité de rétention plus ou moins élevée si elle est au-dessus d'une assise plus ou moins imperméable. Dans ce cas la méthode neutronique aura l'intérêt de rendre compte des conditions réelles de rétention de l'eau des sols dans leur contexte naturel.

Enfin deux améliorations concernant la conduite des expérimentations doivent être signalées. La première consiste à protéger la surface du sol pour limiter le déséchement par évaporation et éviter les apports pluviométriques. La seconde consiste à utiliser un réflecteur neutronique pour effectuer des mesures correctes de l'humidité au voisinage de la surface (profondeur 10 à 20 cm).

4. Conclusion

L'obtention en champ du profil à la capacité de rétention présente un intérêt indéniable dans l'évaluation des réserves hydriques et la conduite des irrigations. L'agronome peut décider, à tout moment, de l'opportunité de déclencher un arrosage et déterminer la dose à apporter. Il lui suffit pour cela de ramener le profil hydrique du sol jugé trop sec au profil correspondant à la capacité de rétention jugée idéal jusqu'à une profondeur donnée. Le calcul est à la fois simple, car la mesure donne directement l'humidité volumique, et précis, puisque l'on compare des profils hydriques en un même lieu et que l'on s'assurant des erreurs dues à l'hétérogénéité du sol.

DISCUSSION

H.W. SCHARPENSEELE: Measurements of downward water flow in the profile with the neutron probe, as demonstrated in this and foregoing papers, disclosed a fairly fast and intensive dispersion of the administered water within the profile. This conflicts with the package-like water migration model which was established by the Heidelberg group (Münich and co-workers) on the basis of tritium studies of water flow.

M.J. FRISSEL: The differences in water dispersion may be explained by the following equation:

\[ D_{\text{apparent}} = D_{\text{water}} \times (\gamma + \lambda d_{\text{w}}) \]
where:
\[ \gamma = \text{Tortuosity factor} \]
\[ \lambda = \text{Packing factor} \]
\[ u_w = \text{Interstitial water velocity} \]
\[ d = \text{Diameter of the grains} \]

The influence of the factor \( u_w \) (which is usually much higher in laboratory experiments than in the field) results in different apparent diffusion coefficients and thus in a different picture of water dispersion, even when all other conditions are the same.

U. Zimmermann: There is in my view no discrepancy between the measurements made by Mr. Marcesse, showing an increase in water content at a relatively great depth shortly after a fairly long irrigation period, and the hypothesis of layered water movement in soils, which can be checked by tritium tracer experiments. If a tracer is pushed down relatively quickly into an unsaturated soil over a fairly long irrigation period, the water in the soil layer directly below the tracer front is pushed into the next layer, thus producing a higher water content there, etc.

W. R. Gardner: Apart from this, I think there are two different questions involved here. Dispersion involves the distribution and movement of small packets of water. This depends, as pointed out by Frissel, on velocity distribution on a microscopic scale. Studies such as those of Marcesse cover only gross features of water movement and average velocities.

P. Rod: Could you give some additional information on the neutron reflector to which you referred in the discussion of Mr. Hajdukovic’s paper?

J. Marcesse: When the moisture depth probe is near the surface, neutrons escape into the atmosphere, causing faulty measurement. By placing a material of specially chosen shape and type on the soil surface, the measurement can be converted to that which would be obtained if the medium were infinite. The neutron reflector developed is shown in Fig. 1, and consists of a spherical, polyethylene cap weighing about 1.1 kg. This permits measurements from the required depth up to 10 cm from the surface. At this level, the deviation from a measurement made in an infinite medium does not exceed ±1% humidity by volume. Most workers using the neutron probe in France now employ this neutron reflector. Fuller details can be found in «Emploi d’un réflecteur neutronique, associé à un humidimètre de profondeur pour la mesure de l’humidité au voisinage de la surface des sols», by P. Moutonnet, L. Buscarlet and J. Marcesse, in Annales des Bâtiments et des Travaux Publics, June 1967.
M. DE BOODT: Could reflection be improved by using graphite or iron, rather than polyethylene?

J. MARCESSE: Such a large quantity of graphite or iron would be needed in the reflector that the method would be very difficult to apply in agriculture. Instead of using a simple reflector, we attempted to use a hydrogenous body to serve both as neutron reflector and thermalizer. This gives maximum efficiency for minimum weight and bulk.

Y. BARRADA: Would use of the reflector permit accurate measurements of soil moisture at 10 cm from the surface, independently of the moisture content? Is it possible to over-correct the measurement at low moisture contents?

J. MARCESSE: The neutron reflector permits valid measurements at a depth of 10 cm, whatever the soil moisture. The maximum error involved does not exceed 1% of absolute moisture. However, it must be pointed out that an absolute error of 1% corresponds to an increasingly large relative error as the moisture level drops.

W. K. G. KÜHN: You have mentioned an artificial moderator of a special form, used above the ground to produce an infinite volume near the soil surface. However, such moderators should be compared with soil of the same form, to determine the ratio of both. I think there is no advantage in using moderators for this purpose because they have a constant concentration of atoms which merely increase the intensity of the thermal neutrons.

J. MARCESSE: We were not, in fact, attempting to reproduce an infinite soil medium, but simply to compensate for the drop in the thermal flux due to the surface effect.
DETERMINATION OF SOIL-MOISTURE CHARACTERISTICS FOR IRRIGATION PURPOSES BY NEUTRON-MOISTURE METER AND AIR-PURGED TENSIOMETERS

M. DE BOODT, R. HARTMANN AND P. DE MEESTER
STATE FACULTY OF AGRICULTURAL SCIENCES,
GHENT,
BELGIUM

Abstract

DETERMINATION OF SOIL-MOISTURE CHARACTERISTICS FOR IRRIGATION PURPOSES BY NEUTRON-MOISTURE METER AND AIR-PURGED TENSIOMETERS. Soil-moisture characteristics such as moisture content and capillary conductivity are of the greatest importance for working out a rational system to irrigate land. To realize such a system the following data must be known: (1) how much water leaves the soil profile at a given period of time; and (2) in what direction. Up to now the first point could only be assessed in a non-destructive way by using a lysimeter and assuming that the soil in it is exactly the same and behaves similarly to the soil that is to be irrigated.

The second point can be solved by putting a series of tensiometers in the profile and comparing the total water potential at different depths. Here the problem is to operate the tensiometers so that the true potential is measured; this means that a special device on the tensiometer must be present to purge the water in the cup and in the manometer of air each time a reading is carried out. By combining the data of the two instruments mentioned above, the capillary conductivity can be calculated by using Darcy's law.

When the moisture content, the moisture tension, the direction of the moisture gradient and the capillary conductivity are known, the infiltration rate and the depth that the water front will reach can be predicted when irrigating a given soil with a certain quantity of water. Hence the exact amount of water needed can be calculated to ensure also, on one hand, that no water except the quantity needed to wash out the salts is wasted in the subsoil and, on the other hand, that enough water is given to reach the active-root zone of the plants. Valuable data on the amount of water leaving the soil can be obtained by the neutron-moisture meter, and a comparison is made between these data and the actual evaporation calculated by Penman.

A detailed scheme is also presented on how to rebuild the classical tensiometers to satisfy the requirements stated above.

A. INTRODUCTION

Efficiency of water use in irrigation practice can be studied when the water-balance of a soil profile under changing climatic conditions at any desired spot for practically any crop has been established.

The study of the water balance in the soil consists of calculating the amounts of water entering and leaving the soil profile, taking into account the possible change in the moisture content of the profile itself.

Up to now this study is practically only possible on disturbed soil masses, which is certainly not ideal. The present procedure consists of placing a reconstructed soil profile in a relatively large container provided with a drainage-tube system and resting on a precise weighing device that allows continuous readings. This is the study of the water-balance by means of a lysimeter.
Another disadvantage of this method is that the lysimeter is not readily movable. In practice it is located on a well-defined spot, mostly in the middle of a grass-plot, which is not typical of a region for arable crops.

Water-balance studies are of the utmost importance in order to understand better the water requirements of crops under given climatological conditions and soil types. To be able to abandon results of experience in irrigation practices, readily performable water-balance studies on representative spots with low prices for equipment and manpower are imperative.

This paper examines the extent, at the present state of technical development, to which the combined use of a neutron-moisture meter and air-purged tensiometer can obtain the required results.

B. THE BASIC EQUATION

A water-balance study of the soil profile supposes that the following equation can be solved numerically:

\[ R + C + M_1 = E + D + M_2 \]

- \( R \) = rainfall
- \( C \) = capillary rise
- \( M_1 \) = initial moisture content
- \( E \) = actual evapotranspiration
- \( D \) = percolation
- \( M_2 \) = final moisture content after a given considered period

Of these six items the rainfall and the actual evapotranspiration can be measured by instruments normally present at an agro-meteorological station. The rainfall gauges are cheap but the other instruments are more expensive and call for constant care and observation. The initial and final moisture content of the profile can be determined either by the neutron-moisture meter or by taking samples at regular profile depths and determining the moisture content gravimetrically after drying at 105°C.

The capillary rise of the water from, and the percolation to, the water-table must be assessed by using two independent measurements of (a) the moisture content, and (b) the hydraulic gradient, both at the same point at a given time interval.

C. EXPERIMENTAL

At the agro-meteorological station of the soil-structure research centre (Director Prof. Dr. L. De Leenheer) a 2 × 2 × 2-m weighable lysimeter on a metal bolster was installed. The rainfall was measured by using the standard rainfall gauge of the Royal Meteorological Institute (Ukkel) and was placed 0.5 m above the soil. The evaporation from a free-water surface was calculated by using the Penman formula. The following data were determined: the solar radiation by the Campbell-Stokes sunshine recorder; the average air-temperature \( T_a \) with three daily readings at a 1.5-m height; the dew point \( T_d \) using the wet-bulb
thermometer; and the wind speed with an anemometer at a 2-m height. The \( E_0 \) is calculated by the McCulloch tables (1965) in which a 5% reflection coefficient is supposed. Therefore \( E_1 \) is obtained by multiplying \( E_0 \) by 0.86.

1. Measurement of the soil-moisture content with the neutron-moisture meter

The moisture contents at different depths and times were determined with the Berthold gamma and neutron apparatus. All readings on the integrator type of scaler were expressed as a relative value versus the standard number of counts in the shield, which was 225 cps. Then the moisture content was deduced from the calibration curve. The error on these readings was estimated as follows:

The needle moved continuously around an average but unknown value. Within 30 s the drift of the needle was \( \pm 10 \) cps. By running duplicates the reproducibility also varied by \( \pm 10 \) cps. The possible error by reading the reference value in the shield was \( \pm 5 \) cps.

The calibration curve was established by taking samples from a profile located in the vicinity of the point where the actual readings were made by applying the following procedure. First an access tube was put in place and the whole profile was scanned with a gamma density probe and the neutron-moisture meter. Then a profile pit was dug. At each 20 cm (not on the limit of two horizons) six moisture samples were taken. For a 1-m depth it was possible to establish a calibration curve with five points in the wet section and one point in the dry section of the profile. Through these six points, it was possible to draw a straight line. This procedure was repeated at dryer or wetter moisture contents until 18 or 24 points were disposed of so as to draw the definite calibration curve in relation to the bulk density of the soil.

The error of a soil-moisture determination using the neutron probe was estimated from the above data as being \( \pm 10 \) cps for the neutron-moisture readings, and \( \pm 0.5\% \) for the determination of the gravimetrical moisture content to establish the calibration curve. As the slope of the calibration curve was such that 10 cps = 0.5\% the total error was evaluated at \( \pm 0.5\% + 0.5\% = \pm 1\% \). Although the principle was accepted that the

![FIG.1. Tensiometer showing the height of the pressure needed to calculate the pressure in the cup.](image-url)
precision of the neutron-moisture meter method was better than the classical moisture determination (oven-dry samples), it was noted that this was only true when the calibration curve was considered as being established without errors. However, as the only interest was in measuring moisture differences the error on the calibration curve might be neglected so that the final error amounts to ± 0.5%.

(2) The capillary rise and the percolation

In taking into account the moisture content and the moisture tension at different profile depths it is possible to calculate the capillary conductivity using Darcy's law

\[ K = -v \frac{dx}{dP^o} \]

- \( K \) = capillary conductivity
- \( v \) = amount of water passing through a unit surface perpendicular to the direction of the flow per unit time
- \( x \) = distance
- \( P^o \) = hydraulic potential

Using the hydraulic potential profile as established by means of tensiometer readings and gravimetrical determinations it was possible to indicate the direction that the water moves. The amount of water \( v \) was obtained by using a graph on which the different moisture profiles were drawn as a function of the depth at varying times. From the integration of the surface between the moisture profiles at two points located at a distance \( x \), \( v \) was obtained. \( P^o \) was obtained from the manometer readings of the tensiometers taking into account the possible capillary depression when a mercury manometer is used, and the siphon pressure.

Direction of the water movement

The moisture tension profiles were first established on graphs by calculating the real water pressure at the height of the porous cup. This was done by the following means (see Fig. 1):

\[ P_{cup} + P_{siphon} = P_{manometer} \]
\[ P_{siphon} = -(H + h)_{(cm \ H_2O)} \]
\[ P_{manometer} = -13.6 \ h_{(cm \ H_2O)} \]
\[ P_{cup} = -h_{(cm \ H_2O)}^{13.6} + (H - h)_{(cm \ H_2O)} \]
\[ P_{cup} = -(13.6 - 1)h_{(cm \ H_2O)} + H_{(cm \ H_2O)} \]
\[ P_{cup} = -12.6 \ h_{(cm \ H_2O)} + H_{(cm \ H_2O)} \]
\[ P_{cup} = H - 12.6 \ h_{(cm \ H_2O)} \]
A practical example based on the data given in Table I is given in Fig. 2. The water-flow direction in the profile on the two dates mentioned in Table I is inferred from Fig. 2 on which the two hydraulic potential profiles are drawn. From Fig. 2 it is obvious that, on 28 May, the hydraulic potential $P^*$ increased from $-17.8$ through $-14.5$ to $-12.1$ cm Hg for depths of 15, 30 and 45 cm respectively.

As the latter value is the highest, the water moves from there to the soil surface. At the same time this $-12.1$ cm Hg pressure is also the highest value when the lower part of the profile is considered. Consequently from this point at a 45-cm depth, the moisture also moves downwards.

This hydraulic potential curve changes after 15 d to the second curve on the Fig. 2. There the highest potential is found at a 60-cm depth. From this point the moisture will move partly upwards and partly downwards.

This can be put in another way. On the first and second hydraulic potential curve a tangent at 45- and 60-cm depths respectively can be drawn parallel to the $h$-axis. At that depth no water movement will

### TABLE I. CALCULATION OF THE HYDRAULIC POTENTIAL $P^*$ AT DIFFERENT PROFILE DEPTHS USING TENSIOMETER READINGS TO ESTABLISH MOISTURE TENSION PROFILES (see Fig. 2)

(Observation dates, 28 May and 11 June 1966)

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Manometer readings (cm Hg)</th>
<th>Corrected reading for capillary depression (0.6 cm)</th>
<th>Correction due to siphon pressure</th>
<th>Corrected hydraulic potential $P^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>28 May</td>
<td>11 June</td>
<td>28 May</td>
<td>11 June</td>
</tr>
<tr>
<td>15</td>
<td>18.6</td>
<td>62.0</td>
<td>19.2</td>
<td>-</td>
</tr>
<tr>
<td>30</td>
<td>15.0</td>
<td>46.6</td>
<td>15.6</td>
<td>47.2</td>
</tr>
<tr>
<td>45</td>
<td>12.4</td>
<td>30.2</td>
<td>13.0</td>
<td>30.8</td>
</tr>
<tr>
<td>60</td>
<td>13.4</td>
<td>22.0</td>
<td>14.0</td>
<td>22.6</td>
</tr>
<tr>
<td>70</td>
<td>15.5</td>
<td>22.6</td>
<td>16.1</td>
<td>23.2</td>
</tr>
<tr>
<td>110</td>
<td>20.5</td>
<td>23.4</td>
<td>20.6</td>
<td>24.0</td>
</tr>
<tr>
<td>140</td>
<td>23.2</td>
<td>26.7</td>
<td>23.8</td>
<td>27.3</td>
</tr>
<tr>
<td>170</td>
<td>27.2</td>
<td>28.9</td>
<td>27.8</td>
<td>29.5</td>
</tr>
</tbody>
</table>

$a$ The hydraulic potential $P^* = P_{cup} + P_{gravimetric}$. In a tensiometer $P_{cup} = H - 12.6 h$(cm Hg) but expressed in negative pressure as the reference level is at the soil surface.

So, $P_{cup} = -H + 12.6 h = P_{gravimetric} +$ manometer reading corrected for siphon pressure $P^*$ siphon.

Thus $P^* = P_{gravimetric} + P_{corrected} = P_{gravimetric} + P_{corrected}$ for siphon pressure $P^*$ for siphon pressure

As the salt content in the soil is very low, the osmotic pressure is negligible.
occur as $\frac{dP^a}{dh} = 0$. There is an upward water movement when $\frac{dP^a}{dh} > 0$ and a downward water movement when $\frac{dP^a}{dh} < 0$. To enable such curves to be established it must be certain that the tensiometers are working properly. Apart from comments made by Haise and Kelley [1] and Gardner [2] concerning temperature influence and the characteristics of the cups and the surrounding soil, a major source of error might be due to the presence of air in the manometer. Therefore, the manometer must be purged at regular intervals (a few days up to a week). In Fig. 3 such a tensiometer is drawn. To eliminate the air between the cup and the air valve on one hand, and between the air valve and the mercury on the other, a suction and a pressure hand-pump are needed. These items are also shown on Fig. 2.

(3) The percolation rate

To know the amount of water that moves at a given depth in a given direction an analysis of two successive moisture-content curves is
necessary, together with an analysis of the hydraulic potential curves already mentioned. The direction of the water movement is already known. The inversion of the direction of water movement starts at the plane where $dP_0/dh = 0$, i.e., where no water movement will occur. As the two curves show two different planes where $dP_0/dh = 0$, an average value must be detected that is valid for both curves. The average hydraulic potential curve must be drawn (see Fig. 3). Therefore, the mean hydraulic potential for each depth is calculated as shown in the first column of Table II. These values were put on a graph and through these points a fluent curve was drawn. The point $dP_0/dh = 0$ was determined. This can also be done graphically by detecting the place where a tangent on the curve is parallel to the $h$-axis. In Fig. 3 this point happens to be located at a 60-cm depth.
TABLE II. THE CALCULATION OF THE HYDRAULIC CONDUCTIVITY AS BASED ON HYDRAULIC POTENTIAL AND MOISTURE-CONTENT DATA FOR THE PERIOD 28 MAY–11 JUNE 1966

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Average hydraulic potential $p^*$ (cm Hg)</th>
<th>Hydraulic gradient $\Delta p^*/\Delta h$ (cm Hg/cm)</th>
<th>Moisture moved per layer $(\text{mm H}_{2}\text{O}/15 \text{d})$</th>
<th>Moisture moved per day $(\text{mm H}_{2}\text{O}/\text{d})$</th>
<th>Hydraulic conductivity $K = -\nu(dp^*/dh)$ $(\text{mm/d})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>30</td>
<td>20.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>45</td>
<td>20.3</td>
<td>-7.97</td>
<td>3.30</td>
<td>0.32</td>
<td>0.07</td>
</tr>
<tr>
<td>60</td>
<td>17.0</td>
<td>-2.99</td>
<td>3.90</td>
<td>0.27</td>
<td>0.06</td>
</tr>
<tr>
<td>80</td>
<td>16.2</td>
<td>+0.81</td>
<td>-1.40</td>
<td>-0.10</td>
<td>0.07</td>
</tr>
<tr>
<td>120</td>
<td>20.7</td>
<td>+1.13</td>
<td>-3.30</td>
<td>-0.23</td>
<td>0.07</td>
</tr>
<tr>
<td>140</td>
<td>23.7</td>
<td>+1.36</td>
<td>-3.00</td>
<td>-0.21</td>
<td>0.07</td>
</tr>
<tr>
<td>170</td>
<td>26.6</td>
<td>+1.31</td>
<td>-4.20</td>
<td>-0.30</td>
<td>0.07</td>
</tr>
</tbody>
</table>

To know the amount of water that moved the moisture-content curves determined with the neutron-moisture probe should also be drawn on a graph. On Fig. 4 the two curves of 28 May and 11 June are given. On this graph the level is drawn at the depth where no water movement occurs following the data of Fig. 3. On Fig. 4, the surface between the two moisture curves and that above the level where $dp^*/dh = 0$ represents the amount of water that moved upwards. It is obvious that the surface between the two moisture curves and that below the level mentioned represents the amount of water that moved downwards. The quantity of water moving in both directions is assessed as follows. On Fig. 4 the moisture content is given in volumetric percentages (see also Table III) and the depth in centimetres. The amount of moisture that moved from a given layer is the difference in moisture content of that layer at two different times. In practice this means that the surface between the moisture curves and the levels B and b must be calculated. To express the amount of water in millimetres one has to divide the surface by 10, thus $(B + b)/2 [h/10]$. This calculation method is logical since the volume moisture per cent of a soil layer is equivalent to a water layer expressed in millimetre height per 100 mm or 10 cm of soil layer. Consequently, for a 1-cm-high soil layer the quantity is 10 times less, and for a layer h cm high the quantity is h times more. As the soil layer is also horizontally extended this quantity must be multiplied by the average width, that is $(B + b)/2$.

The amount of water that moved through each layer under the influence of the hydraulic potentials mentioned earlier can be calculated according to the formula just mentioned. For the results see column 3, Table II.
(4) The hydraulic conductivity

As already mentioned, to calculate the hydraulic conductivity in the unsaturated phase Darcy's law must be applied. From the foregoing paragraphs it is evident that all factors needed to calculate $K$, the hydraulic conductivity, are known. How it can be worked out in practice is shown in Table II.

The over-all picture of the $K$-value as a function of the moisture tension is given in Fig. 5. It is both the result and the summary of numerous observations during the 1966 summer. It should be noted that the time intervals for the cases given above are rather long. Therefore, the hypothesis that the moisture-content gradients and moisture-tension gradients are linear between two successive measurements must be considered. How all these data can be used to assess the water-balance are now discussed.
TABLE III. DETERMINATION OF MOISTURE CONTENT BY MEANS OF THE NEUTRON-MOISTURE METER ON TWO SUCCESSIVE DATES, 28 MAY AND 11 JUNE 1966 (see Fig. 2)

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Average cps</th>
<th>Corrected cps</th>
<th>Moisture content per volume as read from the calibration curve</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>28 May</td>
<td>11 June</td>
<td>28 May</td>
</tr>
<tr>
<td>15</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>30</td>
<td>860</td>
<td>725</td>
<td>890</td>
</tr>
<tr>
<td>45</td>
<td>840</td>
<td>825</td>
<td>880</td>
</tr>
<tr>
<td>60</td>
<td>850</td>
<td>865</td>
<td>890</td>
</tr>
<tr>
<td>90</td>
<td>910</td>
<td>900</td>
<td>911</td>
</tr>
<tr>
<td>120</td>
<td>885</td>
<td>920</td>
<td>927</td>
</tr>
<tr>
<td>150</td>
<td>895</td>
<td>925</td>
<td>937</td>
</tr>
<tr>
<td>180</td>
<td>885</td>
<td>900</td>
<td>927</td>
</tr>
</tbody>
</table>

![Graph showing log K (mm/day) vs. pF with various soil types](image)

FIG. 5. Relationship between log K and pF values found by De Boordt and co-workers as compared with data found in the literature.

When the moisture content, the moisture tension, the direction of the moisture gradient and the capillary conductivity are known, the infiltration rate and the depth reached by the water front can be calculated when irrigating a given soil with a certain quantity of water.
If $Q$ is the quantity of water put on the dry soil but inferior to the quantity necessary to bring the whole soil profile to the field capacity $C$, the waterfront will move to a depth $Z$ so that

$$Z = \frac{Q}{C}$$

$Q$ and $C$ are given in mm water height.

The speed with which this will happen will be given through the capillary conductivity $K$ (see Fig. 5) for a given tension difference as measured by the tensiometers put in the wet and the dry parts of the profile.

When scanning a soil profile it is possible to see, by means of the neutron-moisture meter, up to what depth the soil moisture is still close to the field capacity $C$ and what part is most depleted. In the example given on Fig. 4 the field capacity is in the vicinity of 30%, while it is further evident that the first 60 cm can benefit from a new water supply.

Hence the exact amount of water needed can be calculated. To continue the example given previously, it is evident from Table IV that the calculated amount of water that moved upwards between 28 May and 11 June is $9.30 + 3.90 + 0.85 = 14.05$ mm, the upper 15 cm of the soil profile not being taken into account because accurate data with the neutron-moisture meter in this layer are lacking.

Therefore, if one wants to restore the moisture content or to apply a more elaborate moisture supply scheme, as mentioned in reference [3], all the data are available.

**TABLE IV. COMPARISON BETWEEN THE CALCULATED $E^+$ AND $E^+_t$ VALUES**

<table>
<thead>
<tr>
<th>Period (1966)</th>
<th>$\Delta V$ (mm)</th>
<th>$P$ (mm)</th>
<th>$R$ (mm)</th>
<th>$E$ (mm)</th>
<th>$E^+_t$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22 April - 28 May</td>
<td>-95.4</td>
<td>0</td>
<td>46.3</td>
<td>141.9</td>
<td>116</td>
</tr>
<tr>
<td>28 May - 11 June</td>
<td>-32.6</td>
<td>0</td>
<td>9.8</td>
<td>42.4</td>
<td>62</td>
</tr>
<tr>
<td>10 June - 1 July</td>
<td>+92.6</td>
<td>0</td>
<td>164.8</td>
<td>72.2</td>
<td>71</td>
</tr>
<tr>
<td>1 July - 14 July</td>
<td>-23.2</td>
<td>0</td>
<td>65.3</td>
<td>88.2</td>
<td>42</td>
</tr>
<tr>
<td>14 July - 26 July</td>
<td>+13.0</td>
<td>1.0</td>
<td>50.1</td>
<td>36.1</td>
<td>38</td>
</tr>
<tr>
<td>26 July - 12 August</td>
<td>-40.1</td>
<td>7.0</td>
<td>37.3</td>
<td>70.4</td>
<td>51</td>
</tr>
<tr>
<td>12 August - 25 August</td>
<td>-38.3</td>
<td>1.6</td>
<td>22.9</td>
<td>59.6</td>
<td>34</td>
</tr>
<tr>
<td>25 August - 26 September</td>
<td>-17.8</td>
<td>1.3</td>
<td>30.2</td>
<td>46.7</td>
<td>76</td>
</tr>
</tbody>
</table>

Total: 557.5 488

$^+$ Given by the formula $E = R - P + \Delta V$

$^t$ Obtained from the formula $E^+_t \times 0.86$ (grass cover)

1 A possible solution might be the use of a polyethylene reflector on the surface of the soil as suggested by Moorten, Bucarlet and Marcense from Cadarache, France (Personal communication).
From the study of the moisture profiles, together with the hydraulic potential profiles, as discussed here, it is evident that the amount of water that will drain in the subsoil and that can eventually serve to wash out the excess of salts, can also be calculated analogously.

D. COMPARISON OF THE WATER BALANCE OBTAINED FROM A LYSIMETER AND NEUTRON-MOISTURE METER, AND FROM CALCULATED EVAPOTRANSPIRATION

The $2 \times 2 \times 3$-m lysimeter was a semi-enclosed hydraulic type as described by Forsgate, Hosegood and McCulloch [4]. The container with the reconstructed profiles rested on bolsters filled with water. The pressure difference on the bolsters, as measured by a water-manometer, gave the amount of water lost from the soil mass. The amount of water lost through drainage can be measured by means of a receptacle put under the lysimeter. Therefore, it is possible to establish a water balance by using the following formula

$$E = R - P + \Delta V$$

in which:

- $\Delta V = \text{difference in moisture content of the soil profile in the lysimeter calculated in millimetres according to data obtained with the neutron-moisture meter during a given period,}$
- $P = \text{percolation during a given period; this is the amount of water drained in the lysimeter during a given period and expressed in millimetres,}$
- $R = \text{precipitation measured during the same period and also expressed in millimetres,}$
- $E = \text{evaporation (water leaving the profile) calculated in millimetres according to the above formula.}$

In Table IV a comparison is made between the $E$ data obtained for different periods of 1966 and the potential evapotranspiration $E_t$ calculated according to Penman's formula $E_t \times 0.86$ (grass cover). The value $E_t$ was obtained by means of the data from the agro-meteorological station in which the lysimeter is located. The calculation was done by using McCulloch's table [5] in which a 5% reflection coefficient is taken into account. It should be noted that these measurements were carried out on the lysimeter while the data pertaining to the first part of this paper were obtained on undisturbed profiles in situ.

The comparison of the $E_t$ value with the calculated $E$ (water leaving the profile), is reasonable since 1966 was a very wet year and the soil was mostly at field capacity or above. As can be seen from Table IV the agreement between $E_t$ and $E$ for such types of studies is rather good. The relative deviation from each other is much smaller than that found by Holmes and Colville [6], who, however, were working in a dry region.
ACKNOWLEDGMENTS

The financial support for the equipment received from the Joint FAO/IAEA Division and F. N. R. S. (Brussels) is gratefully acknowledged. We would also like to thank Euratom for the assistance given in this project.

REFERENCES


DISCUSSION

P. BENECKE: I am surprised that you found air in your tensiometers after a short time. I used tensiometers myself and found no air in the instruments after 2 or 3 months. Your trouble may have been caused by the porous cup.

M. DE BOODT: It is normal to get air bubbles in a tensiometer. While a low air-entry value is useful, it is important to have high permeability, otherwise it takes too long to achieve equilibrium between the soil and the tensiometer.

C. E. MAERTENS: Do you think that potential differences in a profile tending towards equilibrium can explain large downward water movements, especially in covered soils, where upward water movements may be caused by the plants?

M. DE BOODT: When the tensiometer is working properly, it will indicate the matrix potential at any point in the soil, whether covered by vegetation or not.

J. A. DAMAGNEZ (Chairman): Have you compared the water-potential values obtained in situ with tensiometers and the matrix-potential values measured simultaneously in the laboratory?

M. DE BOODT: Yes, but we always found good correlation between both methods when dealing with sandy soils. In loamy and other heavy soils, the correlation was not so good. In the latter case, we preferred the field determination as described in the paper, because it causes least disturbance of the soil.

J. A. DAMAGNEZ: Do you think that the accuracy of the method gives reason to hope that we shall be able to detect flux differences between two levels? In other words, would it enable us to determine the
way in which groundwater is used by the roots? A downward movement does not necessarily mean a loss of water from the evapotranspiration balance if the roots are deeper than the inversion of the potential gradient.

M. DE BOODT: I believe that the value of the method lies precisely in the possibility of detecting the depths at which water starts to move upwards and downwards and the amount of water doing so. By placing series of tensiometers vertically, we can detect the vertical movement either upwards or downwards. When they are placed horizontally at various depths, we can detect the lateral movement due to attraction by the roots.
THE NEUTRON-MOISTURE METER IN STUDIES OF THE EFFECT OF FALLOW ON WATER CONSERVATION IN ARID REGIONS

NURINNISA ÖZBEK, TEVFIK AKSOY AND GURKAN GELEBI
RADIOPHYSIOLOGY AND SOIL FERTILITY DEPARTMENT,
FACULTY OF AGRICULTURE,
UNIVERSITY OF ANKARA,
ANKARA, TURKEY

Abstract

THE NEUTRON-MOISTURE METER IN STUDIES OF THE EFFECT OF FALLOW ON WATER CONSERVATION IN ARID REGIONS. For a long time it has been a common practice for the Central Anatolian farmers to leave half the land fallow the whole year in order to increase the amount of water conserved.

The main object of these studies was to ascertain whether fallow has an effect on moisture conservation in soils of this region and to what extent its degree of efficiency on a yearly basis. In view of the intensity and distribution of rainfall Ankara, Konya and Eskişehir were selected for moisture-measurement areas.

Altogether 60 holes were dug and 60 access tubes were used for moisture measurements by a neutron-moisture meter, and they were placed at six different locations on either state farms or a dry-farming experimental station.

In each location the first group of access tubes were placed in fallow soil, the second in a wheat field and the third in a wheat field after harvest. Each treatment had three replicates. In all holes the moisture measurements were made at five different depths at intervals of either 15 days or one month. At the beginning of the moisture measurements a separate calibration curve was prepared for each location and for each treatment. The measurements were begun in 1964 and are continuing, but with some variations in the sampling technique.

Some physical properties of the soils that were sampled from measurement areas, such as texture, field capacity and wilting point, were determined. Some bulk-density measurements were also made by gamma-ray transmission. The results obtained are averaged and illustrated in tables and figures. Necessary calculations and comparisons were made to show the efficiency of the fallow system in the moisture conservation in this dry soil.

The results can be summarized as follows: (1) The total amount of water conserved in the soil down to a depth of 1.60 cm was higher in fallow soil than in the other two cases. This was true for all locations over a period of two years. (2) The amounts of water conserved by the effect of fallow changed, depending upon the locations and years, but differences were generally small. (3) With some exceptions, the increase in the amount of conserved water in fallow soil reached 20-22% of the average annual rainfall of the region. This was true for all locations over a period of two years.

INTRODUCTION

The fundamental object of all dry-farming systems is to overcome water shortage by providing necessary conditions for the crops grown so that available water is used in the best way. In practice this can be done in different ways, fallow being the most widespread practice used in dry-farming areas, the main purpose being to store moisture for crop production for the following growing season.

However, the effectiveness of the fallow practice in conserving moisture changes according to different factors, mainly the intensity and distribution of rainfall, type of soil, type of farming, kind of crop.
and weed control, all of which determine the efficiency or inefficiency of fallow and consequently the yield obtained from the fallow land in the following year.

Therefore, particularly from the economic point of view, fallow cannot be always considered as a desirable practice without controlling its effectiveness in storing moisture.

Today, in Turkey there are altogether approximately 8.5 million ha of fallow land, which form about 32.7% of the total cultivated land, and more than half of this is in Central Anatolia [1].

In this region the average annual rainfall is about 350 mm and its seasonal distribution is not uniform as the summer months are mostly dry. The main crop is winter wheat, which is grown according to the dry-farming system.

Since it is generally believed that water is the primary factor limiting crop production in Central Anatolia, the conservation of moisture and its efficient use by crops are therefore the first considerations, and fallow has been a common and ancient practice of the farmers in order to increase the amount of water conserved.

But today adequate experimental data are not available to show exactly the effect of fallow in moisture storage for this region. Therefore, it is essential that the effect of fallow in moisture conservation be determined experimentally by using the most suitable and sensitive method to make numerous reliable soil-moisture measurements.

These preliminary studies are the first step in resolving the fallow problem for Central Anatolia and the main object of these studies is: (1) To find out whether fallow has an effect on moisture conservation for the subsequent growing season; (2) if so, what is the degree of its efficiency from an economic point of view, in other words, how much water is conserved by the effect of fallow as a percentage of the average annual rainfall.

EXPERIMENTAL PROCEDURES AND METHOD

Taking into consideration the intensity and distribution of the rainfall, three representative places – Ankara, Konya and Eskişehir – were selected as experimental areas in Central Anatolia.

An experimental plan was prepared with details covering the number of holes to be dug and their location, treatments, measurement depths and intervals between two measurements. Accordingly 60 holes were dug in the experimental areas at six different locations on either state farms or a dry-farming experimental station.

In each location the first group of access tubes was placed in fallow land, the second in a wheat field and the third in a wheat field after harvest. Each treatment had three replicates.

Thin-walled aluminium tubes of specified diameter were used as access tubes and, considering the particular importance of close contact between access tubes and soil, optimum access tube placement was accomplished with the aid of a hydraulic probe that was able to remove soil with constant diameter from desired depths.

While boring, undisturbed soil samples were taken on a volume basis at 30-cm intervals down to a depth of 180 cm. Neutron-meter readings were also taken at the same depths.
The volume of each soil sample was 256.6 cm$^3$. Immediately after the samples were taken their moisture contents by volume were determined by measuring the weight loss from drying 48 h in an oven at 105°C. Besides moisture sampling undisturbed soil samples near the holes were also collected to determine some physical characteristics such as texture, field capacity and wilting point, and to show the variability of these characteristics within the same profiles and at different locations. The data obtained from these determinations are given in Table 1. As these data show, investigated soils varied in texture between clay and clay loam. The soils varied somewhat in field capacity and wilting point depending on their locations.

Since bulk density of a soil has a marked effect on most of its properties, some bulk-density measurements were also made by gamma-ray transmission, and dry-bulk-density values obtained varied from 1.26 to 1.48.

As indicated above, for the moisture measurements the neutron method was preferred since it possessed almost all the properties of an ideal method. In particular it enabled continuous and reliable measurements without disturbing the soil system [2, 3].

The neutron meter was calibrated in the field and for each location a separate calibration curve was made. For example, two calibration curves, which belong to two different locations, are given in Figs.1 and 2, including correlation coefficients for depths of 30-180 cm.

The moisture measurements, which were begun in 1964, are still continuing, but with some variations in sampling technique. In all holes the moisture measurements were made at five different depths with intervals of 15 cm or a month.

To compare and to discover the effect of fallow in moisture conservation, measurements were performed at the same dates and depths in three cases — a wheat field, fallow land, and a wheat field after harvest.

The last treatment was included in these studies to show the effectiveness of soil-cultivation and weed-control practices on the moisture conservation during the fallow period.

Another noteworthy point is that the commonest fallow system used by the farmers of Central Anatolia is summer fallow and, particularly in experimental areas after harvest (June), the stubble is left to stand during winter, and tillage operations are started in the early spring (usually during March) before weeds have removed much water. This soil-cultivation practice is repeated three times during the fallow period in order to control weeds and to keep the soil surface loose for water penetration.

In addition, the highest rainfall is during winter and spring, and the spring rainfall is the main factor in determining the amount of yield obtained. Therefore, the effectiveness of fallow in storing water during this period is particularly important.

RESULTS AND DISCUSSION

The results obtained from studies concerning moisture-storage efficiency of fallow are averaged and presented in Tables II-XIII.
FIG. 1. Calibration curves and correlation coefficients for 30-40-cm depth.
FIG. 2. Soil-moisture content as a function of time for different depths.
As can be seen from these tables the amounts of water contained in the soil, either at different soil layers or for the three treatments, are expressed in m$^3$/ha.

According to the data in the tables it is obvious that the treatments used in these studies have a different effect on the moisture content of the soils investigated. The total amount of water conserved in the soil down to a depth of 1.80 cm was higher in fallow soil than the other two cases. This was true for all locations and for both years.

On the other hand the data also indicated that the amounts of water conserved by the effect of fallow changed, depending upon the locations and years, but differences were generally small.

Figures 2 and 3 show the effect of fallow in storing water, both as a function of time and as a function of depth, during fallow period (Bašić, 1968).

It is clearly seen from Fig. 2 that the water-storage efficiency of fallow shows some seasonal variation and its moisture-storage
efficiency was highest in spring. This was true for different depths. In addition, according to Fig. 3, it is obvious that the moisture content of fallow soil increased as the depth increased.

With regard to the efficiency of fallow as a percentage of average annual rainfall, this was calculated separately for each location for two years and the calculation was based on the differences found between the total moisture content of fallow soil and that of a field of wheat.

It was found, with some exceptions, that the efficiency of fallow varied, generally from 20 to 22%, in other words the increase in the amount of conserved water in fallow soil reached 20-22% of the average annual rainfall under the conditions of the experiment. This increase in the amount of conserved water was not as high as expected.

However, much work has been carried out by various investigators to ascertain the effectiveness of fallow practice in moisture conservation, particularly in arid and semi-arid regions where the water factor is a vital problem. Their results generally confirmed our results.

Russell [4] insists that the water-storage efficiency of fallow varies, depending on the seasons, and is highest in the autumn, winter and spring for the Anatolian plains. He concludes that, even in the cooler part of this region, the efficiency of summer fallow for moisture storage seldom exceeds 30%.

According to Evans and Lemon [5] at Fort Hays, Kansas, the 40-yr average efficiency of summer fallow was as low as 15%. Barnes [6] at Swift Current, Saskatchewan, found a 29.7% efficiency of moisture storage during the summer fallow period. For the same location Staple and Lehane [7] reported that the fallow-storage efficiency was only about 21%. This quite large difference found by various investigators for the same place was because the same suitable weed control to prevent run-off or deep percolation was not applied in the experiments of the latter investigators.

Barrada [8] has experimented in Morocco (Guich and Ellouizia) to find out the effect of fallow in storing moisture, and he obtained data to show that, through fallow, about 10% more of the total soil-moisture content was conserved annually. He concluded that fallow could not be considered as a satisfactory practice in water conservation under the conditions of the experiment.

ACKNOWLEDGEMENTS

The generous support of NATO and the Ministry of Village Affairs, General Directory of Land and Water, Turkey, in providing the necessary equipment for this research work is gratefully acknowledged.

REFERENCES

TABLE I. SOME PHYSICAL CHARACTERISTICS OF SOILS IN EXPERIMENTAL AREAS

<table>
<thead>
<tr>
<th>Location</th>
<th>Texture</th>
<th>Clay fraction (%)</th>
<th>Field capacity (%)</th>
<th>Wilting point (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ankara</td>
<td>Polatlı</td>
<td>Clay</td>
<td>49.3-71.5</td>
<td>35.0-40.4</td>
</tr>
<tr>
<td></td>
<td>Batı</td>
<td>Clay</td>
<td>39.6-49.8</td>
<td>25.6-30.6</td>
</tr>
<tr>
<td></td>
<td>Alınova</td>
<td>Clay</td>
<td>40.4-45.3</td>
<td>26.2-32.1</td>
</tr>
<tr>
<td>Konya</td>
<td>Gözle</td>
<td>Clay</td>
<td>45.4-62.5</td>
<td>35.7-42.4</td>
</tr>
<tr>
<td></td>
<td>Konuklar</td>
<td>Clay loam</td>
<td>28.2-46.1</td>
<td>18.3-29.8</td>
</tr>
<tr>
<td>Eskişehir</td>
<td>Dry-framing experimental station</td>
<td>Clay loam</td>
<td>26.0-41.2</td>
<td>31.4-40.3</td>
</tr>
</tbody>
</table>
TABLE II. AMOUNTS OF WATER CONTAINED IN THE SOIL (m³/ha)
Ankara⁺ - Balla
(October 1964 - July 1965)

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Wheat field</th>
<th>Fallow soil</th>
<th>Wheat field after harvest</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-60</td>
<td>834</td>
<td>1074</td>
<td>780</td>
</tr>
<tr>
<td>60-90</td>
<td>888</td>
<td>1014</td>
<td>864</td>
</tr>
<tr>
<td>90-120</td>
<td>942</td>
<td>1044</td>
<td>1092</td>
</tr>
<tr>
<td>120-150</td>
<td>912</td>
<td>1119</td>
<td>1143</td>
</tr>
<tr>
<td>150-180</td>
<td>882</td>
<td>1107</td>
<td>1071</td>
</tr>
<tr>
<td>Total</td>
<td>4458</td>
<td>5358</td>
<td>4950</td>
</tr>
</tbody>
</table>

⁺ Ankara rainfall: 359.2 mm
Efficiency of fallow = 25.0%

TABLE III. AMOUNTS OF WATER CONTAINED IN THE SOIL (m³/ha)
Ankara⁺ - Polattli
(October 1964 - July 1965)

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Wheat field</th>
<th>Fallow soil</th>
<th>Wheat field after harvest</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-60</td>
<td>561</td>
<td>903</td>
<td>764</td>
</tr>
<tr>
<td>60-90</td>
<td>870</td>
<td>1062</td>
<td>894</td>
</tr>
<tr>
<td>90-120</td>
<td>972</td>
<td>1098</td>
<td>978</td>
</tr>
<tr>
<td>120-150</td>
<td>1098</td>
<td>1131</td>
<td>1094</td>
</tr>
<tr>
<td>150-180</td>
<td>1098</td>
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<td>1086</td>
</tr>
<tr>
<td>Total</td>
<td>4599</td>
<td>5409</td>
<td>4816</td>
</tr>
</tbody>
</table>

⁺ Ankara rainfall: 359.2 mm
Efficiency of fallow = 22.5%
### TABLE IV. AMOUNTS OF WATER CONTAINED IN THE SOIL (m$^3$/ha)
Konya$^a$ - Altinova
(October 1964 - July 1965)

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Wheat field</th>
<th>Fallow soil</th>
<th>Wheat field after harvest</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-60</td>
<td>648</td>
<td>852</td>
<td>834</td>
</tr>
<tr>
<td>60-90</td>
<td>714</td>
<td>963</td>
<td>864</td>
</tr>
<tr>
<td>90-120</td>
<td>726</td>
<td>975</td>
<td>945</td>
</tr>
<tr>
<td>120-150</td>
<td>921</td>
<td>969</td>
<td>1029</td>
</tr>
<tr>
<td>150-180</td>
<td>987</td>
<td>918</td>
<td>936</td>
</tr>
<tr>
<td>Total</td>
<td>3996</td>
<td>4077</td>
<td>4002</td>
</tr>
</tbody>
</table>

$^a$ Konya rainfall: 315.1 mm
Efficiency of fallow = 21.6%

### TABLE V. AMOUNTS OF WATER CONTAINED IN THE SOIL (m$^3$/ha)
Konya - Gözü (1965)

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Wheat field</th>
<th>Fallow soil</th>
<th>Wheat field after harvest</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-60</td>
<td>714</td>
<td>786</td>
<td>881</td>
</tr>
<tr>
<td>60-90</td>
<td>810</td>
<td>849</td>
<td>794</td>
</tr>
<tr>
<td>90-120</td>
<td>887</td>
<td>1026</td>
<td>918</td>
</tr>
<tr>
<td>120-150</td>
<td>930</td>
<td>1110</td>
<td>999</td>
</tr>
<tr>
<td>150-180</td>
<td>984</td>
<td>1149</td>
<td>1014</td>
</tr>
<tr>
<td>Total</td>
<td>4225</td>
<td>4920</td>
<td>4600</td>
</tr>
</tbody>
</table>

Efficiency of fallow = 22.0%
### TABLE VI. AMOUNTS OF WATER CONTAINED IN THE SOIL (m³/ha)
Konya*  = Konuklar
(October 1964 – July 1965)

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Wheat field</th>
<th>Fallow soil</th>
<th>Wheat field after harvest</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-60</td>
<td>474</td>
<td>576</td>
<td>447</td>
</tr>
<tr>
<td>60-90</td>
<td>576</td>
<td>618</td>
<td>511</td>
</tr>
<tr>
<td>90-120</td>
<td>633</td>
<td>722</td>
<td>665</td>
</tr>
<tr>
<td>120-150</td>
<td>651</td>
<td>819</td>
<td>801</td>
</tr>
<tr>
<td>150-180</td>
<td>651</td>
<td>650</td>
<td>651</td>
</tr>
<tr>
<td>Total</td>
<td>2998</td>
<td>3465</td>
<td>3215</td>
</tr>
</tbody>
</table>

* Konya rainfall: 315.1 mm
  Efficiency of fallow = 12.9%

### TABLE VII. AMOUNTS OF WATER CONTAINED IN THE SOIL (m³/ha)
Eskişehir* Dry Farming Experimental Station
(October 1964 – July 1965)

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Wheat field</th>
<th>Fallow soil</th>
<th>Wheat field after harvest</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-60</td>
<td>708</td>
<td>660</td>
<td>960</td>
</tr>
<tr>
<td>60-90</td>
<td>665</td>
<td>648</td>
<td>705</td>
</tr>
<tr>
<td>90-120</td>
<td>759</td>
<td>897</td>
<td>1263</td>
</tr>
<tr>
<td>120-150</td>
<td>945</td>
<td>1233</td>
<td>1395</td>
</tr>
<tr>
<td>150-180</td>
<td>1233</td>
<td>1452</td>
<td>1374</td>
</tr>
<tr>
<td>Total</td>
<td>4278</td>
<td>4890</td>
<td>5757</td>
</tr>
</tbody>
</table>

* Eskişehir rainfall: 368.3 mm
  Efficiency of fallow = 16.6%
TABLE VIII. AMOUNTS OF WATER CONTAINED IN THE SOIL (m³/ha)
Ankara - Balâ
(October 1965 - July 1966)

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Wheat field</th>
<th>Fallow soil</th>
<th>Wheat field after harvest</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-60</td>
<td>504</td>
<td>717</td>
<td>576</td>
</tr>
<tr>
<td>60-90</td>
<td>552</td>
<td>681</td>
<td>708</td>
</tr>
<tr>
<td>90-120</td>
<td>672</td>
<td>771</td>
<td>846</td>
</tr>
<tr>
<td>120-150</td>
<td>678</td>
<td>810</td>
<td>777</td>
</tr>
<tr>
<td>150-180</td>
<td>687</td>
<td>888</td>
<td>900</td>
</tr>
<tr>
<td>Total</td>
<td>3093</td>
<td>3867</td>
<td>3807</td>
</tr>
</tbody>
</table>

Efficiency of fallow = 21.5%

TABLE IX. AMOUNTS OF WATER CONTAINED IN THE SOIL (m³/ha)
Ankara - Polatlı
(October 1965 - July 1966)

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Wheat field</th>
<th>Fallow soil</th>
<th>Wheat field after harvest</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-60</td>
<td>591</td>
<td>951</td>
<td>621</td>
</tr>
<tr>
<td>60-90</td>
<td>723</td>
<td>945</td>
<td>564</td>
</tr>
<tr>
<td>90-120</td>
<td>819</td>
<td>807</td>
<td>831</td>
</tr>
<tr>
<td>120-150</td>
<td>909</td>
<td>948</td>
<td>984</td>
</tr>
<tr>
<td>150-180</td>
<td>726</td>
<td>849</td>
<td>887</td>
</tr>
<tr>
<td>Total</td>
<td>3768</td>
<td>4500</td>
<td>3867</td>
</tr>
</tbody>
</table>

Efficiency of fallow = 20.4%
TABLE X. AMOUNTS OF WATER CONTAINED IN THE SOIL
(m³/ha)
Konya – Altinova
(October 1965 – July 1966)

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Wheat field</th>
<th>Fallow soil</th>
<th>Wheat field after harvest</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-60</td>
<td>636</td>
<td>693</td>
<td>717</td>
</tr>
<tr>
<td>60-90</td>
<td>666</td>
<td>762</td>
<td>633</td>
</tr>
<tr>
<td>90-120</td>
<td>630</td>
<td>822</td>
<td>604</td>
</tr>
<tr>
<td>120-150</td>
<td>732</td>
<td>867</td>
<td>801</td>
</tr>
<tr>
<td>150-180</td>
<td>744</td>
<td>739</td>
<td>957</td>
</tr>
<tr>
<td>Total</td>
<td>3408</td>
<td>4083</td>
<td>3732</td>
</tr>
</tbody>
</table>

Efficiency of fallow = 21.4%

TABLE XI. AMOUNTS OF WATER CONTAINED IN THE SOIL
(m³/ha)
Konya – Gözlü
(October 1965 – July 1966)

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Wheat field</th>
<th>Fallow soil</th>
<th>Wheat field after harvest</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-60</td>
<td>825</td>
<td>1146</td>
<td>1074</td>
</tr>
<tr>
<td>60-90</td>
<td>900</td>
<td>1227</td>
<td>1133</td>
</tr>
<tr>
<td>90-120</td>
<td>983</td>
<td>1167</td>
<td>1086</td>
</tr>
<tr>
<td>120-150</td>
<td>1029</td>
<td>1062</td>
<td>1047</td>
</tr>
<tr>
<td>150-180</td>
<td>1017</td>
<td>1047</td>
<td>1149</td>
</tr>
<tr>
<td>Total</td>
<td>4734</td>
<td>5649</td>
<td>5469</td>
</tr>
</tbody>
</table>

Efficiency of fallow = 29.9%
TABLE XII. AMOUNTS OF WATER CONTAINED IN THE SOIL (m³/ha)
Konya - Konuklar
(October 1965 - July 1966)

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Wheat field</th>
<th>Fallow soil</th>
<th>Wheat field after harvest</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-60</td>
<td>636</td>
<td>843</td>
<td>782</td>
</tr>
<tr>
<td>60-90</td>
<td>783</td>
<td>951</td>
<td>903</td>
</tr>
<tr>
<td>90-120</td>
<td>846</td>
<td>948</td>
<td>964</td>
</tr>
<tr>
<td>120-150</td>
<td>816</td>
<td>897</td>
<td>930</td>
</tr>
<tr>
<td>150-180</td>
<td>765</td>
<td>912</td>
<td>993</td>
</tr>
<tr>
<td>Total</td>
<td>3846</td>
<td>4551</td>
<td>4452</td>
</tr>
</tbody>
</table>

Efficiency of fallow = 22.4%

TABLE XIII. AMOUNTS OF WATER CONTAINED IN THE SOIL (m³/ha)
Eskişehir Dry Farming Experimental Station
(October 1965 - July 1966)

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Wheat field</th>
<th>Fallow soil</th>
<th>Wheat field after harvest</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-60</td>
<td>642</td>
<td>1119</td>
<td>960</td>
</tr>
<tr>
<td>60-90</td>
<td>687</td>
<td>1017</td>
<td>765</td>
</tr>
<tr>
<td>90-120</td>
<td>1326</td>
<td>1149</td>
<td>1263</td>
</tr>
<tr>
<td>120-150</td>
<td>1314</td>
<td>1308</td>
<td>1395</td>
</tr>
<tr>
<td>150-180</td>
<td>1407</td>
<td>1416</td>
<td>1374</td>
</tr>
<tr>
<td>Total</td>
<td>3286</td>
<td>6009</td>
<td>5757</td>
</tr>
</tbody>
</table>

Efficiency of fallow = 19.6%
DISCUSSION

D. KIRKHAM: Do the percentages shown in the last three columns of Table I refer to weight or volume and could you say what rain fell in the area during the sampling period?

N. ÖZBEK: They are weight percentages. I have not got the rainfall figures with me, but I shall be publishing them as soon as the study is completed.

M. DE BOODT: Your tables, especially Tables XI and XIII, lead one to expect that an important amount of water may be entering the profile by capillary rise. It would be very useful if you could place tensiometers at various depths in the profile to see if there is in fact capillary rise from the ground water table. If so, this reserve of water could be used by adapted varieties of crops.

N. ÖZBEK: Thank you for your suggestion. We do plan to use tensiometers at some points.

Y. BARRADA: Were all the soil-moisture measurements made at the same time? Topography is a very important factor which might influence the results. Was this factor given due consideration when selecting the field plots?

N. ÖZBEK: Yes, the soil-moisture measurements were made simultaneously at each location for the different treatments. We selected experimental field plots with similar topographical features.

H. W. SCHARPENSEEL (Chairman): At what stage in the vegetation period did you make your readings?

N. ÖZBEK: Measurements were made throughout the vegetation period, starting in October.

M. DAGG: The water totals in the tables are quoted in m³/ha. Are these integrated totals over the whole season?

N. ÖZBEK: Yes.
THE NEUTRON-MOISTURE GAUGE IN AGRICULTURAL AND HYDROLOGICAL FIELD STUDIES IN SUB-HUMID AREAS

M. Dagg,
EAST AFRICAN AGRICULTURE AND FORESTRY RESEARCH ORGANIZATION,
MUGUGA, KENYA

Abstract

The neutron-moisture gauge in agricultural and hydrological field studies in sub-humid areas. In areas where the annual potential evapotranspiration appreciably exceeds the annual precipitation, but where there are seasonal surpluses of rain to recharge the soil profile to a considerable depth, the natural vegetation and successful crops have deep root systems which develop large soil-moisture deficits in the dry seasons. The clarification of many agronomic and hydrological problems in these circumstances requires frequent field estimates of the quantitative soil-moisture status for which the neutron soil-moisture gauge is admirably suited, and surface soil-moisture difficulties are minimized. Moreover, it is self-contained and needs no external power supply, which is an important consideration in remote areas.

Research workers involved in earlier studies in East Africa have had to make do with resistance units for qualitative information on soil-water status, and several illustrations of their use from catchment area experiments, root development studies and water penetration studies are given. All these types of investigation could have benefited from the quantitative neutron method with little extra effort involved.

Experience with a single soil-moisture probe with the source mounted at the end of the detector points to the importance of having a suitable geometry of source and detector to ensure a linear response curve over a very large range of soil-moisture content.

Little use has been made so far in East Africa of radiation techniques in the investigations of soil-water-plant relationships but there would appear to be considerable scope for their introduction. In particular, the neutron-moisture gauge represents an advance in technique that can be of great value in studies of crop water-use efficiency in developing countries. It may seem paradoxical to recommend such a sophisticated piece of equipment in such unsophisticated surroundings as East Africa, and certainly when it comes to maintenance, it presents more of a problem than a soil auger. However, the taking of measurements with the neutron-moisture gauge is essentially simple, and relatively unskilled personnel can be drilled in the routine. Furthermore, the equipment is self-contained and makes no demands on a mains supply. "Simple" gravimetric soil-moisture sampling takes on a different aspect when the nearest power-supply oven is a hundred miles away and the scope for errors between sample and result is prodigious.

Consequently, for routine soil-moisture measurements at remote experiments, recourse must be had to a self-contained system. Accordingly, many experiments have been conducted in East Africa using resistance units and a dynamo-operated ohm-meter as the sole indicator of the soil-moisture status. Because of certain favourable characteristics of soil and climate, it has been possible to arrive at some useful conclusions with this qualitative technique but much more fruitful conclusions could have been made for the same effort if a quantitative device like the neutron-moisture gauge had been available.

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East Africa is not entirely sub-humid, but only about 3% of the land surface reliably receives more rainfall annually than the evaporative demand from open water, and while this area is critically important for the maintenance of perennial streams, the bulk of the agricultural enterprise is carried out in areas where the annual rainfall is exceeded by the evaporative demand to a considerable degree, with evaporation rates varying from more than 2500 mm/yr to about 1200 mm at 9000 ft in cloudy areas. The magnitude of the evaporative demand has perhaps not been adequately appreciated in the past, nor the corollary that most of the crops growing in East Africa are periodically short of water and cannot afford to lose any of the rain that falls. Furthermore, with the steady increase in population there is a tendency to push more areas of marginal rainfall into cultivation without adequate consideration for water conservation practices or the selection of suitable varieties of crop. Fortunately, there is still the opportunity to influence future planning with facts on crop-water requirements and efficiency of water use (past planning was carried out largely in the absence of any guiding facts) and there is an urgent need to obtain significant quantitative data on crop-water relationships where most of the crop production is limited by the water supply: the shortage of free water resources severely restricts the scope for irrigation.

A few examples, illustrated with resistance unit data, will serve to show how suited the neutron-moisture gauge would be to this type of study.

CATCHMENT STUDIES

In the high rainfall, stream-source areas the pattern of land use can seriously affect the pattern of the emergent stream flow both in total quantity (by transpiration) and in time (more or less surface flood flow). Optimum land use must take into consideration the immediate crop production. Several catchment-area experiments are in progress at present in East Africa where the effects of changes in land use on streamflow are being studied [1, 2], with the aim of specifying the changes in transpiration loss and direct storm runoff. For this approach to be successful quantitatively, it is necessary to be able to set limits on the water-tightness of the catchment by comparing the predicted soil-moisture deficit as calculated by rainfall, streamflow and meteorological observations, with a direct measurement of soil-moisture deficit in the catchment. The direct soil-moisture measurements have been made with much till and tribulation by gravimetric sampling in two experiments and with much less effort for a qualitative result by resistance units in a third experiment.

Figure 1 shows the results obtained from two small catchments with uniform bamboo cover at Kimakia in the Aberdare Range, Kenya. The solid line shows the deficit predicted from the streamflow and meteorological data. The direct measurements of deficit diverge progressively from the predicted values demonstrating that there was a considerable "leak" in the catchment. The dotted line is the deficit predicted from the $E_i/E_0$ relationship from a nearby catchment that proved to have little or no leak. The satisfactory fit suggests that the two covers of bamboo were transpiring at closely similar rates.
The key measurement is that of direct soil-moisture deficit. Because of the favourable conditions of deep uniform soil, gentle topography, no aspect problem on the equator and a very uniform cover, it was possible to arrive at a reasonable estimate of the soil-moisture deficit over the catchment with a relatively small number of sampling sites. Any increase in non-uniformity would have made direct soil sampling prohibitively difficult. With the neutron-moisture gauge, not only could more sites be sampled easily but the sampling could be done more frequently.

Figures 2 and 3 refer to a catchment experiment in Mbeya Range, Tanzania, comparing the pattern of stream-flow from high forest and
from peasant-cultivated steep slopes. The streamflow pattern from the forested area might have a "leak", thus reducing the flow measured over the weir. The rainfall and streamflow measurements show that, in the absence of a leak, the forest must transpire at close to 0.9 $E_o$ ($E_o$ is the Penman estimate of evaporation from open water) for the whole year. This requires the trees to develop a soil-moisture deficit of 750 mm during the dry season, which can therefore be checked by direct observation. The water-holding capacity of the soil and rotten rock is such that this deficit would require the top 4 m of the soil and rock to be dried out. Resistance records are incomplete in that the units were only installed to 3 m, but water was being extracted from the 3-m depth as early as August, with every likelihood that water loss from greater depths also took place. The roots of a typical tree extended more than 13 m deep. The resistance units from the cultivated area showed no water loss beyond a depth of 1.5 m.

The qualitative soil-moisture data confirms that it is not necessary to invoke a leak to explain the streamflow results. Systematic direct soil-moisture sampling was ruled out in this case because of the difficulty of penetrating a line of large stones at about 1 m depth; quantitative data would have been readily obtained using the neutron-moisture gauge.

In the striking of a catchment water balance it is necessary to take account of the changes in soil-moisture storage between the ends of the year as illustrated in Table 1, for high forest at Kericho, Kenya. Again the estimate from direct sampling is only possible because of the uniformity of the terrain and cover. With more disturbed conditions, the increase in sampling sites necessary would make the neutron-moisture gauge essential.

ROOT DEVELOPMENT

Under conditions of an over-all water deficit but with seasonal surpluses of rain, successful species of the natural vegetation tend to develop deep
<table>
<thead>
<tr>
<th>Water year</th>
<th>Rainfall R</th>
<th>Streamflow Q</th>
<th>R-Q</th>
<th>Change in soil moisture</th>
<th>$E_t$</th>
<th>$E_o$</th>
<th>$E_t/E_o$</th>
<th>Uncorrected $E_t/E_o$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1958-59</td>
<td>1880</td>
<td>311</td>
<td>1569</td>
<td>- 23</td>
<td>1592</td>
<td>1679</td>
<td>0.95</td>
<td>0.93</td>
</tr>
<tr>
<td>1959-60</td>
<td>1830</td>
<td>306</td>
<td>1524</td>
<td>+ 59</td>
<td>1465</td>
<td>1638</td>
<td>0.89</td>
<td>0.93</td>
</tr>
<tr>
<td>1960-61</td>
<td>2334</td>
<td>920</td>
<td>1414</td>
<td>- 201</td>
<td>1615</td>
<td>1733</td>
<td>0.93</td>
<td>0.82</td>
</tr>
<tr>
<td>1961-62</td>
<td>2672</td>
<td>965</td>
<td>1707</td>
<td>+ 154</td>
<td>1553</td>
<td>1761</td>
<td>0.88</td>
<td>0.97</td>
</tr>
<tr>
<td>1962-63</td>
<td>2570</td>
<td>1004</td>
<td>1566</td>
<td>+ 137</td>
<td>1429</td>
<td>1624</td>
<td>0.88</td>
<td>0.96</td>
</tr>
<tr>
<td>1963-64</td>
<td>1903</td>
<td>683</td>
<td>1220</td>
<td>- 146</td>
<td>1366</td>
<td>1560</td>
<td>0.88</td>
<td>0.78</td>
</tr>
<tr>
<td>1958-64</td>
<td>13189</td>
<td>4189</td>
<td>9000</td>
<td>- 20</td>
<td>9020</td>
<td>9995</td>
<td>0.90</td>
<td>0.90</td>
</tr>
</tbody>
</table>

The final column shows the $E_t/E_o$ ratios uncorrected for changes in soil moisture.
root systems to make full use of the water that goes into storage during the rains. In the ensuing dry seasons it is often possible to reach useful conclusions on the minimal rates of root development by using simple resistance units as "on-off" switches at different depths. The growth of perennial grasses at Muguga offers an example. At Muguga, annual rainfall expectation is about 900 mm in two seasons and open water evaporation is about 1700 mm.

Figure 4 shows the record of one replicate of resistance units at various depths up to 6 m under a uniform cover of Cenchrus ciliaris var. biloela. The area (1 acre) was planted from splits in mid-April 1965 and weeded to obtain a very pure stand. Recording commenced in June when the soil profile was full to 3.5 m, and partially filled beyond that depth to 6 m. By October 1965, the grass was extracting water from a depth of 3.5 m, and by March 1966 from a depth of 6 m. The profile was at wilting point to 6 m by the end of October 1966. Other perennial grasses were slower in development but were all extracting water from 6 m by the end of December 1966.

Besides indicating the minimum rate of root development of the grass, this observational trip yields information of local hydrological significance. It can be concluded that, under the conditions prevailing, a deficit of at least 500 mm can be expected under perennial grass (and trees) at the start of the April-May and November-December rains.

For there to be any appreciable recharge of the groundwater reserves, this deficit would have to be made up in a concentration of 700 mm of rain in two months. This has occurred twice in 16 yr yielding a maximum recharge of 350 mm out of 16,000 mm of rain.

Furthermore, all the stored water and all the rainfall in the period was used by the grass. The initial amount stored is not known with any
precision but it must have been not less than 460 mm. From June 1965 to October 1966 the total rainfall was 1050 mm, giving a total water use of not less than 1510 mm, while the evaporative demand was 2325 mm, giving an average $E_t/E_o$ ratio of 0.65. This is not much short of the potential transpiration rate of 0.75 $E_o$ determined for a similar perennial grass (Pennisetum clandestinum) by hydraulic lysimeter techniques at Muguga and this high rate of transpiration was maintained despite very large soil-moisture deficits over much of the period. Quantitative values for the rates of water use at these higher levels of moisture deficit could have been obtained for the same degree of effort if a neutron-moisture gauge had been available.

RAINFALL PENETRATION

In marginal areas, water loss by surface runoff can make the difference between crop survival and failure. In these areas, it is imperative that land preparation practices should be directed to efficient water conservation. Measurement of runoff rates from plots of a realistic size is very costly and difficult but it is possible to compare different cultivation techniques by studying the manner in which the rainfall manages to penetrate into the soil. Figure 5 shows records of resistance units from such an experiment. Qualitatively the result is evident; quantitatively it was not possible to deduce much from the few gravimetric samplings taken at considerable inconvenience. A neutron-moisture gauge would have provided a complete picture without any more effort than that involved in taking the resistance records.
### TABLE II. THEORETICAL WATER BALANCE FOR CASHEW NUT TREES WITH COMPLETE CANOPY, NACHINGWEA, SOUTHERN TANZANIA

<table>
<thead>
<tr>
<th>Dec.-May</th>
<th>$E_t/E_o = 0.85$</th>
</tr>
</thead>
<tbody>
<tr>
<td>June-July</td>
<td>$E_t/E_o = 0.70$</td>
</tr>
<tr>
<td>Aug.-Nov. (1966)</td>
<td>$E_t/E_o = 0.50$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaporative demand, $E_o$ (Penman)</td>
<td>186</td>
<td>134</td>
<td>150</td>
<td>159</td>
<td>158</td>
<td>118</td>
<td>141</td>
<td>165</td>
<td>186</td>
<td>203</td>
<td>201</td>
<td>210</td>
<td>2014</td>
</tr>
<tr>
<td>Transpiration demand, $E_t$</td>
<td>158</td>
<td>114</td>
<td>128</td>
<td>135</td>
<td>134</td>
<td>83</td>
<td>99</td>
<td>82</td>
<td>93</td>
<td>102</td>
<td>100</td>
<td>181</td>
<td>1409</td>
</tr>
<tr>
<td>Average rainfall</td>
<td>208</td>
<td>183</td>
<td>198</td>
<td>99</td>
<td>20</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>38</td>
<td>150</td>
<td>201</td>
<td>901</td>
</tr>
<tr>
<td>Accumulated water stored in soil</td>
<td>50</td>
<td>119</td>
<td>189</td>
<td>153</td>
<td>39</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*All quantities in mm.*
TABLE III. THEORETICAL WATER BALANCE FOR AN ISOLATED CASHEW NUT TREE SURROUNDED BY BARE SOIL, NACHINGWEA, SOUTHERN TANZANIA

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E_t/E_o = 0.85</td>
<td>E_t/E_o = 0.50</td>
<td>E_t/E_o = 0.00</td>
<td></td>
<td></td>
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<tr>
<td>Evaporative demand, E_o (Peuman)</td>
<td>186</td>
<td>134</td>
<td>150</td>
<td>159</td>
<td>158</td>
<td>118</td>
<td>141</td>
<td>145</td>
<td>186</td>
<td>203</td>
<td>201</td>
<td>213</td>
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<td>Transpiration demand, E_t</td>
<td>112</td>
<td>80</td>
<td>90</td>
<td>95</td>
<td>95</td>
<td>25</td>
<td>30</td>
<td>35</td>
<td>39</td>
<td>43</td>
<td>42</td>
<td>128</td>
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<tr>
<td>Average rainfall</td>
<td>208</td>
<td>183</td>
<td>198</td>
<td>99</td>
<td>20</td>
<td>-</td>
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<td>-</td>
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<td>38</td>
</tr>
<tr>
<td>Accumulated water storage in soil</td>
<td>123</td>
<td>226</td>
<td>304</td>
<td>338</td>
<td>263</td>
<td>233</td>
<td>208</td>
<td>173</td>
<td>134</td>
<td>91</td>
<td>87</td>
<td>27</td>
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<tr>
<td>Long-term accum. water storage in soil</td>
<td>252</td>
<td>355</td>
<td>(+81D)*</td>
<td>(+4D)²</td>
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a Drainage beyond 10 ft

All quantities are in mm.
SPACING OF TREES

Where potential transpiration grossly exceeds the rainfall, the optimum spacing of trees is frequently a problem that is tedious, expensive and slow to solve empirically. Such a case arises with cashew nut trees in the coastal areas of Tanzania, where cashew nuts constitute the fourth most valuable export. In southern Tanzania the 900 mm of rainfall arrives in six months and the annual evaporation is 2015 mm. Despite this unfavourable situation, the cashew flowers and develops its crop entirely in the dry season maintaining a full cover of leaves throughout. The bulk of the crop is harvested from small groups of isolated trees in peasant farms. An attempt to rationalize production in plantations flourished for a few years and then, as the trees began to close the canopy, there was complete failure, with the trees defoliating. Much manual effort revealed a root system that maintained a lateral spread twice that of the canopy and exploited the soil to at least a depth of 10 ft. A theoretical analysis of the situation is given in Tables II and III for the closed canopy and isolated tree situation. They show quite clearly, despite broad assumptions, that under plantation practice at too close a spacing, the cashew tree is deprived of its ecological gambit and soon encounters severe moisture stress, whereas in its normal isolated state it has access to quite enough water to survive the dry season comfortably. Final advice on optimum spacings must however, depend on a quantitative soil-moisture study to yield more precise transpiration rates. This and many other similar studies in remote regions where gravimetric soil-moisture sampling techniques are difficult to apply with a routine would seem ideally suited to the neutron method. Characteristically, the measurements have to be made in relatively deep soils over extensive root systems thus minimizing the importance of measuring surface moisture, which poses a difficulty for the neutron method. The markedly seasonal pattern of the rain makes interpretation of the water-use data easier and, in the drier parts at least, water loss by slow drainage only rarely enters into the quantitative studies.

EXPERIENCE WITH ONE NEUTRON-MOISTURE GAUGE

Recognizing the potential usefulness of the neutron-moisture gauge in East African studies, the IAEA presented a set of equipment to E.A.C.S.O. In selecting the model stress was laid on simplicity of operation and robustness in the field. Unfortunately these criteria were inappropriate and attention should have been directed to the very high moisture contents encountered in many East African soils. Under these conditions the geometry of the probe and detector becomes the most important factor and the particular model obtained was very insensitive over the ranges of volumetric moisture contents obtaining in several important soil types. It was also insensitive on another soil where the gravimetric moisture contents were apparently below the critical level. Heating the soil to higher temperatures, however, revealed appreciable quantities of "bound" water that carried the total moisture contents into the insensitive range of the neutron-moisture gauge. These difficulties have drastically curtailed the useful work that could have been accomplished with this neutron-moisture gauge, which has been particularly unfortunate in that the technical departments of the East African governments have expected a
confirmatory lead from the East African Agriculture and Forestry Research Organization on the use of the neutron method. While even more convinced of the basic efficiency of the technique for soil-moisture studies in East Africa, it has been gallling not to be able to demonstrate it. In future, in cases of aid from the International Atomic Energy Agency, it might perhaps be necessary for an expert to pay a preliminary visit to ensure that the proposed model is appropriate to the local conditions.

REFERENCES


DISCUSSION

Y. BARRADA: As you mention in the paper, the Agency delivered to the EACSO a neutron moisture meter having the source at the end of the detector. I should like to make it clear that this equipment was supplied in accordance with a request from the Government of Kenya, which included background information and a description of the project, but did not specify the exceptionally high range of soil-moisture commonly encountered in Kenya.

M. DAGG: The difficulties resulting from very high soil-moisture contents were not described in the literature at the time, and the EACSO specification was based on the latest information available. The comment in the paper was intended only as a warning for future cases.

M. DE BOODT: You mention the use of resistance blocks to assess soil-moisture content. Can you comment on their usefulness for quantitative or qualitative (pF) determinations?

M. DAGG: We do not attempt to make direct quantitative assessments with the resistance units and do not calibrate them. They are used more like on-off switches, giving information on whether or not water is available to plants at any depth, at any time. However, with deeply rooting crops, deep soils and marked wet and dry seasons, it is often possible to arrive at semi-quantitative conclusions, knowing from other measurements the water-holding capacity of the soil; an illustration of this is provided in the paper, regarding the water extraction of grass at Muguga.

J. MARCESSE: What type of entry tubes did you use for your neutron measurements?

M. DAGG: Standard aluminium irrigation tubes of nominal 2 in. diam. Placing these at depths down to 20 ft presented no serious difficulty.

G. HAUSER: You mentioned the need, under East African conditions, to use neutron gauges suited to high moisture levels, and at the same time reported that some soils lose 15% more water when heated from 105°C to over 400°C. I cannot imagine that plants can produce the energy necessary to use this water. Was this tightly held water included in your data for soil moisture?
M. DAGG: Naturally, this tightly held water is not used by plants. My point was that at apparent moisture contents (105°C) of about 35%, the sensitivity of the neutron gauge was unexpectedly low. The real moisture content of the soil as sensed by the neutron gauge was nearer 50%, as revealed by heating the soil to 450°C. The neutron moisture gauge senses to total water.
SECTION III
WATER-MOVEMENT STUDIES
THE KINEMATICS OF SOIL WATER *

P.A.C. RAATS
UNITED STATES DEPARTMENT OF AGRICULTURE,
UNIVERSITY OF WISCONSIN,
MADISON, WIS.,
UNITED STATES OF AMERICA

Abstract

THE KINEMATICS OF SOIL WATER. Relatively simple physical-mathematical models have been quite successful in describing the flow of water in saturated and in partially saturated soils. The main features in these models are, (1) a balance of mass for the water, (2) a dynamical statement relating the velocity of the water relative to the solid phase, to the forces causing the movement of the water, and (3) a capacity relation, e.g., for a partially saturated soil the relationship between the water content and the pressure head. These models treat the soil water in a macroscopic sense as a continuous medium.

Kinematics deal with concepts that are useful in characterizing the motion of a continuous medium. Regarding the soil water as a continuous medium leads naturally to a discussion of the kinematics of soil water. Among the kinematic concepts considered are: velocity, vorticity, stream line, path line, streak line, and collections of particles forming a surface. The main purpose is to describe the restrictions imposed upon the kinematics of the soil-water movement by conservation of mass, the dynamical law, and the capacity relation. Several special cases are discussed. The soil may be saturated; the solid phase may be homogeneous or not homogeneous; and the flow of the water may be steady or unsteady. The nature of the velocity field of the water in the various cases is discussed. The relationship between the kinematics of the motion and surfaces of equal total potential, of equal pressure potential, and, in the case of a partially saturated soil, of equal water content, is described.

Radioactive tracers are very useful in studying the kinematics of soil water. The aims and limitations of several tracer techniques will be interpreted in terms of kinematic concepts.

INTRODUCTION

Theoretical discussions on the water movement in soils may be classified according to whether the point of view is molecular, microscopic, or macroscopic. In the molecular approach an attempt is made to describe the behaviour of individual water molecules. In the microscopic approach the water in the pores is treated as a continuous medium, most often as a Navier-Stokes fluid, bounded by the solid phase and by the gaseous phase. In the macroscopic approach one does not consider the motion of an individual water molecule or the flow in an individual pore, but instead attention is focused upon the water contained in a macroscopic differential volume element whose dimensions are large compared with the size of individual pores, but small compared with the whole flow system. We refer to the water contained in such a volume element as "a particle of water", and denote it by the symbol x.

In the macroscopic approach a soil is regarded as a mixture of phases: a saturated soil as a mixture of a solid phase and an aqueous phase, a partially saturated soil as a mixture of a solid phase, an aqueous phase.*

* Contribution from the Soil and Water Conservation Research Division, Agricultural Research Service, United States Department of Agriculture, Madison, Wisconsin, USA, in co-operation with the Wisconsin Agricultural Experiment Station.
and a gaseous phase. An elegant framework for the study of the motion of mixtures was introduced in 1957 by Truesdell [1]. The central idea in Truesdell’s continuum theory of mixtures is that a mixture may be regarded as a superposition of as many continua as there are constituents. Each constituent is assumed to be present at every point and all concepts that are used ordinarily for the description of one-constituent continuous media are defined for each constituent. Many aspects of macroscopic porous-media hydrodynamics can be discussed very naturally within the framework of the continuum theory of mixtures [2].

Kinematics is the study of the geometry of the motion of a continuous medium. Regarding the soil water as a continuous medium leads naturally to a discussion of the kinematics of soil water. To describe the motion of the water one needs to know at any time $t$ for any particle $X$ the place $\mathbf{x} = (x_1, x_2, x_3)$ it occupies:

$$\mathbf{x} = \mathbf{x}(X, t)$$  \hspace{1cm} (1)

In this paper it is assumed that the solid phase undergoes only rigid motions, and the rectangular Cartesian co-ordinate system $\mathbf{x}$ is taken as being attached to the solid phase. The velocity of the water is defined as:

$$\mathbf{v} = \left. \frac{\partial \mathbf{x}}{\partial t} \right|_{X}$$  \hspace{1cm} (2)

i.e., it is the time rate of change of the position $\mathbf{x}$ of the particle $X$. Note that the functional relationship between $\mathbf{x}$, $X$, and $t$ indicated in Eq. (1) leads naturally to the definition of $\mathbf{v}$ given in Eq. (2).

In most studies concerned with soil-water movement the flow is assumed to be one-dimensional. However, in recent years there has been an increased interest in two- and three-dimensional problems. The study of kinematics is fruitful mainly in connection with such more complex problems.

The implications of Eq. (1) must be closely examined, since this is the essence of the study of soil-water kinematics. Particularly interesting are the restrictions imposed upon the kinematics by the conservation of mass, the dynamical law, and the capacity relation. After a review of these main ingredients of the physical-mathematical model for the soil-water movement, the discussion of kinematics will be continued.

**PHYSICAL-MATHEMATICAL MODEL FOR MOVEMENT OF SOIL WATER**

A balance of mass for the water in a soil can be written as:

$$\left. \frac{\partial \rho}{\partial t} \right|_{\mathbf{x}} = - \mathbf{\nabla} \cdot (\rho \mathbf{v})$$  \hspace{1cm} (3)

where $\nabla$ is the vector differential operator, $\rho$ is the mass of water per unit volume of entire space, i.e., including space occupied by the solid
phase and by the gaseous phase, \( \bar{v} \) is the velocity defined by Eq. (2). The density of the water in the pores will be denoted by \( \rho \). The ratio of \( \rho \) and \( d \) is the volumetric moisture content \( \theta \). As in most discussions of water movement in soils it will be assumed that the density \( d \) is independent of time \( t \) and position \( \bar{z} \). Then, dividing (3) by \( d \) yields:

\[
\frac{\partial \theta}{\partial t} \bigg|_{\bar{z}} = - \nabla \cdot (\theta \bar{v})
\]  

(4)

It is assumed that, macroscopically, the water is subject to three forces: (a) a force arising from spatial variations of the water pressure, (b) the gravitational force, and (c) a drag force associated with the water movement relative to the solid phase. As a balance of forces for the water we adopt:

\[
- \frac{\rho}{d} \nabla p + \rho \bar{g} - R \bar{v} = 0
\]  

(5)

where \( p \) is the pressure of the water, \( \bar{g} \) is the gravitational force per unit mass of water, and the product of the resistivity \( R \) and the velocity \( \bar{v} \) is the drag force. Equation (5) may be written as:

\[
\theta \bar{v} = - K \nabla (h + z)
\]  

(6)

with the hydraulic conductivity \( K \), the pressure head \( h \), and the gravitational head \( z \) defined by the following relationships:

\[
K = \frac{\rho \bar{g}}{dR}
\]  

(7)

\[
h = \frac{p}{d}
\]  

(8)

\[
\bar{g} = - g \nabla z
\]  

(9)

Equation (6) may in turn be written as

\[
\theta \bar{v} = - K \nabla H
\]  

(10)

where the total head \( H \) is defined as

\[
H = h + z
\]  

(11)

To complete the model several relationships among the variables are assumed. The pressure of the gaseous phase is assumed to be homogeneous and constant. The pressure head \( h \) is assumed to be a function of the history of the moisture content \( \theta \) from some initial time \( t_0 \) up to the present time \( t \) and, because of possible non-homogeneities in the
solid phase, also of position $\bar{x}$:

$$ h = h \left[ \theta_{t}, \bar{x} \right] $$

(12)

Equation (12) is the capacity relation referred to in the introduction. A similar assumption is adopted for the hydraulic conductivity $K$:

$$ K = K \left[ \theta_{t}, \bar{x} \right] $$

(13)

From (12) and (13) it follows that:

$$ K = K \left[ h_{t}, \bar{x} \right] $$

(14)

The explicit dependence upon $\bar{x}$ in (12), (13), and (14) may arise from differences with regard to such properties as bulk density, particle-size distribution, and nature of the surface of the particles.

If the water movement is steady then (3) reduces to:

$$ \nabla \cdot (\theta \bar{v}) = 0 $$

(15)

Equations (3) and (5) arise naturally in the continuum theory of mixtures [2]. A recent review by Miller and Klute [3] indicates that Eqs. (4), (10), (12), and (13) have been quite successful as a basis for describing water movement in partially saturated soils.

In a saturated soil the volume fraction $\theta$ at $\bar{x}$ is independent of $t$, and Eq. (15) will apply, whether the flow is steady or unsteady. Equation (10) is still the appropriate dynamic expression for the volumetric flux $\theta \bar{v}$. However the functional relationships (12), (13), and (14) are to be replaced by:

$$ K = K \left[ \bar{x} \right] $$

(16)

If the soil is saturated and the solid phase is homogeneous then the moisture content $\theta$ and the hydraulic conductivity will be independent of position $\bar{x}$. The balance of mass for the water then reduces to:

$$ \nabla \cdot \bar{v} = 0 $$

(17)

and $\bar{v}$ will be given by:

$$ \bar{v} = \nabla \left( \frac{K}{\theta} H \right) $$

(18)

THE VELOCITY FIELD

A stream line is a curve which at every point is tangent to the velocity [1]. At any instant the stream lines may be determined experimentally by injecting a tracer at many points and following the tracer for a short time. According to Payne [4], this principle was used by Mairhofer [5] to determine the direction of flow in an aquifer. Mairhofer injected
into a borehole a radioisotope, which was adsorbed on the aquifer material and later scanned radially to determine in which direction the radioisotope had been carried by the water. A stream sheet is a surface, which is tangent at each point to the velocity. The stream lines and stream sheets specify the flow pattern at any instant. In general the flow pattern changes as time passes.

The path line of a particle $\chi$ is the curve in space traversed by $\chi$ as $t$ varies [1]. The path lines of a particle $\chi$ may be determined experimentally by labelling it with a tracer and then keeping track of it. The passage of a certain particle through a certain point may have a more or less lasting effect and, in view of this, path lines may be important. Also of interest are the paths of a collection of particles forming a surface. Basically, tritium and $^{14}$C dating amount to keeping track of labelled collections of water particles. This type of radioactive tracer technique has been quite successful in hydrology. Insertion of several labelled surfaces in a laboratory column could, in principle at least, be used to study the pattern of water uptake by roots [6].

The velocity $\nabla$ is sometimes measured by putting a tracer, such as $^{85}$Br, in an injection well and measuring the time required for the tracer to reach an observation well. In such tests the path of the tagged particle is most often assumed to be a straight line. Information regarding the hydraulic conductivity will only result if something is known about the distribution of the total potential $H$.

A streak line through the point $\bar{x}$ at time $t$ is the locus at time $t$ of all particles $\chi$ which at any time, past or future, have occupied or will occupy the point $\bar{x}$ [1]. Parts of a streak line through $\bar{x}$ may be determined by simultaneously injecting tracer at $\bar{x}$. Streak lines of particles of the aqueous phase of a soil are important in connection with convective transport of fertilizers, harmful salts, herbicides, and other pollutants. If a certain surface or volume in the solid phase is such that contact of the water with it affects the water significantly, then the streak volume associated with this surface or volume is of interest. For example, the water passing through a feed lot may elsewhere contribute nutrients and/or pollute the water supply.

The stream line, the path line, and the streak line associated with the point $\bar{x}$ at time $t$ are all tangent to the velocity at $\bar{x}$ and $t$. If the motion is steady then the three lines coincide. Therefore, in steady flow the stream line through $\bar{x}$ may be determined by the simple method, which in unsteady flow will produce a streak line, namely by continuously injecting tracer at $\bar{x}$. Dyes have been widely used for studying steady flow patterns in sand-tank models [7]. In view of the above discussion, it appears that the potential of this simple tracer technique has not been exhausted.

A curve is a stream line if, at any point along the curve, its tangent $d\bar{x}$ and the flux $\nabla$ have the same direction, i.e.

$$\nabla \times d\bar{x} = 0 \quad t = \text{constant} \quad (19)$$

or equivalently [1]:

$$\frac{dx_1}{\partial v_1} = \frac{dx_2}{\partial v_2} = \frac{dx_3}{\partial v_3} \quad t = \text{constant} \quad (20)$$
The integrals of (20) are stream sheets. The stream lines are curves of intersection of two families of stream sheets. Suppose that the surfaces \( f = \text{constant} \) and \( g = \text{constant} \) are two such families of stream sheets. Then the field \( \theta \psi \) is given by:

\[
\theta \psi = h \nabla f \times \nabla g
\]

where \( h \) is an appropriate scalar field. Finding the scalar fields \( f, g \) and \( h \) is a difficult task in general. In the following some special cases are considered.

A vector field whose divergence vanishes is called solenoidal. The vector field \( \theta \psi \) satisfies (15), and is therefore solenoidal, in two cases:
(a) if the soil is partially saturated, but the flow is steady, and (b) if the soil is saturated. It can be shown that if \( \theta \psi \) is solenoidal the scalar field \( h \) in (21) is a function of the scalar fields \( f \) and \( g \). More particularly, if \( \theta \psi \) is solenoidal, it may be represented as:

\[
\theta \psi = \nabla f' \times \nabla g'
\]

These particular properties of solenoidal fields were discovered by the 18th century mathematician Euler [8]. Nelson [9, 10, 11] pointed out their usefulness for studies of flow in porous media.

We now assume not only that \( \theta \psi \) is solenoidal but also that the motion is plane, say, with regard to the \( x_3 \)-direction. The balance of mass then reduces to:

\[
\frac{\partial \psi_1}{\partial x_1} + \frac{\partial \psi_2}{\partial x_2} = 0
\]

Surfaces \( x_3 = \text{constant} \) are now stream sheets and (22) reduces to:

\[
\theta \psi = \nabla f' \times \nabla x_3 = \frac{\partial f'}{\partial x_2} \nabla x_1 - \frac{\partial f'}{\partial x_1} \nabla x_2
\]

so that:

\[
\psi_1 = \frac{\partial f'}{\partial x_2} \quad \psi_2 = \frac{\partial f'}{\partial x_1}
\]

Note that (25) satisfies (23). Equation (25) implies that knowledge of \( f'(x_1, x_2) \) determines the velocity field completely. That a curve \( f' = \text{constant} \) is a stream line, may be shown as follows. Along a curve \( f' = \text{constant} \):

\[
df' = \frac{\partial f'}{\partial x_1} \, dx_1 + \frac{\partial f'}{\partial x_2} \, dx_2 = 0
\]
Re-arranging (26) and substituting (25) yields:

\[
\frac{dx_1}{dx_2} \bigg|_{f' = \text{const.}} = -\frac{\frac{\partial f'}{\partial x_1}}{\frac{\partial f'}{\partial x_2}} = -\frac{\theta v_2}{\theta v_1} \tag{27}
\]

This shows that at every point \((x_1, x_2)\) the flux \((\theta v_1, \theta v_2)\) is tangent to a curve \(f' = \text{constant}\), and thus that these curves are indeed stream lines. The function \(f'(x_1, x_2)\) is often called stream function [7]. Slichter [12] considered the case when Eq. (17) applies and introduced the function \(f'/\theta\) which he called current function.

Integration of (25) between the points \((x_2^0, x_2^1)\) and \((x_1^0, x_1^1)\) yields:

\[
f_{x_1}^1 - f_{x_1}^0 = \int_{x_2^0}^{x_2^1} \theta v_2 \, dx_2
\]

\[
f_{x_2}^1 - f_{x_2}^0 = \int_{x_1^0}^{x_1^1} \theta v_1 \, dx_1
\]

The difference in stream functions between two points is equal to the flux through any line connecting the two points. Nelson [10] discussed the three-dimensional extension of (28) for steady flow.

The path line of a particle is the integral curve of [1]:

\[
dx = \hat{v} \, dt \quad \chi \text{ fixed} \quad -\infty < t < \infty \tag{29}
\]

Some of the implications of (28) for unsteady, saturated flow were studied by Nelson [11]. The study of path lines is inherently difficult since it involves moving particles. The same is true for streak lines.

RELATIONSHIP BETWEEN THE VELOCITY FIELD AND THE FIELDS OF TOTAL HEAD, PRESSURE HEAD, GRAVITATIONAL HEAD, AND MOISTURE CONTENT

A vector field \(\mathbf{a}\) is called complex-lamellar if there exist scalar fields \(k\) and \(\ell\) such that [8]:

\[
\mathbf{a} = k \nabla \ell \tag{30}
\]

A complex-lamellar field \(\mathbf{a}\) is everywhere normal to the equipotential surfaces \(\ell = \text{constant}\). A vector field \(\mathbf{a}\) is complex-lamellar if, and only if, it is normal to its curl, i.e.

\[
\mathbf{a} \cdot \nabla \times \mathbf{a} = 0 \tag{31}
\]
Comparison of Eqs (10) and (30) shows that in general the volumetric flux field \( \theta \vec{v} \) is a complex-lamellar field, as was pointed out recently by Nelson [13]. A significant implication, which was not stated by Nelson, is that the volumetric flux \( \theta \vec{v} \) is normal to surfaces of equal total head \( H \). This makes it possible to infer the flow direction at any point from measurements of \( H \) at a sufficient number of points. Evidently a decade ago there was some doubt among the experts with regard to this orthogonality in systems in which the hydraulic conductivity depends upon position, perhaps because systems consisting of layers of different hydraulic conductivity exhibit an apparent anisotropy if the technique for measuring the hydraulic conductivity yields averages over more than one layer. However, Bouwer and Little [14] constructed lines of equal total head for steady, plane flow in saturated and in partially saturated soils from resistance-network measurements and then, at the suggestion of Childs, drew the stream lines as orthogonals. Nelson [9,11] did indicate that, for steady flow in an isotropic soil, the flux is normal to surfaces of equal total head. It should be emphasized that in isotropic soils this orthogonality holds no matter whether the flow is steady or unsteady. Generally the volumetric flux is not perpendicular to surfaces of equal pressure head or of equal moisture content.

A vector field \( \vec{b} \) is called lamellar if there exists a scalar \( m \) such that [8]:

\[
\vec{b} = \nabla m
\]  
\( (32) \)

A lamellar field \( \vec{b} \) is everywhere normal to the equipotential surfaces \( m = \text{constant} \). A vector field \( \vec{b} \) is lamellar if and only if its curl vanishes, i.e.,

\[
\nabla \times \vec{b} = 0
\]  
\( (33) \)

For this reason lamellar vector fields are usually called irrotational vector fields.

Comparison of Eqs (18) and (32) shows that, if the soil is saturated and homogeneous the velocity field, \( \vec{v} \) is a lamellar field. The scalar \( (K/\theta)H \) is the scalar potential of the velocity \( \vec{v} \). The field \( \vec{v} \) being lamellar implies that it is irrotational, i.e., that its curl vanishes. Jacob [15] has pointed out that the viscous flow in individual pores will always be rotational, even if the macroscopic field \( \vec{v} \) is irrotational.

Any vector field \( \vec{c} \) may be represented as the sum of a complex-lamellar vector field and a lamellar vector field [8]:

\[
\vec{c} = u + \nabla v + \nabla w
\]  
\( (34) \)

Truesdell calls the scalars \( u, v, \) and \( w \) the Monge potentials of \( \vec{c} \).

If the solid phase is homogeneous, then the explicit dependence of \( K \) upon \( \vec{x} \) expressed in Eq. (14) does not arise so that Darcy's law may be written as:

\[
\theta \vec{v} = -\nabla \psi - K \left[ h^s \right] \nabla z
\]  
\( (35) \)
with the potential \( \varphi \) defined as:

\[
\varphi = -\int K[h_{oi}'] \ n h
\]

Comparing Eqs (34) and (35) shows that in this instance the complex-lamellar field \( \vartheta \varphi \) consists of a lamellar part \(-\nabla \varphi = -K[h_{oi}'] n h\) and a complex-lamellar part \(-K[h_{oi}'] n z\). Taking the curl of (35) gives:

\[
\nabla \times (\vartheta \varphi) = \nabla K[h_{oi}'] n \nabla z
\]

The vector field \( \nabla \times (\vartheta \varphi) \) is called the vorticity [8].

In fluid dynamics the velocity of a particle relative to velocities of neighbouring particles plays an important role. It can be shown [8] that any motion at each instant may be decomposed into a uniform translation, a dilatation along three mutually perpendicular axes, and a rigid rotation of these axes. The uniform translation is measured by the velocity \( \varphi \). The dilatation along three perpendicular axes is in part measured by the time rate of change in water content. The rate of rotation is measured by the vorticity. It appears that tracers could be helpful in elucidating some of these features.

The vorticity \( \nabla \times (\vartheta \varphi) \), given by (37), vanishes if the vectors \( \nabla K \) and \( \nabla z \) are collinear, which is the case for vertical infiltration and for capillary rise. It is only the horizontal component of \( \nabla K \) that contributes to the rotation.

If the solid phase is not homogeneous, so that the explicit dependence of \( K \) upon \( \bar{x} \) indicated in Eq. (14) needs to be considered, then a potential \( \varphi \) as defined in Eq. (36) does not exist. The vorticity is then given by:

\[
\nabla \times (\vartheta \varphi) = \nabla K_{h=\text{const.}} \times \nabla h + \nabla K \times \nabla z
\]

The first term on the right-hand side of (38) represents a contribution to the rate of rotation from explicit dependence of \( K \) upon \( \bar{x} \).

CONCLUDING REMARKS

The foregoing discussion was mainly concerned with some of the implications of the physical-mathematical, macroscopic model which has been widely used to describe the water movement in saturated and in partially saturated soils. At several points it was indicated that tracer techniques are useful in studies of soil-water kinematics. The main limitation of tracer techniques arises from the fact that a labelled particle \( \bar{x} \) tends to lose its tracer to surrounding particles. Of course, as Nielsen and Biggar [18] argue convincingly, this limitation need not be a reason for despair, but instead offers a challenge to anyone who wishes to understand the limitations of the model.

The concepts discussed in this paper are certainly not new. For example the terms lamellar, complex-lamellar, and solenoidal were
introduced by Kelvin in 1850 [17]. As in most sciences, our main task is to learn and to put to use existing knowledge.

REFERENCES

[17] THOMSON, W., (Lord Kelvin), Phil. Trans. R. Soc. 142 (1853) 245.

DISCUSSION

M.J. FRISSEL: Do you think it is possible to build in the effect of salt concentration on the water potential, or would we have to calculate it from irreversible thermodynamics?

P.A.C. RAATS: The dynamics of the dispersion of salts and water are difficult in any macroscopic theory, including the thermodynamics of irreversible processes, especially if the soil is only partially saturated.

D. KIRKHAM: You mention the drawing of streamlines orthogonal to equipotentials in three-dimensional flow. Would it not be well to point our, as Sommerfeld has done in his book on mechanics, that no set of unique streamlines can be drawn such that the difference in value of the stream function passing through two points will give the flux?

P.A.C. RAATS: Yes. The development resulting in Eq. (28) in the paper is very special. However, it can be shown that for three-dimensional steady flow there is a relationship between the stream surfaces and the distribution of fluxes.

L.G. KING: Regarding Mr. Kirkham's question, I would point out that if one formulates the stream surfaces properly, in three dimensions, for steady flow, integration over the surface orthogonal to the stream surfaces does give the volume flow-rate in the stream tube. In fact, we
perform this integration numerically in some of our work. Those interested in the subject may like to refer to papers by R.W. Nelson (Refs [9-11] in Mr. Raats' paper).

P. COUCHAT: Mr. Raats spoke of saturated and partly saturated media and I should like to know, with reference to the papers presented by Marcesse\(^1\) (SM-94/14) and Rançon\(^2\) (SM-94/16), whether it would be possible to consider extension of the analogue method (e.g. electrical conductivity) used to study steady flow.

P. A.C. RAATS: The paper by Bower and Little (Ref. [16]) deals with an electrical analogue for steady saturated and partially saturated flow. Unsteady flow is more complex because of the dependence of hydraulic conductivity on moisture content.

W.K.G. KÜHN: I think there is a difference between electrical conductivity and water movement. We are not concerned with potential gradient alone, but also with possible rotation of the water.

P. A.C. RAATS: In all analogues for groundwater flow, we work with a conductivity, consisting of a representative value, distributed over a fairly large volume. We are not trying to make a model of detailed processes in an individual core.

H.W. SCHARPENSEEL (Chairman): Could you give an example of your suggested tracer applications for the elucidation of processes such as dilation and rotation?

P. A.C. RAATS: Tests of some of the ideas discussed could be performed in sand tank models. For example, one could label particles that initially form a circle and observe their movement relative to each other.

\(^1\) MARCESSE, J., «Détermination in situ de la capacité de rétention d’un sol au moyen de l’hydromètre à neutrons», these Proceedings.

\(^2\) RANÇON, D., «Évolution de l’humidité d’un sol soumis à un apport continu d’eau sur une petite surface», these Proceedings.
MIGRATION OF WATER AND IONS IN UNDISTURBED SOIL COLUMNS AND ITS DESCRIPTION BY SIMULATION MODELS

P. POELSTRA AND M.J. FRISSEL
EURATOM-ITAL,
WAGENINGEN,
THE NETHERLANDS

Abstract

MIGRATION OF WATER AND IONS IN UNDISTURBED SOIL COLUMNS AND ITS DESCRIPTION BY SIMULATION MODELS. This paper describes (1) the technique of taking 100-cm-high and 12-cm-diam. soil columns without disturbing the natural build-up of the profile; (2) the rain installation, controlled by an automatic device, that enables fluxes from 0.05 ml cm⁻² d⁻¹ to 20 ml cm⁻² d⁻¹ and supplies the water in drops of about 0.04 ml. In this installation 25 columns can be handled simultaneously at five different flow-rates while 10 different solutions can be used for leaching; (3) the column scanner specifically developed for measuring the distribution pattern of the labelled compound in the column; and (4) the results of several leaching experiments in a podosolic soil with tritiated water and solutions of strontium- and calcium-labelled CaCl₂ at different flow-rates and concentrations.

As soil is a heterogeneous system it is not possible to describe the migration by the usual chromatographic theories such as those of Gleichauf or Hister and Vermeulen. The mathematical description, therefore, is done by simulation models. In these models the calculation is carried out step by step by a computer whereby the conditions are varied as necessary after each step. Several models that have been tested are described and compared with experimental results.

INTRODUCTION

It is desirable to obtain a quantitative insight into transport phenomena occurring in soils in relation to such processes as: salinization, application of fertilizers, accumulation of biocides and fallback products.

To enable an interpretation of the results of laboratory experiments and to apply them to field conditions, these investigations should be carried out on undisturbed soils because the structure of the soil is an important factor in transport phenomena. Effective research on this problem involves the following:

(1) The soil columns should be taken from a field and transported to a laboratory without the natural build-up of the profile being disturbed.

(2) There should be an installation simulating rain with different constant fluxes, which are adjustable. The drops should be distributed equally over the column surface.

(3) An apparatus should be available which enables the migrating compound to be located without the soil column being destroyed. This devise involves labelling the compound to be studied with a γ-emitting isotope, and the column must be assembled so that it can be easily mounted and dismounted.
1. Obtaining the column

A perspex tube 100 cm high and 12 cm diam., with a screw-thread at the lower end on which was fitted a sharp-edged hollow augerhead was used. An anchor was screwed into the soil on each side of the column and a horizontal beam mounted between the anchors, while between beam and tube, a jack was placed. Jacking slowly, the tube was gradually pressed into the soil and then dug out. The augerhead was unscrewed and the column taken to the laboratory, where a filter system was screwed on to the bottom of the column.

2. The rain installation

On each column a rain head was placed consisting of a piece of perspex tube, with a 6-mm-thick perspex base, with 25 capillaries in a fixed pattern. The capillaries had a 0.2-mm internal diameter and were 12 mm long (Fig. 1). Around the top of each capillary was a thin-walled perspex cup, with a 0.26-ml capacity.

![Diagram of rain head.](image)

The rain head was filled with water to a level a few millimetres above the cups and drained off, the cups remaining filled. There was no leakage through the capillaries because the internal diameter was too small. Extra pressure, needed for them to flow, was obtained by an air compressor connected to the rain head. The water then fell on to the soil surface in drops of about 0.04 ml.

Each column had such a rain head and the supply and discharge of water were completely automatic. The installation was operated by control units provided with timers and cycle counters. The flux was adjustable from 0.05 ml cm⁻² d⁻¹ to 20 ml cm⁻² d⁻¹. Thus, one cycle consisted of:

1. Water supply: water was pumped to the rain heads.
2. Water discharge: when pumping stopped, a valve opened and the water flowed back to the supply.
3. Compression in the rain head: when excess water had drained off, air was blown into the rain heads by a compressor and the cups drained by the capillaries.

More than one pump was connected to each control unit so that, per series of columns with the same flux, more than one solution can be used for leaching.

3. Detection of the γ-labelled compound

To carry out this detection, an apparatus was designed to enable the column to be scanned and the migration pattern to be registered.
directly on to a recorder. This soil-column scanner consisted of a single-channel \( \gamma \)-spectrometer and a framework with a heavily shielded detector, which can move vertically along the column at variable speeds. This vertical movement was by steps of adjustable size. Thus, the measurement occurred layer by layer; for example the activity of each 2-mm column length was measured during 30 s and registered on to the recorder. During the measurement the column rotated.

EXPERIMENTS

Leaching experiments were set up on 20 soil columns, in four series each of five columns. The migration of tritiated water, \(^{85}\)Sr, \(^{43}\)Ca and \(^{36}\)Cl with four different fluxes and five different CaCl\(_2\) concentrations, was investigated. The cycle frequency was 14, 38, 80 and 200 min, corresponding to fluxes of 5.8, 2.3, 1.0 and 0.4 ml cm\(^{-2}\)d\(^{-1}\).

Before the activity was introduced into the column, the columns were percolated with 0.05 N CaCl\(_2\) to reach a uniform occupation of the adsorption sites. Then the column was equilibrated with CaCl\(_2\) of the concentration to be used during the leaching experiments. Both when the labelled compound was introduced and while it was being leached, this CaCl\(_2\) concentration was maintained. All additions were supplied through the rain head; throughout the experiment the flux was maintained at the same level. The applied CaCl\(_2\) concentrations varied from 0.001 to 0.01 N.

When experiments with \( \beta \)-emitters are carried out the columns must be divided into layers and analysed, or breakthrough curves must be made. To follow the transport of tritiated water breakthrough curves were prepared. On one hand these curves were used to eliminate spreading effects as a result of ion exchange; on the other hand they were used to check whether the columns behaved identically.

RESULTS

Figure 2 presents the tritium breakthrough curves for one series of columns. The figure permits an easy comparison of the breakthrough curves of all four columns. For each column there is a separate horizontal axis, representing time. The flux was about 0.1 ml cm\(^{-2}\)h\(^{-1}\).

![FIG. 2. Breakthrough curves for tritiated "rain" percolated through undisturbed soil columns.](image-url)
The vertical axis overlaps; the relative concentrations \( c/c_0 \) are given, in which \( c_0 \) is the concentration of the activity of the supplied rain. An open dot indicates the 50% point of the increase in tritium concentration. The time needed to reach this 50% point multiplied by the flux is a measure of the water volume of the column. This results in water volumes of 3100, 3090, 2870 and 2990 ml/column of 97.5 cm length and a cross-section of 110 cm². (The exact times were 286, 290, 274 and 260 h; the fluxes were 0.0905, 0.0970, 0.0954 and 0.1054 ml cm⁻² h⁻¹.) The addition of tritiated rain ceased after 268 h. Again the time needed to reach half the tritium concentration gives another measure of the water volumes. Calculated volumes were 3190, 3140, 2980 and 3140 ml (times were 294, 294, 284 and 274 h; fluxes equal). Bearing in mind that these columns were undisturbed natural profiles, these data indicate that the columns were fairly uniform and could be used for further experiments.

Figure 3 shows some distribution curves of \(^{85}\text{Sr} \) at different times. Curve 1 represents the situation when all the activity had been supplied.

![Graph](image)

**FIG. 3.** Inflow pattern of \(^{85}\text{Sr} \), which has been added to "rain", into an undisturbed soil column. The respective curves 1 to 5 are determined 9.9, 16.4, 21.1, 36.1 and 53.1 d after the start of the experiment.

The curves are corrected for radioactive decay. The flux was 8.18 ml cm⁻² d⁻¹; the \( \text{CaCl}_2 \) concentration was 0.001 N. The curves show an enormous spreading effect. The soil was a non-loamy fine sand, which had been used as arable land for a long time and as pasture during the last three years. The particle-size fractions were: < 0.1 mm : 0.18, 0.1 - 0.2 mm : 0.56, 0.2 - 0.3 mm : 0.17, > 0.3 mm - 0.09. The exchange capacity varied from 9 meq/100 g soil in the upper layers to 2 meq in the lower layers; the humus content varied from 5.6 to 1.5%; the pH(KCl) was 4.5. The mean moisture content during the experiment was 28.1%.

**SIMULATION MODELS**

Our purpose was a general interpretation of the results to enable predictions for situations other than those of the experiments. In general
it can be stated that, within the laboratory, the water flux and dispersion can be accelerated but diffusion processes and chemical reactions cannot. The procedure must therefore show the time dependence of the factors determining the flux, dispersion, diffusion and velocity of chemical reactions. If this time dependence has been evaluated from experiments the factors mentioned above can be calculated for other circumstances, so a fair prediction for the required circumstances is then possible. In homogeneous systems this calculation is rather easy: many chromatographic theories are available \([1, 2, 3, 4, 5]\).

In a heterogeneous system such as soil, the situation is more difficult. Almost any chromatographic theory involves integrations in which many parameters are assumed to be constant. The equations, therefore, give only a rough picture of situations in the soil. The more complex situations cannot even be treated in this way.

Therefore, the authors have described the experiments by simulation models. In the models used, soil and time were divided into numerous small soil layers and small time steps. For every time step the events were calculated in each soil layer. For each layer the soil parameters were assumed to be constant during the time step, but for different layers and for successive time steps the parameters may vary. If the variation between the steps or layers was such that it influences the results of the calculation, it was repeated with smaller time steps or layers. Thus, the procedure of making the steps and layers smaller was repeated till their further decrease no longer influenced the result of the calculation.

The kind of models considered can best be seen from Figs. 4-7.

![Simulation model of vertical transport. Influence of diffusion and dispersion.](image)

In the models to be discussed the authors limited themselves to the transport of materials in the dissolved state (including tritiated water in water). For dissolved materials the models were transient state models; however, the water movement is considered to be a steady state or at least a combination of steady states.

Figure 4 shows the effect of diffusion and dispersion during the downward migration of a limited amount of material. At the beginning all the material involved was present in the topmost layer. Exchange reactions were assumed to be so fast that they caused no broadening of the band.
THE VELOCITY IN THE 3rd AND 4th LAYER IS 2 TIMES HIGHER THAN IN THE FIRST 2 LAYERS. IN THE NEXT 2 LAYERS IT IS AGAIN DOUBLED.

![Diagram](attachment:image.png)

**FIG. 5.** Simulation model of vertical transport. Movement through a heterogeneous system.

**ADSORBED SOLUTION**

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**EQUILIBRIUM**

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**DURING THE 1st TIME STEP**

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**A CERTAIN AMOUNT OF SOLUTE ENTERS THE TOP LAYER**

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**IN THE 1st STEP 50 PERCENT IS ADSORBED, THEN THE LIQUID PHASE IS TRANSPORTED DOWNWARDS**

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**THE MUTATION OF ADSORPTION AND DESTRUCTION TAKE PLACE, THE LIQUID PHASE IS AGAIN TRANSPORTED**

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**THE TIME STEP AND LAYER THICKNESS CAN BE VARIED INDEPENDENTLY**

**FIG. 6.** Simulation model of vertical transport. Influence of chemical reactions (adsorption and desorption).

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**100 PERCENT OF THE COMPOUND IS IN THE TOP LAYER**

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**THE 1st STEP DISTRIBUTION INTO ADSORBED AND DISSOLVED PARTS**

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**THE MATERIAL IS AGAIN DISTRIBUTED INTO ADSORBED AND DISSOLVED PARTS, THE DISSOLVED PART MOVES DOWNWARD**

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**FIG. 7.** Simulation model of vertical transport. Plate model.
during downward migration of the soil solution (this assumption was not at all essential — it will be dealt with later).

During the first time step, $\Delta T/2$, the material is transported towards the second layer. Thereafter, diffusion towards the first and third layers is calculated during a period $\Delta T$, after which there is another vertical transport step for $\Delta T/2$.

In model B of Fig.4 the same process is described, but with three diffusion steps, each of $\Delta T/3$, so that simulation is more refined. From this example it appears that the number of transport steps and number of diffusion steps can be chosen independently of each other. One is completely free in the choice of the layer thickness, although the relation $\Delta S = \Delta T \cdot v$ (in which $\Delta S$ is the layer thickness and $v$ is the mean velocity of the material involved) correlates the quantities $\Delta S$ and $\Delta T$.

Figure 5 shows that this system can also simulate heterogeneous situations. A situation is outlined in which the transport velocity increases with depth. Every two layers the velocity is doubled. Because the velocity is determined by the experiment and the equation $\Delta S = \Delta T \cdot v$ must be satisfied, $\Delta S$ or $\Delta T$ must be varied. It is more convenient to vary the layer thickness $\Delta S$ and keep the time step $\Delta T$ constant.

This does not mean that one is limited in the choice of the layer thickness, but in this example the upper layers must be thinner than the lower layers. During transport diffusion occurs.

Figure 6 expresses the influence of chemical reactions; they may be exchange reactions, adsorption and desorption phenomena or other processes. The figure, which is kept as simple as possible, shows an adsorption-desorption reaction. During the first step the material enters the liquid phase, thereafter adsorption starts. If the adsorption has proceeded to some degree (at equilibrium 90.9% is adsorbed; in the example only 50%) the liquid phase is transported downwards, after which desorption takes place in the upper layer and adsorption in the second layer. Thus, during this time step, neither reaction can reach equilibrium; long before this situation is reached, the liquid phase is again transported downwards. In this model the layer thickness can also be chosen independently. The choice of the time step is optional as well, but must be short. If, for instance, $\Delta T$ is so long that equilibrium is almost reached, reaction velocity can no longer be introduced into this model.

If the equilibrium situation is wanted, for instance because the equilibrium conditions are known, but the reaction velocities are not, the situation created is as given in Fig. 7. In chromatographic theories this model is known as the plate model. The text in the figure needs no further explanation. The feature of this model is that there is no choice in the layer thickness, but the thickness is dependent on experimental conditions. If the layer thickness in this model is made increasingly smaller no band broadening eventually results. The material is transported downwards as a block (that this situation never happens in an experiment arises from the fact that diffusion and dispersion cannot be avoided in any experiment). This piston flow occurs when the reaction velocity is high in relation to the vertical velocity. This consideration has led us to the assumption in Figs. 4 and 5 that band broadening through exchange reactions need not be considered.
Naturally a more sophisticated scheme is to introduce exchange velocities into the model (as in Fig. 6).

Apart from the fact that these velocities are unknown, this also causes technical difficulties. The model must then work with time steps of seconds, but for an experiment which sometimes takes a year, this is too heavy a task even for a computer.

For slow chemical processes such as reactions between gypsum and dissolved salts the velocities are indeed taken into account.

The programme we now use involves about 150 soil and other variables. These are tortuosity, packing factor, grain size, amount adsorbed, cation-exchange capacity, surface conductance, quantity in solution and moisture content, all of which vary with depth. Other parameters are for artificial rain and time. This programme adequately simulates the experimental results. In the future we plan to study the slower chemical reactions to enable prediction also for complicated soils.

REFERENCES


DISCUSSION

U. ZIMMERMANN: I think the results of your laboratory experiments can be applied under field conditions only where rain intensity is low.

On a macroscopic scale of about dm$^2$ or m$^2$, the heterogeneity of soils leads — especially if there is intense rainfall — to large variations in hydraulic conductivity, causing considerable spreading of the tracer front and appreciable variations in its position from place to place. This is because variations in soil-water velocity over greater distances cannot be levelled out by lateral molecular diffusion.

However, I believe that in Central Europe, where intense rainfall occurs only rarely, it is a very good method of obtaining a quantitative picture of transport phenomena in soils.

M.J. FRISSEL: It is true that columns of only 12-cm diam. are not suitable for the conditions you mention. However, there is no reason to use larger columns. Moreover, so far as I can see at present, it should be possible to take these irregularities into account in our computer programme.

D. RANCÓN: Have you also carried out experiments on soils consisting mainly of clay? We ourselves carried out experiments on sandy soils with small columns and obtained satisfactory results. However, with clay soils, we noted preferential paths close to the walls of the column. Did you notice this abnormal circulation?
M.J. FRISSEL: We have done some preliminary experiments with loess soils. Although we have not yet tried other soils, we would not expect to encounter any difficulties.

P.A.C. RAATS: It seems to me that use of the point of 50% increase in tritium concentration to calculate the water volume of the column is not always justified. In heterogeneous media in particular, this may result in a lot of the water being by-passed.

M.J. FRISSEL: In principle, you are right, but from independent conventional measurements of the water volume (drying at 105°C) we know that the error is negligible compared with the variations calculated from the breakthrough curves.

W.R. GARDNER: If I understood your paper correctly, your computer model does not clash in any essential way with the general theories of ion-exchange dynamics, insofar as the basic assumptions are concerned. This being so, I would suggest it may be worthwhile looking at the simpler problem, for which solutions are available, before having recourse to a computer to solve a finite difference equation.

M.J. FRISSEL: I quite agree; one should not use a computer if one has no insight into chromatographic theories. However, there are many chromatographic theories which cannot be adapted to suit soil studies, even if the system is homogeneous. In some theories, for instance, the assumed flow-rates are in metres per second. Many phenomena which may be important in soil are not considered in these theories. We have recently published a review on this subject in Plant and Soil (No. 26, 1967).

H.W. SCHARPENSEEL (Chairman): Your experimental rig was equipped with a gamma spectrometer, but you referred mainly to the beta emitters 3H, 45Ca and 36Cl as tracers. I presume that you used other equipment for measuring them.

M.J. FRISSEL: Yes, we either divided the column into layers and analysed them, or drew breakthrough curves.

H.W. SCHARPENSEEL: Did you observe any marginal distortions or preferential flow paths in the columns?

M.J. FRISSEL: Before placing our columns in the soil, we treated the inner wall with silicon oil, just as you advised us when we visited you. Afterwards, we never observed any downward movement of drops along the inner wall, although we watched it frequently.
MOVEMENT OF IONS AND COLLOIDS
IN UNDISTURBED SOIL AND
PARENT ROCK MATERIAL COLUMNS

W. KERPEN
ARBEITSGRUPPE, INSTITUT FÜR LANDWIRTSCHAFT
DER KFA JÜLICH, BONN,
AND
H. W. SCHARPENSEEL
INSTITUT FÜR BODENKUNDE DER UNIVERSITÄT BONN,
FEDERAL REPUBLIC OF GERMANY

Abstract

MOVEMENT OF IONS AND COLLOIDS IN UNDISTURBED SOIL AND PARENT ROCK MATERIAL COLUMNS. Undisturbed columns of different soils (Great Soil Groups) are subjected to percolation with repeated definite volumes of water, and the eluted rates of cations and anions are determined. The transportation of 14C-labelled humic acid, 56Fe⁺⁺ and 59Fe-labelled montmorillonite, applied to the surface of the profile column, is checked by liquid-scintillation techniques.

The results show the characteristic solubility rates and sequences of the different tested ions as well as the fractions in the individual soil types. This allows the balances of annual ions to be correlated with precipitation levels.

After termination of the experiments (three to four years), the soil columns are transformed into thin-section layers which, by stripping emulsion autoradiography, reveal the localization of the labelled substances within the dispersal system of the soil skeleton and plasma.

To study the sequential order and quantitative relation of ion liberation in different parent rock materials, 0.5-5 mm grain size particles are continuously percolated with distilled water in columns at 60°C. The recycling system allows the dissolved and collected eluted material (ions and colloids) to be analysed at constant intervals of 1 to 2 months.

Diagenetic concretions from duripan, fragipan, pseudogley, latereite, podsol and caliche are continuously leached in solvent extractors and the dissolved substances analysed.

To investigate the movements of ions and colloids in dispersion systems such as soils or rock particles with radioactive tracers in-vitro tests are necessary so as to avoid health hazards such as those resulting from the spilling of radioactive material.

The main problem with such tests on the soil lies in the need to obtain undisturbed samples of the natural profile. It is very important to use a soil body with fully preserved structural characteristics. When this condition is met the model test has the advantage of allowing different soils to be compared under similar climatic conditions such as temperature and precipitation.

These conditions lead to the development of three experimental model set-ups specific to ion and colloid migration studies in soil, rock material and diagenetic substances:

(1) Model test on undisturbed soil columns in single-walled glass tubes [1, 2]¹
(2) Model test on rock particles in double-walled thermostatically controlled glass columns¹

(3) Model test on concretions and other diagenetic accumulations in the Soxhlet extractor.

1. MODEL TEST ON UNDISTURBED SOIL COLUMNS (Fig. 1)

1.1. Description of the model test on soil columns

To study the dynamic processes in the soil, especially the migration of ions and colloids, undisturbed soil columns with well-preserved 10-cm-diam. structures were taken with a Utah borer [1, 3]. In 1962, the first year of the experiment, paraffin and plexiglass coating in the form of semi-lunar shells were used, the latter joined with rubber fittings and plastered along the seams with polyester resin.

For the radioactive labelling the simplest method of coating the soil with paraffin proved inadequate since drying out and wetting alternately cause swelling and shrinking. Thus, during the subsequent years, only
glass tubes with a slightly larger diameter than the soil columns were used. These proved to be simpler and more efficient than the plexiglass columns.

The inner wall of the glass tube is coated with a thin film of silicon oil so that the columns can be easily pushed into the glass casing. This procedure also prevents the marginal flow of water and tracer compounds along the wall surface.

The glass tubes containing the soil columns were fastened to a steel grating in thermostatically controlled rooms. They were then labelled on the upper surface with radioactive soil constituents. For this purpose \(^{14}C\)-labelled humic acid produced in a plant-raising cabin, \(^{55}Fe_2(OH)_3\), and \(^{56}Fe\)-montmorillonite, synthesized hydrothermally in high-pressure autoclaves, were especially suitable [4, 5].

Measured fixed amounts of distilled water were pumped by drops into the labelled soil columns, normally in four parallels for each soil type (Great Soil Group). Once the radioactive tracer material in the percolates had passed through the soil column, it was measured by scintillation spectrometry. At the same time chemical analyses of the percolates indicated the characteristic composition of the dissolved compounds for the individual soil. These tests produced evidence concerning the extent of the yearly drainage losses in the various soils.

After the experiment was completed the labelled soil columns were prepared with resin and cut into thin sections. Those radioactive soil constituents, which do not migrate through the column, can be precisely localized by thin-section autoradiography.

1.2. Preliminary results of the model tests on undisturbed soil columns

A migration of radioactive \(^{14}C\)-humic acid and of \(^{55}Fe\)-clay through the soil columns cannot be established with either the Parabraunerde (Grey Brown Podsollic) or the Saure Braunerde (Acid Brown Earth). Only traces of \(^{55}Fe_2(OH)_3\) moved through the Parabraunerde and these were discovered in the percolate (Table I).

The composition of the dissolved compounds found in the percolation of the examined soils (Table II) shows the most important typological differences of the soil in the CaO mobilization. This is greatest in the Pararendzine with 224 mg/150 mm percolate and smallest in the podsol with only about 12 mg/150 mm percolate, i.e. about 1/20 of the Pararendzine. Parabraunerde and Saure Braunerde lie between with 100 and 67 mg/150 mm percolate. If the CaO mobilization alone does not permit an absolute prediction concerning a soil, together with the absorption capacity of clay and humus materials and the water content it characterizes the fertility value.

The MgO washout amounts to approximately 1/10 of the amount of CaO. The exceptionally high values with the Saure Braunerde are determined by the substrate. To indicate the morphological phenotype, the displacement of small amounts of materials which strongly impregnate the soil was sufficient. The red brown mark of podsol-B₃-horizons was already evident with 1.5 mg Fe₂O₃/150 mm percolate. This is about five times as much as with Parabraunerde and Saure Braunerde.

Al₂O₃ mobilization was only observed in the Saure Braunerde (2 mg/150 mm percolate) and especially in the podsol (5.5 mg/150 mm percolate). These values are not yet final. They decrease with the
<table>
<thead>
<tr>
<th>200 ml distilled water</th>
<th>Parabraunerde field</th>
<th>Parabraunerde forest</th>
<th>Saure Braunerde field</th>
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<tr>
<td></td>
<td>$^{14}$C-h. a. (\text{dpm/ml})</td>
<td>$^{55}$Fe-clay (\text{dpm/ml})</td>
<td>$^{56}$Fe (\text{dpm/ml})</td>
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<tr>
<td>1</td>
<td>(CR$_a$) 2800 (CR$_b$) 12000</td>
<td>(CR$_a$) 1500 (CR$_b$) 19400</td>
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<td>(CR$_a$) (CR$_b$) 22200</td>
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<td>(CR$_a$) (CR$_b$) 23200</td>
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<td>4</td>
<td>(CR$_a$) (CR$_b$) 7300 (CR$_b$) 3700</td>
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<tr>
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<tr>
<td>6</td>
<td>(CR$_a$) - 700 (CR$_b$) 1500 (CR$_b$)</td>
<td>(CR$_a$) (CR$_b$) 1500</td>
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<tr>
<td>7</td>
<td>- - 2100 (CR$_b$) -</td>
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* h. a. = humic acid
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### TABLE II. AVERAGE DISSOLVED QUANTITIES FROM 1-m SOIL COLUMNS (mg/ ~ 150 mm PERCOLATE AFTER 200-mm PRECIPITATION) AND CALCULATED DRAINAGE LOSSES (kg/ha in ~ 150 mm PERCOLATE)

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<th>Parabeaume</th>
<th>Parabeaume</th>
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<td>Percolate (mm)</td>
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<td>120</td>
<td>154</td>
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<td>4.9-7.0</td>
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</table>

* Abbreviations: p = percolate; ha = hectare; o.l. = organic substance
duration of the experiment. The importance of the little-known aluminium migration lies in the extreme lowering of the pH. In future close attention will be given to this phenomenon.

Surprisingly, the silica migration in all soils is nearly the same, with about 20 mg/150 mm percolate. The highest values were with the Parabraunerde under forest and the podsol under heath-forest vegetation. Obviously the humus in these soils is favourable to solubility and transport. Whether the slight silica washouts in the Parabraunerde under crops were characteristic or an exception is not yet clear. At the moment the phenomenon can only be explained by the low humus content in this soil.

The shifting humus material in podsol indicates above all the dynamics of this type. From the aspect of quantity, it considerably exceeds all other material. The mobilization of iron, aluminium and phosphorous and the higher content of silica are closely connected with the humus material migration. The observed washouts of $P_2O_5$ in the Saure Braunerde and in surprisingly large quantities in podsol (4 mg and 19 mg/150 mm percolate) show, in the same way as the aluminium, that mobilization in the advanced tests tends to decrease.

For the actual clay dynamics the material migrations in a soil must not be considered only in their absolute quantities. For example, silica occupies first place among the inorganic components in the podsol; in this soil type, however, a similar proportion of silica plays a more important role than, for example, in the Parabraunerde. For the clay dynamics the relation of the dissolved compounds in a soil type play an especially important role. In 1960-62, when we developed the method, we were stimulated primarily by the concept that the clay substance enrichment in the B$_1$ horizon of the Parabraunerde is not, as generally accepted, only a result of mechanical clay leaching, but mainly a process of clay re-formation from the dissolved compounds [2]. The widespread idea of clay percolation is based primarily on the observed fine substance accumulations in soil-thin sections on porous systems. That the movement takes place is then deduced from the observed static picture.

What effect do soil-column experiments to date have on these questions? No appreciable displacement of the radioactive tracers through the soil columns has yet been seen in the critical profiles for the fine-substance displacement of Parabraunerden, especially in Fe-clay. The same applies to Saure Braunerden. The percolates of these profiles are water-like and contain no colloids. Only the podsol percolate carries with it humus material, iron and aluminium in colloidal form.

From the investigations on clay mineral syntheses we know that the relation 3-valence (Fe, Al) to 2-valence cations, above all Ca, is very important for the formation of clay minerals. Beckmann et al. [5] found that a mixture of silica with 2-valence cations shows a prevailing tendency for montmorillonite minerals to form, whereas with predominantly 3-valence cations there is a marked tendency to the formation of kaolin minerals. Because silica appears in almost equal amounts in the examined profiles, the extent of the clay mineral formation in the different profiles is determined from the number of cations, above all calcium.

According to this the conditions for the formation of clay minerals are greatest in Pararendzine and Parabraunerde, less in Saure Braunerde and least in podsol. Because 3-valence cations are lacking in Pararendzine,
only montmorillonite clay minerals can be formed. In the development of soil towards Parabraunerde the appearance of traces of iron causes the formation of small quantities of kaolin alongside the montmorillonite.

Besides predominantly montmorillonitic minerals (among which illite is also included here) a small quantity of kaolin, corresponding to the small portions of Fe and Al, is expected even in the Saure Braunerde.

In podsol with only a slight clay mineral formation kaolin is predominant even if, corresponding to the portion of 2-valence cations, montmorillonitic minerals can also be formed. If this mechanism of clay mineral formation is correct, after sufficient time it must be possible to control this, and through this the soil fertility.

Calcium fertilizer with a slow calcium delivery such as foundry lime [6], which primarily consists of gehlenite, $\text{Ca}_2\text{Al}_2\text{SiO}_7$, and $\text{CaCO}_3$, and probably trace elements, together with organic matter, is favourable for the formation of montmorillonitic clay minerals.

If it is true that the clay formation follows from the dissolved compounds, then the question of the origin of $B_1$ in the Parabraunerde
and of B<sub>v</sub> in the Saure Braunerde remains open. We feel that the pH profile, the filter frame and the saturation zone are primarily responsible. In the Saure Braunerde the pH profile progresses equally from top to bottom. In the Parabraunerde it differs, the pH increasing towards the bottom. This means that, in the Saure Braunerde in all horizons, there is an extensive availability of the dissolved compounds for the clay mineral formation, while in the Parabraunerde profile the composition of the dissolved compounds must be similarly differentiated. Thus, one expects to find the most ions and favourable moisture for clay formation in the upper region of the carbon horizon. In advanced soil development this border slowly shifts towards the bottom until it reaches the the final boundary, which is indicated by the climatically determined saturation zone.

To check this supposition further the Parabraunerde percolates will be collected under each horizon. New synthesis investigations on minerals from various Parabraunerde horizons also point in this direction [7].

2. MODEL TESTS WITH ROCK PARTICLES (Fig. 2)

2.1. Description of the model test with rock particles

To study the beginnings of soil genesis in rock, double-walled glass columns were filled with rock particles and fastened to a steel grating. To accelerate the process, thermostatically controlled water at 50°C was circulated between the two glass columns to indirectly heat the rock.

From a fixed storage flask beside the column distilled water was evaporated by a heating apparatus. The evaporated water condensed in one of the mounted cooling coils of the rock column. From here the condensed water dripped through a glass sieve onto the rock, migrated through it and, along with the dissolved materials, was re-pumped by dose pumps into the storage vessel. Thus, the circulation process is repeated continuously.

It is important to take care that the collected materials in the storage vessel are always surrounded by sufficient water so as to avoid over-heating above 100°C, which would result in drying, glass breakage and loss of substance. Platinum electrodes, which dipped into the solution and shut off the heating apparatus, were first used to regulate the water level in the storage vessel once it sank below them. Unfortunately the concentrated dissolved materials often encrusted the platinum electrodes within a short time so that the switch did not always function. Recently a mechanical micro-switch was fitted outside the storage vessel to regulate the level by using the weight difference of the solution in the storage vessel through on-off switching of the heating apparatus.

The rock column pairs with various rock sources like basalt, trachyte-tuff, sand or loess, where one of each pair contains a layer of humus on the top, receive, as well as the soil columns, radioactive soil constituents on the surface such as $^{14}$C-humic acid and $^{55}$Fe$_2$(OH)$_3$ as soon as the process reaches a steady state.

2.2. Preliminary results of the model test on rock particles

The dissolved and migrated materials that are freed by weathering of rock enable one, in various respects, to obtain a surprising view of the initial dynamics of soil genesis (Table III).
<table>
<thead>
<tr>
<th>Material</th>
<th>Basalt Without humus</th>
<th>Basalt With humus</th>
<th>Trachyte Without humus</th>
<th>Trachyte With humus</th>
<th>Sand Without humus</th>
<th>Sand With humus</th>
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<tr>
<td></td>
<td>% m *</td>
<td>% m h *</td>
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</table>

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**TABLE III.** AVERAGE DISSOLVED QUANTITIES FROM 1-m ROCK COLUMNS AFTER ONE MONTH'S CONTINUOUS PRECIPITATION (DISTILLED WATER)

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* Abbreviations: rel. = relative No. [without humus = 100%]; m = mineral compounds (100%); m+h = mineral and humic compounds (100%); o. s. = organic substance; dim. = dissolved compounds; rel. = solution; val. = valence cations; g = gram.
The composition of the dissolved compounds in the mineral materials of the investigated rocks, basalt, trachyte and sand, revealed a silica content of about 50%. Next was found alternating layers of calcium, potassium, and sodium with a content between 2 and 12%. There were traces of from 0.1 to 0.2% of iron in the basalt, in the trachyte, and in the sand probe with humus.

The effect of the humus layer is interesting. The second basalt column contains a 10-cm grass humus (muliform) on the surface, and the second sand column 10-cm podsol raw humus. On the second trachyte column traces of raw humus (2 to 3 mm) were introduced in order to observe the influence of small quantities of humus.

The amounts of washed-out organic components were equal in basalt and trachyte, being 13 to 14% of the total dissolved elements, while in sand they slightly surpassed the total mineral components with 51%.

In basalt and sand under the humus layer twice as much dissolved quantities of mineral materials were obtained as in the parallel probes without humus. Even the traces of raw humus on the trachyte accounted for 1.2 times the dissolved mineral materials. Not only the dissolved quantities but also the concentration of the dissolved compounds within the mineral material were decisively influenced by the humus material.

In basalt and sand the solubility of calcium under humus increases considerably (basalt 5 to 16%; sand 3 to 19%). The traces of humus in trachyte cause no changes (8%). The same is true for magnesium (basalt 1 to 4%; sand traces 1.2%; trachyte 1.3 to 1.5%). Potassium and sodium also behave similarly (potassium basalt 2 to 3%; trachyte 5 to 7%; sand 2 to 2.5%; sodium: basalt 6 to 8% (exception); trachyte 6 to 9%; sand 1 to 1.2%).

The silica concentration is lessened by the humus in basalt. In trachyte and in sand, on the contrary, it is slightly raised. The Fe concentration shows conspicuous differences in the sand probes only (2.6% without humus and 0.5% with).

Similarly the aluminium concentration under humus decreases considerably (basalt 10 to 3%; trachyte 6 to 5%; sand 13 to 7%).

Compared with the total dissolved quantities, if the relative number of dissolved mineral materials is set in the probes with humus in opposition to the probes without humus (100), then the effect of the humus-controlled differences becomes clear. In basalt with humus seven times as much calcium is dissolved, and in sand even fourteen times as much, as in the probe without humus; two to seven times as much magnesium, potassium, and sodium is dissolved.

The silica loss also increased in all probes; in basalt about 1.6 times, in trachyte around 1.2 times, and in sand about 2.1 times. The iron solubility in sand under humus is considerably reduced by 1/27.

Despite the total higher dissolved quantities of mineral materials the aluminium loss in the humus probe reached 75% in basalt, 95% in trachyte and, exceptionally, 115% in the sand of the probe without humus.

The lowering of the aluminium concentration and the unusual decrease of iron in the percolate of the humus columns can only be explained at this stage by assuming that a part of the migrating humus material forms a complex with the aluminium and especially with the iron, and as such is precipitated somewhere in the rock profile. That the colloidal constituents of the podsol percolate consist of humus materials, iron and aluminium is also evidence for this assumption.
For the clay mineral formation in the different rock substrates the ratios of SiO₂: 2- (and 1-) valence, and SiO₂: 3- valence cations are important (Table III). In all rocks under humus the relationship of SiO₂: 2-valence cations is smaller (basalt 3.5:1; 1.3:1; trachyte 2.5:1; 2.1:1; sand 7.7:1; 2:1), against this the ratios of SiO₂ to the 3-valence cations is greater (basalt 5.2:1; 11.4:1; trachyte 8.8:1; 11.1:1; sand 2.9:1; 6.1:1).

Considering the demonstrated connections concerning the clay mineral dynamics in soils (compare section 1.2) – in the presence of 2-valence cations, montmorillonite formation; in the presence of 3-valence cations, kaolin formation – the following surprising conclusion is reached: the humus layer, regardless of the humus form, considerably enhances the tendency towards the formation of montmorillonite. If this is true then far-reaching consequences for soil fertility are apparent.

It is to be hoped that the tracer investigations now in progress on the rock columns with ⁵⁵Fe₂(OH)₃, ¹⁴C-humic acid, and ⁵⁶Fe-clay minerals will give a further insight into the initial mechanism of the metamorphosis from rock to soil.
3. MODEL TEST WITH CONCRETIONS AND DIAGENETIC ACCUMULATIONS

To test their reversibility, concretions and other diagenetic accumulations were continuously extracted in the Soxhlet extractor (Fig. 3).

Each parallel probe contained a humus addition, which was labelled with $^{14}$C-humic acid. $^{55}$Fe$_2$(OH)$_3$ was added to the humus-free probes. The importance of humus for the possible decomposition or dissolution of the accumulations was established, and the exchange and interchange of radioactive components with the hardened probe was proved.

The tests are still being carried out so that it is too early to give the results. Nevertheless it already can be seen that the results should be along the same lines as those with the rock columns.

SUMMARY

To study the solubility and migration of materials in soils, rock particles, and diagenetic accumulations with radioactive soil constituents such as $^{14}$C-humic acid, $^{55}$Fe$_2$(OH)$_3$ and synthetic $^{55}$Fe-clay, three model tests were developed and are described here:

1. Model test on undisturbed soil columns in single-walled glass tubes.
2. Model test on rock particles in double-walled thermostatically controlled glass columns.
3. Model test on diagenetic accumulations in the Soxhlet extractor.

The preliminary results are given.

The model test on undisturbed soil columns helps to explain the material migrations and the compositions of the dissolved compounds in different soils under equal climatic conditions.

After several years of precipitation the radioactive soil constituents $^{14}$C-humic acid and $^{55}$Fe-clay did not migrate through either Parabraunerde or Saure Braunerde. The yearly drainage losses from the different soils can be estimated. Finally, these tests reveal the conditions for clay mineral formation.

The model test on rock particles shows the initial dynamics of the soil genesis in basalt, trachyte and sand. The effect of humus on the solubility, migration and composition of the dissolved compounds is extensive. While the total solubility as well as the proportion of 1- and 2-valence cations is significantly increased by humus, the 3-valence cations, aluminium and especially iron, are reduced by humus. The obvious importance of humus for the clay dynamics and the soil fertility becomes evident.

Both tests are especially suitable for characterizing various soils throughout the world under similar conditions. In cases of unsettled relationships, for example with black soils (chernozem, regur, badob, smonitza, and bog soil), they can clarify the differences and similarities in soil dynamics.

The model test still in progress on diagenetic accumulations should explain the importance of humus for the dissolution and the exchange-interchange processes of radioactive tracers.

REFERENCES

DISCUSSION

M. J. FRISSEL: Did your columns have a normal oxygen supply, or did you use a closed system?

W. KERPEN: As Fig. 1 shows, the soil columns were open on the top, so that we were working under normal aerobic conditions. The stone columns had holes in the top cover. In addition, the humus was exchanged from time to time.

H. KICK: What was the CO₂ content of your water, because under natural conditions the CO₂ content of the percolating water must have an important influence on the quantity of constituents dissolved out of the rock material?

W. KERPEN: The CO₂ content of the distilled water administered to the soil columns was that of ordinary distilled water of about pH 5.5. During the recycling experiment on the rock materials, the content was lower, because of the heating process.

M. DE BOODT: Did the soil in your columns dry down to at least the wilting point? We need to know this in order to assess whether the reported loss in K₂O reflects what happens in nature. As you know, the K₂O release in Parabraunerde, which is rich in illite clay mineral, is due to the alternative drying and wetting of the soil.

W. KERPEN: The columns were irrigated for two days a month, each time receiving 100 mm, in a room at 25°C. In the interval, moisture dropped below field capacity.

As expanding illites are not prominent in our Parabraunerde, K₂O losses from moisture changes and drought certainly are not important.

O. TEODORU: Your paper is of great theoretical and practical importance, as your method provides a means of expressing quantitatively changes in the chemical properties of irrigated and drained soils. Did you note any physical changes in the soils?

W. KERPEN: Our rock and soil columns were cut into sections in the final stages and used to study structural changes and translocation of colloidal particles.

The main purpose of the method is to permit a comparison of dynamic processes in soils, by micromorphological treatments and chemical analysis. The practical importance lies in the knowledge provided about mode, sequence and ratio of soil mineral release and the specific influence of the soil's organic matter in regulating these processes. It also enables us to plan measures to prevent soil degradation, through knowledge of the relations between soil percolate constituents and clay mineral formation.
INVESTIGATIONS INTO THE BEHAVIOUR OF PRECIPITATION WATER IN SOILS BY MEANS OF $^{131}$I*

P. BENECKE
INSTITUT FÜR BODENKUNDE DER FORSTLICHEN
FAKULTÄT DER UNIVERSITÄT GÖTTINGEN,
FEDERAL REPUBLIC OF GERMANY

Abstract

INVESTIGATIONS INTO THE BEHAVIOUR OF PRECIPITATION WATER IN SOILS BY MEANS OF $^{131}$I. In a drained silty soil the groundwater was filled to surface level by using artificial precipitation. After this a K $^{131}$I-solution was added at a defined spot between two drains. By the help of a scintillator the spread of the radioisotope was recorded at varying times.

The results were plotted as isolates (lines connecting points of equal activity at the same time in the soil profile). The activity maximum remained at the spot of initial activation during the investigation period (two weeks). Within a few minutes after application, however, small activities of $^{131}$I were found one metre away from the point of application, in both a vertical as well as a lateral direction towards the nearest drain.

The movement was mainly directly downwards and closely followed a half-logarithmic time-distance relationship. From this, the minima of the observed water-flow velocity were calculated. The influence of the physical soil properties on the spreading was represented by a proportionality constant. An interpretation of this constant is difficult because of the complexity of factors involved. In addition to these quantitative results interesting qualitative conclusions can also be drawn from studying the pattern of the isolate lines:

1. The streamlines towards drainage penetrated the subsoil to a depth of more than 2 m,
2. A former drain ditch showed a higher permeability than the undisturbed soil. This meant that mechanical cultivation remains effective even after decades in silty soils,
3. Vertical water flow was hindered at the borders of layers of different texture, even where there was a higher permeability in the underlying layer.

INTRODUCTION

For more than ten years soil mapping on 1:5000 and 1:25000 scales have been carried out on the Federal German coastal marsh areas. These areas, with about 750 mm annual rainfall and an average annual temperature of 9°C, are decidedly humid. The soils originate from the holocene deposits. They contain mainly clay and silt, the clay content ranging from less than 5% to more than 60%. Depending upon the parent material and the sedimentation conditions, characteristic soils have developed, which vary in value as agricultural soils.

Soils with unfavourable properties, mainly physical, are called brackish marshes. They are characterized by high clay contents, poor structure, low permeability, and hence drainage has little effect. Thus, only greenland farming is possible. On the other hand the most favourable soils are the so-called sea marshes originating from flocculated sea deposits rich in lime and with a lower clay content. They are characterized by a fine structure, causing a good or even high permeability. In many cases drainage would not be required if it were possible to lower

* This work was carried out at the Niedersächsisches Landesamt für Bodenforschung, Hanover.

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the groundwater sufficiently. But this is impossible owing to their being only 1-2 m above sea level. Thus, a permanent supply of capillary water results because of the high groundwater table. This together with the high rainfall leads to temporarily water-logged conditions that necessitate drainage at least of the arable land.

While mapping these soils the desirability of estimating the drainage conditions from the results of in-situ measurements has often been expressed. Thus, the purpose of this experiment was to investigate the route and, if possible, the velocity of the infiltrating rainfall water towards the drain pipes by the aid of $^{131}$I. It was chiefly proposed that we obtain more qualitative information on the water movement as influenced by different permeable layers between the soil surface and the drain pipes. The behaviour of soil layers below the drain pipes was of special interest. From model experiments it was known that these layers played a decisive role, as is clear from Fig.1, which shows the streamlines towards a drain.

![Streamlines and equipotentials](image)

**FIG.1.** Streamlines and equipotentials (E.C. CHILDs, see Bibliography at the end of the paper).

Because of the lack of experimental data an uncomplicated soil like the sea marsh already mentioned was chosen first. Table I shows some of this soil's characteristics.

Since being embanked about 300 years ago, the soil has been used as arable land and produces high yields. About 30 years ago it was drained by 12-m pipe lengths.

**EXPERIMENTAL SET-UP**

The planning of such an experiment necessitated the use of a suitable isotope with a sufficiently high penetrating capacity so as to obtain comparable results in tubes vertically inserted in the soil. To check the danger of contamination of the groundwater, its half-life should be rather small, but at the same time it should not fall below a traceable
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<th>Depth (cm)</th>
<th>pH</th>
<th>Carbonate (%)</th>
<th>Organic matter (%)</th>
<th>C.E.C.* (meq/100 g)</th>
<th>Cations (meq/100 g)</th>
<th>Ratio</th>
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* C.E.C. = Cation exchange capacity.
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* The percolate was collected in two parts equal to the amount added to the soil.
amount during the experimental period. The isotope should be available in a good water-soluble form and should not be adsorbed by soil particles.

All these requirements were fulfilled by $^{131}$I in the form of KI. It has only medium hard $\gamma$-rays, which are quite suitable for this type of experiment.

To test with certainty the soil's adsorption of iodine, KI solutions of varying very low concentrations were prepared and allowed to percolate through the soil columns. The results (Table II) show that, after the columns were washed, the whole iodide was found quantitatively in the percolate. Therefore, any notable sorption of iodine by the soil was not to be feared.

Figure 2 shows the experimental area. The "R"-marked tubes were arranged at right-angles and oblique to the drain line. The tube at the maximum distance is situated 0.5 m beside the middle line between two of the drain lines. In addition, three tensiometers were also installed. At a distance of 1.20 m from the middle line a shallow hole was made and was filled with sand. Here, later on, the $^{131}$I was applied to the soil. The intention was to direct all the isotopes to only one drain line.
Figure 3 shows a vertical cross-section of the experimental area. First it can be seen that the 2-m-long tubes reach more than double the depth of the drain pipes, which are situated 0.8 m below the surface.

PERFORMANCE OF THE EXPERIMENT

Before the isotopes were added the groundwater table was raised to about surface level by spray irrigation. Thus, the critical water-logging situation was simulated. Then we measured the background counts that were mainly due to $^{40}$K in the soil. The counting was done with a transportable transistor scintillator, which gave the rate in counts per minute (cpm). The background, which ranged (Fig. 4) from 3000 to 5000 cpm, varied directly with the clay content.

![Graph](image)

**FIG. 4.** Background of a counting tube.

After these preparations the isotope, with 1 kg KI as carrier dissolved in 10 litres of water, was added to the site and its spread was followed with the counting tube. After correction for background and decay the counts were expressed as isorate lines, i.e. the sites with the same counts at a given time were put on the same line. Figures 5 and 6 show this distribution after 0.5 h. The maximum activity was found between the point of addition and 50 cm below this point. A fast decrease of activity with depth can be observed. The maximum depth was about 1.30 m from the surface. The lines show spatial irregularities, which will be discussed later.

RESULTS AND DISCUSSION

Figure 6 shows the distribution after two weeks. The maximum activity spread up to 90 cm. A small part of the activity was measured at a 2-m depth. The lines of less activity show a significant lateral distribution, from which two ranges can be clearly distinguished, namely, one in the cultivated horizon and the other about 60 cm deep.

Firstly, for interpretation, the vertical downward movement was observed. This movement is illustrated in Figs. 7-10, where the movement as a function of time is represented by lines of a definite activity. Figure 7
shows that the maximum activity (200 \times 10^3 \text{ cpm}) indicates a strongly retarded transfer. The lines of 10 \times 10^6 \text{ cpm} (Fig. 6) are present up to 1.70 m deep and show a slight tendency towards lateral distribution. This tendency increases as the activity decreases, such as with 1 \times 10^3 \text{ cpm} (Fig. 9) and 0.3 \times 10^3 \text{ cpm} (Fig. 10), the latter to be treated as indicating the limiting measurable line. Before discussing this phenomenon the vertical movement must be considered.
Figure 11 shows that the penetrating depth is related to log time. If \( H \) indicates the penetrating depth, \( T_0 \) the time required by the active solution to reach the counting tube, and \( T \) the time since starting the experiment, then

\[
H = \left( \frac{1}{\lambda} \right) \ln \left( \frac{T}{T_0} \right)
\]
where $\lambda$ is a constant. The penetrating velocity $V$ is:

$$V = \frac{dH}{dT} = \frac{1}{\lambda T}$$

At the tube next to the application point, $\lambda$ has a value of $1/14$ cm, i.e., an hour after starting the experiment the isorate line of $0.3 \times 10^3$ cpm moved down tube No. 1 at a velocity of 14 cm/h.
The approximation of the starting velocity is especially interesting because, during the first few seconds, the spatial extension of the active volume and the uptake of isotopes by the bounded soil water was minimal.

![Diagram showing relation between downward movement of the isotopes and time](image)

**Fig. 11.** Relation between the downward movement of the isotopes ($0.3 \times 10^3$ isotope line) and the time at tube 1.

For that matter a knowledge of the profile and of the experimental lay-out led to the following consideration: All the 10 litres of water containing the isotope was put into the sand-filled application hole within one second, thus, for a short time, causing a local hydraulic head. Only in the cultivated horizon was an immediate concentric spreading possible owing to the varying permeability in the different layers. This meant that, in the first moment, the solution spread mainly in the upper 25-cm layer and then began to percolate downwards. Consequently the starting depth for the vertical water movement should be taken as a line 25 cm below the surface. Putting this value in the above equation, one gets $T_v = 1.4 \times 10^{-3}$ h or about 2.5 s. From this, it follows that the spreading velocity was 10 cm/s towards tube No. 1, placed about 30 cm from the application site. At the same tube the downward movement starts after the above-mentioned time, with a velocity of 5.6 cm/s. As can be seen from Fig. 9 the relation of these calculated velocities corresponds to the spreading distances in the horizontal and vertical directions respectively.

Even if the obtained values are possibly uncertain, these results indicate that water can move with a relatively high velocity in saturated soils of good structure. The reported values may be considered as minimum.

The regular spreading of isotopes makes it possible not only to approximate the flow velocity, but also to judge the effect of important soil properties with the help of the constant $\lambda$. This is especially the property of the soil permeability in connection with the pore-size distribution.

Because, as shown above, adsorption plays hardly any role the bound water is decisively important in causing a decrease of the spreading velocity. The fact that the maximum activity undergoes only a slight downward transfer and that this must be partly explained by a diffusion process, indicates that the major part of soil water, even under water-saturated conditions, moves only very little. This confirms the view that rainfall does not percolate immediately through the soil but, instead, a small vertical movement of that water already present in the soil takes place. In some way this mechanism resembles that of electric
current: a distinct amount of rain water enters the soil and an equivalent amount of soil water goes into the drain pipes. But this concept is not completely correct, as can be seen from this experiment. Small amounts of rain water seem capable of penetrating the soil directly with velocities of about 5 or 10 cm/s. The explanation lies in the presence of continuous tensionless pore spaces which, for water movement only, can be used under water-saturated conditions, as in this case. It may be pointed out that λ generally indicates the ability of the soil to retard infiltration and thus the penetration of rain water in the manner discussed. This has important results when fertilizing with easily soluble salts such as nitrate, which the soil sorbs to only a small degree. This mechanism explains that such fertilizers may remain available for plant consumption in the soil for a considerable time as a vegetation period, for example, even in waterlogged soils. The lower the λ the smaller is the tendency to wash out easily soluble nutrients.

The above-mentioned lateral expansions will now be discussed. Figures 9 and 10 show first that those can be observed in the cultivated A-horizon. This movement is directed towards the drain pipes and may be possible only if there exists a potential gradient. Because of its high horizontal permeability this can be assumed for the cultivated horizon. But there must exist a continuous vertical zone of permeability that is higher than that in the neighbourhood. Under present conditions this can be only the former drain ditch, which was made about 30 yr ago to install the drain pipes and later filled in again. This is of great interest as this "deep cultivation" of the soil remained effective for decades, even in the case of the present unstable silty soil.

Another noteworthy conclusion of the experiment concerns the distinct bulging at a 60-cm depth. One finds there a boundary of different textures. The clay content decreases from 24 to 8%. Because mainly lines of low activity are involved in this movement, it can be concluded that it is chiefly gravitational water that is being affected. This bulging indicates an impedance of vertical water flow despite the fact that a coarser texture follows downwards. Apparently the reason for this lies in the greater irregularity of grain-size distribution at this boundary. Then the possibility increases that small particles fill the space between bigger ones, therefore reducing the free space and consequently the discharge rate.

Finally, let us answer the major question posed when starting the experiment. From Figs. 5-10 it can be seen that the main movement of the isorote lines tends vertically downwards and, even at a depth twice that of the drain pipes, it apparently does not divert from this direction. Thus, the experiment indicates that the stream lines agree with what is already well known from model experiments. This can only be seen at the beginning, but one can assume with certainty that any further movement also follows this model. The experiment clearly indicates the necessity of testing the soil and its underground to a depth of at least 3 m in order to judge the drainage conditions. This conclusion had immediate results on the soil mapping mentioned earlier where such questions often arise.

Finally, it can be pointed out that the isotopic technique allowed in-situ measurements which made such manifold studies on the water movement in soils possible and which highlighted theoretical and practical results of interest.
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DISCUSSION

U. ZIMMERMANN: I cannot imagine that the small tracer increase at greater depths (>120 cm) found in your experiments is produced by small amounts of water moving downwards without exchange with the stationary water in the water-saturated soil. This increase must be due to dispersion effects, such as molecular diffusion and mechanical dispersion. If we accept this explanation, it would be more appropriate to determine the downward movement velocity of the tracer front from the distribution of tracer concentrations in the soil, rather than from the relationship between depth position of the 0.3×10^15 cpm isorote line and time.

P. BENECKE: I don't think that you are right, because you obviously do not take into account the effect of good soil structure. Many field observations in water-saturated soils confirm the view that very fast water movement is possible in fissures, tracks, etc.

M.J. FRISSEL: I agree with Mr. Zimmermann's remark on molecular diffusion, but I think it is impossible to assume mechanical dispersion, when there is no water flow. So I do not think this effect is as serious as one might suppose.

U. ZIMMERMANN: I do not believe that there is no water movement at all, but I think that the movement of the tracer is not as large as stated by Mr. Benecke. The wide distribution of the tracer in the soil shows that it is influenced by mechanical dispersion.

J. MARCESSE: At the beginning of your experiments, Mr. Benecke, lateral diffusion was very rapid. Would not the tracer front be detected before the KI actually reached the tube? At what distance from the tube can the presence of such a quantity of ^131I affect the count?

P. BENECKE: From the penetrating capacity of the ^131I, it follows that under the conditions described the radiation was detectable over a distance of about 10 cm in the soil.

D.J. BROWN: You stated that the background count-rate variations were caused by differences in clay content at different depths. Did you observe differences in clay minerals, in addition to the variations in amount?

P. BENECKE: The present holocene sea deposits and the soils developed from them always show the same clay mineral composition, which is mainly illite.

D.J. BROWN: Do you think that the lateral dispersion of the moisture was controlled by the higher clay content at the 50-cm depth? There appears to be a variation in the isorote patterns at this depth.
P. BENECKE: No, I believe the altering of texture at this depth causes a small zone of lower permeability which, in turn, causes the lateral dispersion.

U. ZIMMERMANN: I have three questions. Was the plot irrigated after the tracer applications, and how much water did you apply? Did hydraulic conductivity vary with depth? Do you know the water content of the upper soil layers 400 h after tracer application?

P. BENECKE: The experimental field was irrigated in such a manner as to keep the water table level at about 20 cm below the surface. About 10 or 20 mm of water were needed after starting the experiment. I mentioned the distinct anisotropy of permeability in this soil. Vertical permeability was in the $10^2$ cm/d range. Comparably high horizontal permeability occurred only at the level of cultivation. At lower levels, permeability decreased to less than 10 cm/d. Tensiometer measurements indicated a pF value of 1.6 - 1.8, corresponding to a water content of about 40-45% by volume.

D. RANÇON: Did you inject any iodine into undrained ground? In other words, did you measure iodine diffusion in saturated ground without any water circulation?

P. BENECKE: No, because we assumed this effect to be negligible in relation to the fast motion of the lines of low activity and in any case to have no influence on the behaviour and position of the peak activity.

D. RANÇON: Did you observe any preferential infiltration along the access tubes?

P. BENECKE: Tensiometer measurements in the same soil showed that this kind of infiltration can be avoided if the hole is bored with a drill having a diameter 1-2 mm less than that of the tensiometer. We therefore used a drill slightly narrower than the tubes.

N. AYBERS: It is stated in your paper that $\lambda$ is a constant for soil permeability. However, I believe that the solution had preferred paths through soil, so that $\lambda$ cannot be a true constant.

P. BENECKE: $\lambda$ is a constant only for the relatively fast-moving isorare lines of lower activity. This indicates that movement is occurring in the continuous pore spaces of little or no tension and correspondingly high permeability. $\lambda$ depends not only on the (saturated) permeability, but also on the isotope uptake by the more or less bounded soil water.

W. K. G. KÜHN: What activity did you use?

P. BENECKE: I cannot be sure, but I think we used 1 mCi.
MOVEMENT OF COMPLEX COMPOUNDS THROUGH DIFFERENT SOIL TYPES

Z. Todorović AND A. Filip
BORIS KIDRIĆ INSTITUTE OF NUCLEAR SCIENCES,
BELGRADE,
YUGOSLAVIA

Abstract

MOVEMENT OF COMPLEX COMPOUNDS THROUGH DIFFERENT SOIL TYPES. Results of the behaviour of complex compounds of zinc (bivalent), iron (trivalent), cobalt (trivalent) and chromium (trivalent) on passing through four sorts of soils are given.

The soils had a dominant content of sand, clay, humus and carbonate. The investigations were carried out by the radioactive tracer technique. The complexing was carried out with Na-citrate, EDTA, Na-thiocyanate, potassium cyanide, ammonium-hydroxide, Na-oxalate, Na-tartrate and Na-citrate. The effect of the excess complexing agent on the percentage of the complex compound in the eluate, retention and spread of the elution curve, is shown.

The investigations were carried out on a column always filled with the same quantity of soil of given granulation. The movement of the complex compound was observed by taking samples of the eluate and measuring their activity. For each elution curve parameter $V_{eq}$ was determined as a measure for the retardation and spread of the complex compound waves. The smaller the difference between retardation ($V_{eq}$) and free volume ($V_0$) and the smaller the standard deviation, the smaller was the retardation of the complex compound. From these characteristics and from those of the elution curves for $^{131}I$ and $^{35}S$, which are considered to be passing through the soil without considerable difficulty, we determined those complex compounds which showed the least retardation and wave spread on passage through the soil type investigated.

INTRODUCTION

In studying the movement of salts through different types of soils in relation to the level of underground waters, and in determining the direction and flow-rate of underground waters, tracers such as inorganic salts, dyes and radioactive isotopes are used. Radioactive isotopes are preferable to other tracers because they can be detected in very small concentrations and by direct in-situ measurement. The difficulty in using them as tracers arises when a process must be observed over a long period, when $^{131}I$ and $^{35}S$ are impossible to use because of their short half-lives. Elements with longer half-lives are usually cations to which the soil has a certain adsorption and ion-exchange capacity.

The use of tracers is based on the assumption that they behave similarly to the labelled medium. However, because of the adsorption and ion-exchange capacity of soil, or because of its different porosity, there is more or less a retardation, or even a retention, of the tracer wave behind the wave of labelled water. Theoretically, no tracer exists that can completely avoid the influence of these factors, which is why investigations were made to discover water-soluble compounds which, in given conditions, most closely approach an "ideal" tracer [1-5]. For this work four characteristic soils were investigated under equal conditions to ascertain the behaviour of several cations that have radio-
active isotopes with gamma radiation and different half-lives. In choosing the complexing agents it was considered that, between pH 6 and 7.5, the stability constant of the formed complex or chelate should be greater than the stability constant of elements normally found in soil or water.

EXPERIMENTAL PROCEDURE (See Figs. 1-4)

Four types of soil with dominating contents of sand, clay, humus, and carbonates were used. Sandy soil contains 88% sand, 0.01% humus, 2.2% clay and 9.8% carbonates. Clayey soil consists of 30.3% sand, 4.3% humus and 65.4% clay. Humic soil contains 30.5% sand, 7% humus, 54.5% clay and 7% carbonates. Carbonic soil contains 22.9% sand, 2.1% clay and 75.1% carbonates.

![Graph showing passage of radionuclides through soils](image1)

**FIG. 1.** Passage of $^{60}$Co-EDTA through the column with sandy, humic, clayey and carbonic soils.

![Graph showing passage of radionuclides through soils](image2)

**FIG. 2.** Passage of $^{54}$Cr$^{3+}$-EDTA through the column with sandy, clayey and humic soils.

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1 Soil samples and composition were supplied by the Pedological Department of the Jaroslav Čermi Institute for the Development of Water Resources, Belgrade.
FIG. 3. Passage of $^{54}$Cr in the form of $K_2CrO_7$ through the column with sandy, humic, clayey and carbonic soils.

FIG. 4. Passage of $^{35}$S as $H_2SO_4$ through the column with sandy, humic, clayey and carbonic soils.

The behaviour of the following complexes was observed: bivalent zinc (labelled with $^{65}$Zn), trivalent iron (labelled with $^{59}$Fe), trivalent cobalt (labelled with $^{60}$Co), trivalent chromium (labelled with $^{51}$Cr), and hexavalent chromium in the form of $K_2Cr_2O_7$ (labelled with $^{51}$Cr). To compare the results we also used $^{131}$I and $^{38}$S. Concentrations of solutions of investigated complex compounds, calculated for the elements used, varied from $4 \times 10^{-5}$ to $7 \times 10^{-8}$ g/ml. Radioactive iodine and
sulphur were carrier-free. The complexing agents were sodium thio-
cyanate, potassium cyanide, ammonium hydroxide, sodium oxalate,
sodium tartrate, EDTA (sodium salt of ethylenediaminetetraacetic acid)
and sodium citrate. These agents were added in equivalent amounts or
more. Tracer solutions were prepared by standard methods.

Investigations of the above compounds were made in a 25-mm-diam.
column, always filled with the same quantity of soil, of 0.5-1 mm in
grain size. After determining the free volume, 1 ml of labelled water
was added to the top of the column. In all experiments a flow-rate of
0.8 ml/min was maintained. This flow-rate approximates the average
flow-rate at which water flows under natural conditions.

The movement of the tracer waves was observed by taking eluate
samples and measuring their activities with an error of less than 5%.
A Nuclear Chicago, Model DS 5, well-type scintillation counter with a
NaI(Tl) crystal was used to measure the gamma activity of the samples.
The beta activity was measured with a G-M counter.

From the results of measurements and volume throughput, the
following parameters were calculated: retardation, $\overline{X}$, and standard
deviation, $\sigma$, as a measure of tracer-wave spread. The measure for
tracer retardation is the abscissa for the centroid of the eluent curve.
This means that if all tracer molecules passed the same path at an equal
time, the total activity would be reached after $\overline{X}$ ml of eluate. Therefore,
the difference between the free volume (the volume that fills the vacancies
between soil particles), $X_0$, and the retardation of the tracer waves, $\overline{X}$,
can be taken as the measure for the retardation of the tracer front be-
hind the water front. Parameters $\overline{X}$, $\sigma$ are a criterion for an observed
compound's quality as a tracer. If the difference between the free volume
and the retardation of the tracer waves is smaller and if the expansion of
the waves is smaller the tracer is, in its properties, closer to ideal.
The relation $X_{(0)} = \frac{X_{(0)}}{\overline{X}} - \overline{X}$ makes it possible to determine the abscissa
of the eluent curve up to which a certain percentage of the total eluate
activity has passed. Actually the value $X_{(0)}$ may be considered to be
the appearance of the tracer wave. The value $X_{(0)}$, for a desired per-
centage of tracer passage, can be determined from the tables in math-
ematical handbooks [6].

Such a method of data treatment allows rough determinations of the
most suitable tracer for practical use and of the moment of tracer-wave
appearance and the time between sampling. The tracer-wave parameters
could be correlated with certain hydrological parameters (free volume,
homogeneity of the medium, etc.).

RESULTS AND DISCUSSION

Table I shows the results of investigations on sandy soil. The
passage of complex cations depends on the type of ligand and this is re-
flected in the percentage of the tracer in the eluate, which varies from
21% (Fe$^{3+}$-Na-citrate) to 94-96% (Co$^{3+}$-KCN, Fe$^{3+}$-KCN). The effect
of the ligand exceeding the equivalent amount upon the increase of the
tracer amount emerging from the column varies from 2-9% but, al-
though the effect is negligible, the ligand excess influences the decrease
of the relative retardation, which varies up to 50%. $^{131}$I and $^{35}$S, investi-
gated for comparison purposes, remain on the soil for a relatively short
<table>
<thead>
<tr>
<th>Tracer</th>
<th>Tracer in eluate (%)</th>
<th>Free volume $X_3$ (ml)</th>
<th>$\overline{X} \pm \sigma$ (ml)</th>
<th>Relative wave retardation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{65}$Zn$^{2+}$-EDTA$^a$</td>
<td>77</td>
<td>10.5</td>
<td>15.9 ± 1.7</td>
<td>19</td>
</tr>
<tr>
<td>-400 ppm EDTA$^{a\equiv}$</td>
<td>79</td>
<td>13.6</td>
<td>14.8 ± 1.53</td>
<td>9</td>
</tr>
<tr>
<td>-1000 ppm EDTA$^{a\equiv}$</td>
<td>93</td>
<td>13.6</td>
<td>15.8 ± 1.9</td>
<td>16</td>
</tr>
<tr>
<td>$^{59}$Fe$^{3+}$-EDTA$^a$</td>
<td>72</td>
<td>13.0</td>
<td>13.3 ± 3.04</td>
<td>3</td>
</tr>
<tr>
<td>-700 ppm EDTA$^{a\equiv}$</td>
<td>69</td>
<td>11.6</td>
<td>11.8 ± 2.16</td>
<td>2</td>
</tr>
<tr>
<td>$^{59}$Fe$^{3+}$-Na-citrate$^a$</td>
<td>21</td>
<td>13.6</td>
<td>14.9 ± 1.51</td>
<td>9</td>
</tr>
<tr>
<td>$^{59}$Fe$^{3+}$-KCNE$^a$</td>
<td>96</td>
<td>10.2</td>
<td>10.6 ± 3.10</td>
<td>4</td>
</tr>
<tr>
<td>$^{60}$Co$^{2+}$-EDTA$^a$</td>
<td>83</td>
<td>13.6</td>
<td>15.5 ± 1.37</td>
<td>13</td>
</tr>
<tr>
<td>-200 ppm EDTA$^{a\equiv}$</td>
<td>98</td>
<td>13.6</td>
<td>15.7 ± 1.53</td>
<td>15</td>
</tr>
<tr>
<td>-1000 ppm EDTA$^{a\equiv}$</td>
<td>94</td>
<td>13.5</td>
<td>14.8 ± 1.66</td>
<td>9</td>
</tr>
<tr>
<td>-KCNE$^a$</td>
<td>94</td>
<td>12.3</td>
<td>12.1 ± 2.23</td>
<td>2</td>
</tr>
<tr>
<td>$^{51}$Cr$^{4+}$-K$_2$Cr$_2$O$_7$</td>
<td>81</td>
<td>13.6</td>
<td>15.3 ± 1.71</td>
<td>12</td>
</tr>
<tr>
<td>$^{51}$Cr$^{4+}$-EDTA$^a$</td>
<td>67</td>
<td>13.5</td>
<td>14.6 ± 2.86</td>
<td>7</td>
</tr>
<tr>
<td>-1000 ppm EDTA$^{a\equiv}$</td>
<td>74</td>
<td>13.4</td>
<td>13.8 ± 2.19</td>
<td>3</td>
</tr>
<tr>
<td>-Na-oxalate$^a$</td>
<td>43</td>
<td>14.0</td>
<td>17.0 ± 2.83</td>
<td>21</td>
</tr>
<tr>
<td>$^{131}$I-Na$^a$</td>
<td>96</td>
<td>13.6</td>
<td>16.1 ± 1.76</td>
<td>18</td>
</tr>
<tr>
<td>-1000 ppm NaI$^{a\equiv}$</td>
<td>97</td>
<td>13.6</td>
<td>16.3 ± 1.43</td>
<td>20</td>
</tr>
<tr>
<td>$^{35}$S-H$_2$SO$_4$</td>
<td>88</td>
<td>13.6</td>
<td>16.1 ± 1.74</td>
<td>18</td>
</tr>
<tr>
<td>-1000 ppm Na$_2$SO$_4$ $^{a\equiv}$</td>
<td>87</td>
<td>13.6</td>
<td>14.2 ± 1.71</td>
<td>12</td>
</tr>
</tbody>
</table>

$^a$ Complexing agent in equivalent amount.

$^{a\equiv}$ Complexing agent or carrier in excess.
TABLE II. BEHAVIOUR OF TRACERS PASSING THROUGH HUMIC SOIL

<table>
<thead>
<tr>
<th>Tracer</th>
<th>Tracer in eluate (%)</th>
<th>Free volume $X_0$ (ml)</th>
<th>$X_{\pm 0}$ (ml)</th>
<th>Relative wave retardation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{65}$Zn$^{2+}$-EDTA$^\oplus$</td>
<td>58</td>
<td>14.3</td>
<td>25.7 ± 7.67</td>
<td>79</td>
</tr>
<tr>
<td>-1000 ppm EDTA$^{**}$</td>
<td>66</td>
<td>14.0</td>
<td>25.9 ± 7.55</td>
<td>83</td>
</tr>
<tr>
<td>$^{55}$Fe$^{3+}$-EDTA$^\oplus$</td>
<td>13</td>
<td>15.8</td>
<td>27.2 ± 9.36</td>
<td>72</td>
</tr>
<tr>
<td>$^{35}$Fe$^{5+}$-700 ppm EDTA$^{**}$</td>
<td>45</td>
<td>16.5</td>
<td>36.2 ± 10.28</td>
<td>119</td>
</tr>
<tr>
<td>-Na-citrate$^\oplus$</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>-NaCN$^\oplus$</td>
<td>12</td>
<td>16.9</td>
<td>31.5 ± 12.49</td>
<td>88</td>
</tr>
<tr>
<td>-KCN$^\oplus$</td>
<td>14</td>
<td>16.9</td>
<td>27.3 ± 10.72</td>
<td>61</td>
</tr>
<tr>
<td>$^{60}$Cu$^{2+}$-EDTA$^\oplus$</td>
<td>48</td>
<td>14.2</td>
<td>27.3 ± 7.08</td>
<td>92</td>
</tr>
<tr>
<td>-200 ppm EDTA$^{**}$</td>
<td>84</td>
<td>13.3</td>
<td>24.9 ± 6.51</td>
<td>87</td>
</tr>
<tr>
<td>-1000 ppm EDTA$^{**}$</td>
<td>94</td>
<td>15.2</td>
<td>24.1 ± 7.78</td>
<td>74</td>
</tr>
<tr>
<td>-KCN$^\oplus$</td>
<td>99</td>
<td>16.8</td>
<td>17.3 ± 5.56</td>
<td>9</td>
</tr>
<tr>
<td>$^{13}$C$^{4+}$-K$_4$Cr$_2$O$_7$$^\oplus$</td>
<td>90</td>
<td>14.0</td>
<td>26.0 ± 5.36</td>
<td>86</td>
</tr>
<tr>
<td>$^{51}$Cr$^{3+}$-EDTA$^\oplus$</td>
<td>68</td>
<td>16.9</td>
<td>29.0 ± 10.76</td>
<td>72</td>
</tr>
<tr>
<td>-1000 ppm EDTA$^{**}$</td>
<td>70</td>
<td>16.9</td>
<td>24.7 ± 7.94</td>
<td>46</td>
</tr>
<tr>
<td>-Na-oxalate$^\oplus$</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$^{131}$I-NaI</td>
<td>71</td>
<td>14.7</td>
<td>15.2 ± 3.20</td>
<td>3</td>
</tr>
<tr>
<td>-1000 ppm NaI$^{**}$</td>
<td>96</td>
<td>15.6</td>
<td>13.9 ± 2.53</td>
<td>2</td>
</tr>
<tr>
<td>$^{35}$S-H$_2$SO$_4$</td>
<td>83</td>
<td>15.8</td>
<td>26.3 ± 8.01</td>
<td>91</td>
</tr>
<tr>
<td>-1000 ppm Na$_2$SO$_4$$^{**}$</td>
<td>95</td>
<td>15.9</td>
<td>25.4 ± 8.9</td>
<td>60</td>
</tr>
</tbody>
</table>

* Complexing agent in equivalent amount.
** Complexing agent or carrier in excess.
<table>
<thead>
<tr>
<th>Tracer</th>
<th>Tracer in eluate (%)</th>
<th>Free volume $X_{eq}$ (ml)</th>
<th>$X_{eq} \pm \sigma$ (ml)</th>
<th>Relative wave retardation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{65}$Zn$^{2+}$-EDTA*</td>
<td>81</td>
<td>18.0</td>
<td>18.6 ± 6.55</td>
<td>3</td>
</tr>
<tr>
<td>-1000 ppm EDTA**</td>
<td>90</td>
<td>15.2</td>
<td>15.4 ± 4.85</td>
<td>1</td>
</tr>
<tr>
<td>$^{54}$Fe$^{3+}$-EDTA*</td>
<td>68</td>
<td>17.7</td>
<td>24.7 ± 9.29</td>
<td>39</td>
</tr>
<tr>
<td>-700 ppm EDTA**</td>
<td>85</td>
<td>16.4</td>
<td>23.5 ± 6.96</td>
<td>43</td>
</tr>
<tr>
<td>-Na+citrate*</td>
<td>19</td>
<td>17.7</td>
<td>22.0 ± 7.08</td>
<td>24</td>
</tr>
<tr>
<td>-KCN*</td>
<td>81</td>
<td>17.7</td>
<td>22.3 ± 6.51</td>
<td>26</td>
</tr>
<tr>
<td>-1000 ppm KCN**</td>
<td>94</td>
<td>21.0</td>
<td>21.0 ± 7.04</td>
<td>1</td>
</tr>
<tr>
<td>$^{60}$Co$^{2+}$-EDTA*</td>
<td>94</td>
<td>16.5</td>
<td>18.7 ± 5.98</td>
<td>13</td>
</tr>
<tr>
<td>-1000 ppm EDTA**</td>
<td>92</td>
<td>17.0</td>
<td>19.8 ± 6.39</td>
<td>9</td>
</tr>
<tr>
<td>-KCN*</td>
<td>96</td>
<td>17.2</td>
<td>17.4 ± 6.01</td>
<td>1</td>
</tr>
<tr>
<td>$^{51}$Cr$^{5+}$-K$_2$Cr$_2$O$_7$*</td>
<td>74</td>
<td>18.5</td>
<td>24.7 ± 7.32</td>
<td>37</td>
</tr>
<tr>
<td>$^{65}$Zn$^{2+}$-EDTA*</td>
<td>16</td>
<td>17.8</td>
<td>20.8 ± 6.46</td>
<td>17</td>
</tr>
<tr>
<td>$^{131}$I-NaI</td>
<td>72</td>
<td>16.8</td>
<td>17.1 ± 4.59</td>
<td>2</td>
</tr>
<tr>
<td>-1000 ppm NaI**</td>
<td>94</td>
<td>16.6</td>
<td>16.8 ± 4.26</td>
<td>1</td>
</tr>
<tr>
<td>$^{35}$S-H$_2$SO$_4$</td>
<td>87</td>
<td>21.5</td>
<td>18.8 ± 5.25</td>
<td>9</td>
</tr>
<tr>
<td>-1000 ppm Na$_2$SO$_4$**</td>
<td>92</td>
<td>16.9</td>
<td>18.8 ± 5.29</td>
<td>10</td>
</tr>
</tbody>
</table>

* Complexing agent in equivalent amount.
** Complexing agent or carrier in excess.
TABLE IV. BEHAVIOUR OF TRACERS PASSING THROUGH CARBONIC SOIL

<table>
<thead>
<tr>
<th>Tracer</th>
<th>Tracer in eluate (%)</th>
<th>Free volume $X_i$ (ml)</th>
<th>$\bar{X} \pm \sigma ; (ml)$</th>
<th>Relative wave retardation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{60}Zn^{2+}$-EDTA$^\bullet$</td>
<td>83</td>
<td>18.0</td>
<td>$18.1 \pm 4.43$</td>
<td>0</td>
</tr>
<tr>
<td>-1000 ppm EDTA$^{**}$</td>
<td>94</td>
<td>17.3</td>
<td>$17.2 \pm 4.63$</td>
<td>0</td>
</tr>
<tr>
<td>$^{65}Co^{3+}$-EDTA$^\bullet$</td>
<td>88</td>
<td>17.9</td>
<td>$20.4 \pm 5.52$</td>
<td>17</td>
</tr>
<tr>
<td>-1000 ppm EDTA$^{**}$</td>
<td>94</td>
<td>18.0</td>
<td>$21.0 \pm 6.54$</td>
<td>17</td>
</tr>
<tr>
<td>$^{51}Cr^{3+}$-K$_2$Cr$_2$O$_7$$^\bullet$</td>
<td>98</td>
<td>17.7</td>
<td>$18.3 \pm 5.04$</td>
<td>4</td>
</tr>
<tr>
<td>$^{131}I$-NaI</td>
<td>99</td>
<td>15.9</td>
<td>$16.8 \pm 3.96$</td>
<td>1</td>
</tr>
<tr>
<td>-1000 ppm NaI$^{**}$</td>
<td>98</td>
<td>15.0</td>
<td>$17.8 \pm 4.55$</td>
<td>-</td>
</tr>
<tr>
<td>$^{35}S$-H$_2$SO$_4$</td>
<td>100</td>
<td>16.1</td>
<td>$22.4 \pm 5.72$</td>
<td>39</td>
</tr>
<tr>
<td>-1000 ppm Na$_2$SO$_4$$^{**}$</td>
<td>95</td>
<td>16.5</td>
<td>$22.5 \pm 5.64$</td>
<td>36</td>
</tr>
</tbody>
</table>

$^\bullet$ Complexing agent in equivalent amount.
$^{**}$ Complexing agent or carrier in excess.

time, but the retardation of their waves is almost the same and even greater than most of the complex cations investigated.

In humic soils (Table II) the percentage of the tracer in the eluate varies from 0% ($Fe^{3+}$-Na-citrate, $Cr^{3+}$-oxalate) to 99% ($Co^{3+}$-KCN). However, in this case the excess ligand increases the tracer amount emerging from the column and decreases wave retardation. It is an interesting fact that iron compounds have an unfavourable effect on humic soil.

In the case of clayey soil (Table III), $Fe^{3+}$-Na-citrate (only 19%) and $Cr^{3+}$-EDTA (10%) have the least throughputs. A relatively small retardation of tracer waves and a great influence of the excess of ligand on the decrease of retardation are characteristic in this case.

In carbonic soils (Table IV) the percentage of the throughput of complex cations is large, while the retardation is negligible.
Figure 5 shows the influence of zinc concentration in the starting solution on the form of the waves after passing through the column with clayey and humic soil. Because of the greater wave expansion in humic soil the relative maximum concentration of the tracer is smaller than in clayey soil. It is obvious that 0.008 ppm of $^{68}$Zn-EDTA, even less, can easily be detected.

![Graph showing relative concentration vs volume throughput](image)

**FIG. 5.** Passage of $^{68}$Zn$^{2+}$-EDTA of various concentrations through the column with clayey and humic soils.

**CONCLUSION**

From the results of investigations it can be seen that, as was expected, the behaviour of the same compounds on various types of soils and different compounds on the same type of soil, differs. If the obtained characteristics of eluent curves for investigated compounds are compared, it may be stated that for sandy soil the most suitable tracers are zinc-EDTA, iron-EDTA, iron-KCN, cobalt-EDTA, cobalt-KCN, chromium-EDTA and chromium as $K_2Cr_2O_7$; for humic soil the following tracers can be used: zinc-EDTA, cobalt-EDTA, cobalt-KCN, chromium-EDTA and $K_2Cr_2O_7$; for clayey soil: zinc-EDTA, iron-EDTA, iron-KCN, cobalt-EDTA and cobalt-KCN; and for carbonate soil: zinc-EDTA, cobalt-EDTA and $K_2Cr_2O_7$.

Likewise, it may be concluded that the retardation of tracer waves causes the greatest error in the interpretation of results where radioactive tracers are used for investigating subterranean waters.

The results of the present investigations cannot, a priori, be applied in practice. In each particular case the most suitable tracers, which have proved to correspond to a definite soil type, should be chosen and used for preliminary laboratory experiments on soils taken from terrains intended for investigations.

**REFERENCES**

H. KICK: How long did your percolation experiments run? Could not the organic complex compounds be decomposed by micro-organisms after long contact with the soils, which could considerably change the migration conditions?

A. FILIP: Each experiment continued for 20-30 min, so there was no risk of large changes in tracer solution.

W.R. GARDNER: On behalf of those interested in the theoretical interpretation of tracer studies, I urge that certain measurements should always be made. One important example is the adsorption isotherm. If we know the ratio of the amount of tracer in solution to that adsorbed in unit volume of soil, we can estimate tracer retardation. If the isotherm is non-linear, then the retardation will depend on tracer concentration. The shape of the isotherm also gives some idea of the shape of the tracer peak.

A. FILIP: I quite agree.
INFLUENCIA DE LA CANTIDAD DE RIEGO Y TIPO DE SUELO SOBRE LA EMIGRACION VERTICAL DE HIERRO Y MANGANESCO EN SUELOS DEL SURESTE ESPAÑOL

F. COSTA*, I. ESPARRAGUERA, N. ORTIN, M. del VAL, F. de la CRUZ, O. CARPENA*, Y R.F. CELINI
JUNTA DE ENERGIA NUCLEAR, MADRID, ESPAÑA

Abstract — Resumen

INFLUENCE OF IRRIGATION RATE AND SOIL TYPE ON THE VERTICAL MIGRATION OF IRON AND MANGANESE IN THE SOILS OF SOUTH-EAST SPAIN. The citrus plantations in south-east Spain, situated largely on calcareous soils which are submitted to intensive cultivation, are investigating nutritional changes caused mainly by deficiencies of trace elements, especially iron and manganese, which result in a lower yield and premature exhaustion of the trees.

The paper deals with a radioactive tracer study of the behaviour of these ions in soils and with the factors influencing their migration to the root zone; the object of the work is to develop a rational and economic fertilization policy.

The work has been based on two types of soil, representing extreme situations encountered in practice; one soil is calcareous and the other non-calcereous. A set of columns was assembled, each column having a length of 1 m and a cross-section of 36 cm²; solutions of ⁰⁹Fe and ⁵⁴Mn were added to these columns both in sulphate and chelate form. A definite amount of water, proportional to the requirements of citrus plantations, was intermittently passed through these columns. Soil samples were taken periodically and the total activity and the activity of the assimilable and non-assimilable fractions of the elements being studied were measured.

At the same time an apparatus involving a collimated scintillation detector was developed to follow the vertical migration of these ions in soils; the water drained from the columns after each irrigation was analysed radiochemically for the same purpose.

INFLUENCIA DE LA CANTIDAD DE RIEGO Y TIPO DE SUELO SOBRE LA EMIGRACION VERTICAL DE HIERRO Y MANGANESCO EN SUELOS DEL SURESTE ESPAÑOL. Las plantaciones cítricas del sureste español, radicadas en gran parte sobre suelos calizos y sometidos a cultivos intensivos, experimentan con el tiempo alteraciones de orden nutritivo debido principalmente a deficiencias de oligoelementos, especialmente hierro y manganeso, que se traduce en una menor producción y en un agotamiento prematuro de los árboles.

En la presente comunicación se estudia, mediante trazadores radiactivos, el comportamiento de estos iones en los suelos, así como los factores que influyen en su emigración hacia la zona radicular, con objeto de desarrollar una política de abono racional y rentable.

Para la realización de este trabajo se han seleccionado dos tipos de suelos, que representan situaciones extremas que pueden presentarse en la práctica: uno calizo y otro no calizo. Se ha construido una batería de columnas, cada una de 1 m de longitud x 32 cm² de sección y se han agregado a las mismas soluciones de ⁰⁹Fe o ⁵⁴Mn, tanto en forma de nitratos como de quelatos. Se ha hecho fluir por las columnas de forma intermitente una cantidad constante de agua, proporcional a las necesidades hídricas de las plantaciones cítricas, y periódicamente se han tomado muestras de suelo, determinándose tanto las actividades totales como las actividades de las fracciones asimilables y no asimilables de los elementos en estudio.

Paralelamente se ha desarrollado un equipo que mediante un detector colocado de centímetros permite seguir la emigración vertical de estos iones en los suelos y se han analizado radioquímicamente con el mismo fin las aguas de drenaje de las columnas después de cada riego.

* Instituto Nacional de Edafología y Agrobiología, Centro de Edafología y Biología Aplicada del Segura, Murcia, España.
1. INTRODUCCION

Las plantaciones cítricas del sureste español, radicadas en gran parte sobre suelos calizos y sometidas a cultivos intensivos, experimentan con el tiempo alteraciones de orden nutritivo motivadas principalmente por deficiencias de hierro y manganeso, lo que se traduce en una menor producción y agotamiento prematuro de los árboles.

Estudios anteriores [1] han demostrado que las deficiencias de ambos oligoelementos, tan extendidas en esta región, provienen principalmente del exceso de carbonato cálcico de los suelos, siendo más afectados los citrúneos, sobre todo el limonero.

TABLA I. ANALISIS GRANULOMETRICO Y QUIMICO-FISICO DE LOS SUELOS ENSAYADOS SOBRE ELEMENTOS MENORES DE 2 mm DE DIAMETRO (Hasta 20 cm de profundidad)

<table>
<thead>
<tr>
<th>TIPO DE ANALISIS</th>
<th>SUELO CALIZO</th>
<th>SUELO NO CALIZO</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GRANULOMETRICO</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elementos gruesos (≥ 2 mm φ)</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Elementos finos</td>
<td>100.00</td>
<td>100.00</td>
</tr>
<tr>
<td>Arena gruesa</td>
<td>1.00</td>
<td>57.00</td>
</tr>
<tr>
<td>Arena fina</td>
<td>53.60</td>
<td>32.00</td>
</tr>
<tr>
<td>Limo</td>
<td>31.40</td>
<td>6.80</td>
</tr>
<tr>
<td>Arcilla</td>
<td>11.55</td>
<td>3.39</td>
</tr>
<tr>
<td>Textura</td>
<td>Limo - Arenosa</td>
<td>Arenosa</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>QUIMICO-FISICO</strong></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ci, de Cambio total (mg/100 g)</td>
<td>21.25</td>
<td>11.25</td>
</tr>
<tr>
<td>pH (H2O)</td>
<td>7.95</td>
<td>7.65</td>
</tr>
<tr>
<td>pH (KCl)</td>
<td>7.35</td>
<td>6.85</td>
</tr>
<tr>
<td>NO3 ( μMho cm⁻¹)</td>
<td>499</td>
<td>201</td>
</tr>
</tbody>
</table>

* Valores expresados en tanto por ciento.

Con respecto al hierro, los estados iniciales de clorosis pueden prevenirse con una serie de medidas sistemáticas tales como la fertilización equilibrada, remoción frecuente del suelo, estricto control de los riegos y aportes copiosos de sulfato ferroso asociado con materia orgánica [2]. No obstante, estos tratamientos sólo resuelven un aspecto parcial del problema, ya que estados avanzados de clorosis, particularmente en plantaciones adultas, no pueden restablecerse por estos caminos. Nuestros intentos, con los procedimientos empleados por otros investigadores a problemas similares, tales como la aplicación de hierro en forma de quelato al suelo (Fe - EDTA) y los de inyección al tronco de tabletas de sales de hierro no tuvieron éxito completo [3]. Últimamente, hemos modificado la técnica de inyección con resultados satisfactorios [4].
Otro factor limitante en la producción citrícola del sureste español es la deficiencia de manganeso, que influye extraordinariamente en los rendimientos. Observaciones repetidas [5, 6] han permitido comprobar que el progreso de tal enfermedad tras consigo la disminución de brotes florales y, como consecuencia, de los frutos. La aplicación de sulfato manganeso por vía foliar, en condiciones determinadas, corrige el estado carencial.

Con independencia de las aplicaciones prácticas expuestas, han continuado nuestros estudios sobre los factores causantes de estas deficiencias, a fin de arbitrar tratamientos de eficacia completa.

En la presente investigación se estudia, mediante trasadores radiactivos, el comportamiento del hierro y del manganeso en suelos representativos de las situaciones extremas que pueden presentarse en la práctica, así como su emigración hacia la zona radicular, con objeto de desarrollar una política de abono racional y rentable.

**TABLA II. ANALISIS QUIMICO DE LOS SUELOS ENSAYADOS SOBRE ELEMENTOS MENORES DE 2 mm DE DIAMETRO (Hasta 20 cm de profundidad)**

<table>
<thead>
<tr>
<th>TIPO DE ANALISIS</th>
<th>SUELO CALIZO</th>
<th>SUELO NO CALIZO</th>
</tr>
</thead>
<tbody>
<tr>
<td>QUIMICO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbonato cálcico total*</td>
<td>47.00</td>
<td>1.5</td>
</tr>
<tr>
<td>Carbonato cálcico moitvo*</td>
<td>18.65</td>
<td>1.07</td>
</tr>
<tr>
<td>Carbono total*</td>
<td>1.42</td>
<td>0.47</td>
</tr>
<tr>
<td>Materia orgánica*</td>
<td>2.45</td>
<td>0.81</td>
</tr>
<tr>
<td>Nitrogénio total*</td>
<td>0.155</td>
<td>0.045</td>
</tr>
<tr>
<td>O/N</td>
<td>9.2</td>
<td>10.4</td>
</tr>
<tr>
<td>Fósforo asimilable (ppm)</td>
<td>0.10</td>
<td>13.35</td>
</tr>
<tr>
<td>Potasio**</td>
<td>0.88</td>
<td>0.15</td>
</tr>
<tr>
<td>Calcio**</td>
<td>-</td>
<td>10.00</td>
</tr>
<tr>
<td>Magnesio**</td>
<td>-</td>
<td>4.00</td>
</tr>
<tr>
<td>Sodio total**</td>
<td>1.24</td>
<td>0.46</td>
</tr>
<tr>
<td>Cloruros (Cl -)**</td>
<td>0.65</td>
<td>0.38</td>
</tr>
<tr>
<td>Sulfato cálcico</td>
<td>0.10</td>
<td>0.03</td>
</tr>
</tbody>
</table>

* Valores expresados en tantos por ciento.
** Valores expresados en mg/100 g

2. TECNICAS DE TRABAJO

2.1. Selección de los suelos

Las características fisicoquímicas de los suelos elegidos figuran en las tablas I y II.

El primero de ellos, notablemente calizo, procede de Santomera (Murcia). Presenta una textura limotoarenosa, capacidad de cambio de cationes elevada, de poder cloroantante muy elevado y salinidad ligera. De contenidos bajos en fósforo, potasio y sodio asimilables, medio en materia
orgánica, nitrógeno total, sulfato cálcico y cloruros. Su fracción arcillosa está formada por illita como componente dominante, escasos montmorillonoides y vestigios de caolinita.

El segundo suelo, no calizo, procedente de Santa María de Nieva (Almería), de salinidad baja y textura arenosa, muestra una capacidad de cambio de cationes media y poder clorosante bajo. Tiene un nivel muy bajo en materia orgánica, nitrógeno total y potasio asimilable; bajo en sodio, cloruros y sulfato cálcico y de contenido medio en fósforo asimilable. La arcilla está formada por abundantes montmorillonoides y menor cantidad de illita muy bien cristalizada. La proporción de caolinita es muy baja.

2.2. Preparación de las columnas de suelo

Una vez seleccionados los suelos, se construyó una batería de columnas compuesta por 56 tubos de cloruro de polivinilo (28 tubos por suelo), de 32 cm² de sección y 1,20 m de longitud. Con objeto de facilitar el corte posterior de los suelos estudiados, dichos tubos fueron seccionados en dos mitades en forma de media caña y posteriormente unidos con masilla y cinta adhesiva. Dichos tubos se llenaron con sus respectivos suelos hasta una altura de 1 m. Debido a las diferencias de densidad, el material contenido en las columnas pesó 3760 g y 5160 g para los suelos calizo y no calizo, respectivamente. Después se hizo fluir por cada uno de ellos 1000 cm³ de agua, con objeto de lograr su uniformidad evitando así la formación de vías privilegiadas por donde pudiera fluir la posterior agua de riego.

2.3. Trazadores empleados y formas químicas de aplicación a los suelos

En el abonado normal de una plantación de agrios y en lo referente a sus necesidades de hierro, las cantidades utilizadas son del orden de 1200 kg de FeSO₄·7H₂O por ha y por año. Con objeto de reproducir al máximo en nuestras experiencias de laboratorio las condiciones de campo, y a la vista de las cifras anteriores, la cantidad añadida a cada tubo por elemento en estudio fue de 77,3 mg, con una actividad total de 28 µCl y disueltos en 20 cm³ de agua bajo las formas siguientes: ⁵⁹FeSO₄, ⁵⁴MnSO₄, ⁵⁹Fe-EDDHA (ácido etilendiamino-dil-(hidroxifenil acético)), ⁵⁴Mn-EDTA (ácido etilen-diamino tetraacético).

Tanto el ⁵⁹Fe como el ⁵⁴Mn fueron preparados en la Sección de Radioquímica de la Junta de Energía Nuclear, con actividades específicas de 4,5 y 231 Cl/g, respectivamente.

2.4. Riegos

La cantidad de agua de riego empleada en el sureste español en plantaciones de limoneros y con los suelos en estudio está comprendida entre los 3000 y 4000 m³ por ha y por año, distribuidos en tres o cuatro aplicaciones. De acuerdo a la sección de suelo contenido en cada una de las columnas y considerando los datos anteriores, realizamos el riego de la manera siguiente:

Una vez absorbida la solución radiactiva por las columnas de los suelos se adicionaron 50 cm³ de agua y, retenida ésta, se completó lenta-mente con otros 300 cm³, estimándose que de este modo el suelo había
recibido su primer riego. Los restantes se realizaron por adición de 300 cm³ de agua en cada uno de ellos. Los tres primeros equivalen al riego de un año. Las aguas de drenaje se recogían en botellas de plástico colocadas en el extremo inferior de cada uno de los tubos.

2.5. Determinación de actividades en muestras de suelos y en aguas de drenaje

Después de cada riego y una vez abiertas las columnas se determinaron, en las distintas fracciones de los suelos y a varias profundidades, las actividades totales, así como en algunos de ellos las actividades de las fracciones asimilables y no asimilables [7]. Cuando la movilidad de los compuestos marcados añadidos a los suelos era tal que alguna fracción de dichos compuestos se encontraba en las aguas de drenaje, se determinaba igualmente su actividad. Estas operaciones se realizaron con un contador de centelleo con cristal de NaI(Tl) asociado con una escala automática.
2.6. Sistema para medida de actividades en columnas de suelos

Con objeto de visualizar la emigración vertical de los iones en estudio, se ha proyectado y construido (figuras 1 y 2) un equipo que utilizando un contador de centelleo colimado permite realizar medidas cuantitativas de las actividades totales en las diferentes secciones de los suelos.

El sistema consta de un contador de centelleo (N° 3, figura 1) con cristal de NaI(Tl), blindado con protección de plomo de 70 mm de espesor (N° 4 y 5). La pieza 5 es intercambiable y presenta en su cara anterior una ranura de 50 X 2 mm con objeto de obtener un haz plano colimado de radiación. Todo el conjunto anterior es capaz de desplazarse a lo largo de una columna (N° 10) pudiendo medirse los desplazamientos en un contador de vueltas (N° 30). El movimiento del detector de centelleo está calculado de tal manera que al registrarse una vuelta en dicho contador, el avance del sistema sea de 2 mm. Dicho movimiento puede realizarse manualmente, o por medio de un motor (N° 29). La pieza 5 se ajusta exteriormente a los tubos de plástico, representados por una línea discontinua en la figura 1, y estos se sitúan frente al contador quedando colocados en una posición perfectamente reproducible ya que su base queda fija y la parte superior se sujeta por una tapa en forma de tronco de cono (N° 24) que se desliza a lo largo de dos barras (N° 11).

En la realización del presente trabajo se ha utilizado un motor de 7,5 rev/min y, con objeto de registrar una medida continua del reparto de la actividad en los suelos, el contador de centelleo se ha conectado a un conjunto de medida formado por un amplificador, un integrador y un registro gráfico.

3. RESULTADOS Y DISCUSION

Una propiedad químicamente importante de los elementos estudiados es su facilidad de hidrólisis en medio alcalino, con la formación de hidróxidos y óxidos hidratados insolubles. Por esta razón, en suelos calizos resultan poco asequibles a las plantas. Los agentes formadores de quelatos son muy útiles para mantener a estos oligoelementos en la disolución del suelo.

Thorne y Wiebe [8] han discutido ampliamente las reacciones de los oligoelementos en los suelos, los factores que afectan su solubilidad y la absorción y translocación de dichos elementos por plantas superiores.

El control de la clorosis en experiencias de campo utilizando quelatos de Fe-EDTA al suelo mitigaba la clorosis, debida al cobre en cirrus que crecían sobre suelos arenosos ácidos. Sin embargo, posteriores ensayos en suelos calizos mostraron la necesidad de cantidades mucho mayores de Fe-EDTA y de algunos otros quelatos de hierro, para controlar la clorosis inducida por el carbonato cálcico; las respuestas fueron a menudo variables y no se alcanzaron soluciones favorables desde el punto de vista económico.

Hill-Cotttingham [11] realizó en 1957 un trabajo a escala de laboratorio con seis quelatos de hierro, a fin de explicar las respuestas obtenidas en el campo como correctivos de la clorosis de hierro inducida por el carbonato cálcico. El compuesto que presentó una mayor estabilidad en suelos calizos (pH 7,8, 35% de contenido de arcilla y 28% de CaCO₃) fue el Fe-EDDHA. En alguna de sus experiencias con Fe-EDTA se vio que,
<table>
<thead>
<tr>
<th>Profundidad (m)</th>
<th>Número de Riego</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>100.00</td>
<td>100.00</td>
<td>99.57</td>
<td>100.00</td>
<td>99.77</td>
<td>100.00</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>0.13</td>
<td>0.33</td>
<td>0.57</td>
<td>1.94</td>
<td>2.81</td>
<td>2.54</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>0.23</td>
<td>0.46</td>
<td>1.41</td>
<td>3.41</td>
<td>5.20</td>
<td>4.12</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>0.67</td>
<td>1.41</td>
<td>3.41</td>
<td>5.20</td>
<td>4.12</td>
<td>2.86</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>1.41</td>
<td>3.41</td>
<td>5.20</td>
<td>4.12</td>
<td>2.86</td>
<td>2.62</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>3.41</td>
<td>5.20</td>
<td>4.12</td>
<td>2.86</td>
<td>2.62</td>
<td>4.44</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Número de Riego</th>
<th>Número de Calzado</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
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<tr>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

VALORES EXPRESADOS EN TANTO POR CIENTO (Tratamiento: FeSO₄)
TABLA IV. REPARTO DE LA ACTIVIDAD AGREGADA A CADA COLUMNA
Valores expresados en tanto por ciento (Tratamiento: $^{54}$MnSO$_4$)

<table>
<thead>
<tr>
<th>Profundidad alcanzada (cm)</th>
<th>Suelo Calizo</th>
<th>Suelo No Calizo</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Número de Riegos</td>
<td>Número de Riegos</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>100.00</td>
<td>98.77</td>
</tr>
<tr>
<td>5</td>
<td>1.23</td>
<td>1.53</td>
</tr>
<tr>
<td>10</td>
<td>0.07</td>
<td>0.10</td>
</tr>
<tr>
<td>15</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>20</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>25</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
después de un rápido descenso, la concentración del quelato total permanece prácticamente constante, disminuyendo con el tiempo la del quelato de hierro. Estos resultados sugieren que la reacción entre el suelo y la disolución de quelato tiene lugar en dos fases: la primera consiste en la adsorción rápida del quelato por la arcilla y desplazamiento posterior del hierro quelatado por otro metal, probablemente calcio. La naturaleza del agente formador de los quelatos citados afecta las diferencias cuantitativas referentes a su estabilidad. Kroli [12] muestra que el EDDHA es muy efectivo en el tratamiento de la clorosis como agente quelatante del hierro en suelos calizos, indicando que las reacciones de este compuesto con iones metálicos di- y trivalentes difieren significativamente de las que ocurren con el EDTA. El EDDHA muestra una afinidad muy alta para el Fe(III), moderada capacidad de unión con el Zn(II) y Mn(II) y muy débil para el Ca(II) y Mg(II). Las propiedades del EDDHA en suelos pueden atribuirse a su alta afinidad selectiva para el ion férrico y su relativa baja afinidad para otros oligoelementos esenciales, con la posible excepción del cobre. El Fe(III) – EDDHA es del orden de $10^4$ a $10^6$ veces más estable que otros quelatos de hierro, entre ellos el formado con EDTA.

 Otro factor importante que limita la efectividad de ciertos quelatos metálicos cuando se aplican al suelo consiste en que algunos de ellos se fijan sobre la superficie de las arcillas. Wallace y Lunt [13] sugieren que la fijación es la consecuencia de una unión del quelato al metal y éste a uno de los oxígenos de los bordes del cristal de la arcilla. Los quelatos metálicos que se comportan de esta manera son de escaso valor en cuanto a la nutrición vegetal. La configuraciónespacial es posiblemente un factor importante en la fijación de los quelatos metálicos sobre las arcillas, y esta teoría se apoya a la vista del modelo de fijación de diferentes metales para un quelato dado. Por ejemplo, es conocido que los quelatos Fe–EDTA, Mn–EDDHA y Zn–EDDHA se fijan sobre la arcilla y por el contrario no se fijan los Mn–EDTA, Zn–EDTA y Fe–EDDHA. Kambel y Graham [14] trabajando con $^{59}$Fe y $^{54}$Mn demuestran que estos elementos se adsorben sobre la superficie de la arcilla siguiendo un orden de retención íntimamente ligado con la naturaleza de este colóide. Para el hierro el orden de retención, de mayor a menor, es el siguiente: ilita, montmorillonita y caolinita, y para el manganeso: montmorillonita, caolinita e ilita.

 Las consideraciones anteriores nos han llevado a elegir para este estudio los quelatos a que hicimos referencia en el apartado 2.3. Los resultados del presente trabajo se exponen en las tablas III, IV, V y VI donde se expresan los porcentajes de la actividad total de las diferentes capas de suelo. Asimismo, en las tablas VII y VIII se indican los tantos por ciento de actividad de las fracciones asimilables.

 De la observación de la tabla III se desprende que el total de la actividad agregada bajo la forma de $^{59}$FeSO$_4$ al suelo calizo se encuentra en la capa superficial y ni siquiera después del sexto riego se detecta desplazamiento alguno. El comportamiento del $^{59}$FeSO$_4$ sobre suelo no calizo difiere en el sentido de que la fijación no es absoluta, y se observa una emigración lenta que con el riego de dos años llega a alcanzar una profundidad de 10 cm y un valor del 4,44%.

 En la tabla IV se aprecia que el $^{54}$MnSO$_4$ en el suelo calizo tiene una pequeña emigración de escaso valor, ya que al final de la experiencia solamente el 1,84% de la actividad se encuentra a 5 cm de profundidad y
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**TABLA VI. REPARTO DE LA ACTIVIDAD AGREGADA A CADA COLUMNA**
Valores expresados en tanto por ciento (Tratamiento: $^{54}$Mn-EDTA)
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<tr>
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<th>Número de Muestras</th>
<th>Profundidad (cm)</th>
<th>Tratamiento: $^{59}	ext{Fe SO}_4$</th>
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<td>2</td>
<td>10</td>
<td>-</td>
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</table>

T = Total  
S = Soluble  
FR = Fácilmente reducible  
Ex = Extraído  
C = Cambio  
R = Retenida en suelo
TABLA VIII. DISTRIBUCION EN DIFERENTES FRACCIONES DE LA ACTIVIDAD TOTAL DE CADA SECCION DEL SUELO DENTRO DE LOS RIEGOS DEL PRIMER AÑO

Valores expresados en tanto por ciento

| Tipo de suelo | Profundidad (cm) | Tratamiento $^{59}$Fe-EDDHA | | | Tratamientos $^{54}$Mn - EDTA | |
|---------------|------------------|---------------------------|---|---|---|---|---|---|
|               | T                | Fr                         | R  | T   | S   | C   | P.H.| R  |
| Calizo       |                  |                            |    |     |     |     |     |     |
| 1             | 12.12            | 20.97                      |    | 20.97|    | 20.97|    |     |
| 5             |                  |                            |    | 20.97|    | 20.97|    |     |
| 10            |                  |                            |    | 20.97|    | 20.97|    |     |
| 15            |                  |                            |    | 20.97|    | 20.97|    |     |
| 20            |                  |                            |    | 20.97|    | 20.97|    |     |
| 25            |                  |                            |    | 20.97|    | 20.97|    |     |
| 30            |                  |                            |    | 20.97|    | 20.97|    |     |
| 35            |                  |                            |    | 20.97|    | 20.97|    |     |
| 40            |                  |                            |    | 20.97|    | 20.97|    |     |
| 45            |                  |                            |    | 20.97|    | 20.97|    |     |
| 50            |                  |                            |    | 20.97|    | 20.97|    |     |
| 55            |                  |                            |    | 20.97|    | 20.97|    |     |
| No calizo    |                  |                            |    | 20.97|    | 20.97|    |     |
| 1             |                  |                            |    | 15.66|    | 15.66|    |     |
| 5             |                  |                            |    | 5.39 |    | 5.39 |    |     |
| 10            |                  |                            |    | 4.99 |    | 4.99 |    |     |
| 15            |                  |                            |    | 4.94 |    | 4.94 |    |     |
| 20            |                  |                            |    | 5.37 |    | 5.37 |    |     |
| 25            |                  |                            |    | 4.86 |    | 4.86 |    |     |
| 30            |                  |                            |    | 7.77 |    | 7.77 |    |     |
| 35            |                  |                            |    | 4.66 |    | 4.66 |    |     |
| 40            |                  |                            |    | 5.42 |    | 5.42 |    |     |
| 45            |                  |                            |    | 5.42 |    | 5.42 |    |     |
| 50            |                  |                            |    | 5.39 |    | 5.39 |    |     |
| 55            |                  |                            |    | 3.87 |    | 3.87 |    |     |
| 60            |                  |                            |    | 5.68 |    | 5.68 |    |     |
| 65            |                  |                            |    | 15.66|    | 15.66|    |     |
| 70            |                  |                            |    | 0.16 |    | 0.16 |    |     |

el 1.59 a 10 cm, permaneciendo en la capa superficial el 96.48%. En el suelo no calizo el comportamiento es similar a lo que sucedía con el hierro, aunque la emigración es más profunda, pues al final de los riegos del primer año se detecta actividad en los 10 primeros centímetros y al terminar el sexto ésta alcanza hasta el centímetro 20.

En la tabla V es de destacar la capacidad de emigración que el $^{59}$Fe-EDDHA tiene en ambos suelos. En el calizo y solamente con el primer riego llega a encontrarse actividad a 60 cm de profundidad y ésta viene aumentando en los riegos sucesivos hasta que en el quinto riego el 3.14% de la actividad total de la columna fluye con las aguas de drenaje. En el suelo no calizo esta velocidad de emigración es mayor, pues en el primer riego se halla actividad a lo largo de los primeros 70 cm, y en el tercero el 5.22% de la misma se encuentra en las aguas de drenaje. En los riegos quinto y sexto del 22 al 25% ha emigrado a una profundidad superior a 1 m. A lo largo de las columnas de la tabla V se aprecia una serie de máximos y mínimos correspondientes a los diversos frentes formados por cada uno de los riegos.

El $^{54}$Mn-EDTA, tabla VI, nos presenta una capacidad de emigración más atenuada que la del quelato de hierro en estudio, y ésta es aún más
FIG. 3. Suelo no calizo.
FIG. 4. Suelo calizo.

FIG. 5. Suelo no calizo.

lenta para el suelo calizo que para el no calizo, pues mientras que al final de la experiencia en el primero alcanza los 40 cm, en el segundo llega hasta una profundidad de 75 cm.

Los valores elevados del primer centímetro se deben en parte a que los sucesivos riegos le han ido enriqueciendo en elementos finos, factor a tener en cuenta según indicamos anteriormente.

En lo que se refiere a fracciones asimilables, nuestros resultados indican que el hierro agregado bajo la forma de sulfato, tabla VII, no se encuentra en el extracto de ninguno de los dos suelos, lo que nos da una idea de la alteración y fijación del ion en los mismos.

En los suelos tratados con sulfato de manganeso se observa que en el no calizo, aunque no encontramos actividad en la fracción soluble, sí hallamos un buen porcentaje en la fracción de cambio y aun mayor en la fácilmente reducible, si bien la primera disminuye en el segundo riego como consecuencia de su oxidación progresiva. En el suelo calizo sucede
algo similar aunque las fracciones de cambio y fácilmente reducibles son mucho menores que en el no calizo.

El extracto de estos suelos cuando se aplica $^{59}$Fe-EDDHA, tabla VIII, muestra un buen porcentaje de actividad, siendo éste mucho mayor en el no calizo.

Con el $^{54}$Mn-EDTA solamente nos fue posible determinar actividad en la fracción fácilmente reducible sucediendo como en el caso anterior que ésta es inferior en el suelo calizo.
Según indicamos en el apartado 2.6. se ha seguido de manera gráfica la emigración vertical de los iones en estudio en las diferentes formas químicas adicionadas a los suelos. Las figuras 3, 4, 5 y 6 muestran los resultados obtenidos con los sulfatos de hierro y manganeso para los dos tipos de suelo.

4. CONCLUSIONES

a) Se observa una retención absoluta del hierro cuando se aplica en forma de sulfato al suelo calizo; dicha retención se mantiene a lo largo del riego equivalente a dos años.

b) El sulfato ferroso en el suelo no calizo presenta una lenta y escasa emigración, por lo que su utilidad es muy relativa a los efectos prácticos de abonado para especies arbóreas.

c) La adición de sulfato de manganeso al suelo calizo, aunque presenta cierto grado de movilidad, posee también escaso valor para las plantas.

d) La movilidad del manganeso es más elevada que la del hierro cuando se aplica como sulfato al suelo no calizo. La utilidad del sulfato de manganeso en este caso puede considerarse de tipo medio.

e) Cuando los oligoelementos en estudio se encuentran en la parte aniónica de la molécula de quelato, su comportamiento difiere considerablemente del de los cationes libres.

f) Es de destacar la capacidad de emigración que presenta el Fe-EDDHA en ambos suelos, ya que alcanza plenamente la zona radicular de las plantas perennes arbóreas dentro de los riegos del primer año.

g) El Mn-EDTA tiene una movilidad más atenuada que la del quelato de hierro ensayado, presentando no obstante un interés práctico desde el punto de vista de la fertilización.

h) El suelo calizo muestra una mayor capacidad de retención para los quelatos estudiados.

i) Se ha desarrollado un equipo que, mediante un contador de centelleo colimado, permite evaluar cualitativa y cuantitativamente la emigración vertical de los iones estudiados a lo largo de una columna de suelo.

REFERENCIAS

G. HAUSER: I think it may be useful to mention that FAO's work with fruit trees in various countries provides striking confirmation of Mr. Ortín's results. As you may know, FAO carries out large numbers of field experiments in many countries and we constantly have to fight against lime-induced iron deficiency and deficiencies of other trace elements, such as zinc in citrus fruits, manganese and sometimes magnesium. In this fairly practical work we found that iron-EDDHA is superior in its effect on the plant to iron-EDTA, and greatly superior to iron-sulphate.
DETERMINATION BY INDICATOR ACTIVATION ANALYSIS OF THE SORPTION CONDITIONS, THE MOVEMENT AND THE DE-ENRICHMENT FACTOR OF ANIONS AT A SITE ON THE DANUBE

W. K. G. KÜHN
INSTITUTE OF RADIOBIOLOGY,
TECHNISCHE HOCHSCHULE,
HANOVER,
FEDERAL REPUBLIC OF GERMANY

Abstract

DETERMINATION BY INDICATOR ACTIVATION ANALYSIS OF THE SORPTION CONDITIONS, THE MOVEMENT AND THE DE-ENRICHMENT FACTOR OF ANIONS AT A SITE ON THE DANUBE.

To determine the sorption conditions of anions and their movement in the ground, \(^{137}\)I available as KI in an aqueous solution was evenly distributed over a site of 10×10 m on the Danube. The iodide was determined by indicator activation analysis using neutron activation.

Soil samples were taken from inside and outside the distribution area by Pückhauer drills to a depth of 2.50 m at 50-cm distances after 5, 10, 24, 72 and 1000 h.

After being processed the samples were activated in a reactor. The results show that anionic iodide especially is present directly below the distribution area at a depth down to 2.5 m. Two metres from the edge of the distribution area the concentration was only double the amount of naturally present iodide, while at a distance of 4 m and over, the iodide concentration of more than 70 soil samples was within the iodide background (0.3 ppm).

The migration rate is rather high at first and slows down with time. After five hours a depth-migration rate of about 40 cm/h was found, which earlier must have been considerably higher (about 2–3 m/h). From the iodide concentration at a 2-m depth and at the surface a de-enrichment factor of \(4.5 \times 10^5\) was found.

The degree of de-enrichment obviously depends on the soil structure. The method developed can be used in individual cases to determine the concentration of anions that penetrate the soil at much higher rates than cations. The method can be applied to other anions to determine their movement and concentration in the soil as a function of inter-relationships of depth, soil structure and irrigation.

To determine the influence of natural irrigation on the movement of anions in soil, an investigation was carried out with the aid of inactive iodine. The percolation, the movement and the de-enrichment factor of this anion were determined in a natural undisturbed cultivated soil. Iodine was used because it is a typical anion, and anions are known to have a much higher percolation rate than cations, as is shown by laboratory experiments.

It is more difficult to obtain correct representative values of the de-enrichment factor for anions than for cations because of the high migration speed and the varying local soil conditions, especially at retention horizons. However, cations can also migrate with the speed of anions when they are contained in anionic complexes. In all such investigations it is important to use natural undisturbed cultivated soil rather than artificial soil models. For the experiments the natural stable isotope \(^{127}\)I as KI in aqueous solution was equally distributed by irrigation over a 10×10-m² area on the Danube, near Bertoldshelm in Bavaria.

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The iodine concentration was chosen so that it could still be distinguished from the natural iodine content of the soil, which normally lies between 0.1 and 6 ppm, even if a horizontal spread over an area of 30×30 m² and a vertical spread to a depth of 3 m had taken place. The quantity of the marked solution was equal to a rainfall of 0.3 mm on a 100-m² deposition area, and the concentration was 4.5×10⁶ ppm.

The iodine was identified by neutron activation analysis. After the samples were taken from the soil, the natural inactive iodine, which was used as tracer, was activated in a reactor at a neutron flux of 2 to 3×10¹⁰ n/cm² s. After that, the induced radionuclide was measured by its γ-radiation of 0.45 MeV (half-life 25 min, dominating γ-radiation 0.45 MeV, with 15% disintegration probability). The induced activation of ¹²⁹I yields a disintegration rate of 6×10¹⁰ cpm/g at a neutron flux of 10¹² n/cm² s and a 12-min irradiation time. With a background of 2 cpm per 8.5 keV of the used scintillation counter (channel width = 2% of the line energy) this disintegration rate is equivalent to an iodine quantity of 1×10⁻¹⁰ g. By applying this method, therefore, the same high sensitivity is obtained as is possible by using radioactive tracers (for instance ¹³¹I). Of course the high detection sensitivity causes the limiting accuracy of the method to be determined by the natural iodine content of the soil.

The experimental area is about 400 m north of the Danube. The stratification in Fig. 1 shows, to a depth of 0.2 m, a humus layer which borders a more or less sandy silt layer about 2.1 m deep. Sand and gravel of varying granulation follow. The groundwater level lies at about 2–2.5 m depth. It is very dependent on the amount of rainfall and is therefore subject to considerable variations.

![Soil profile](image-url)
Before the iodine was placed in the soil, samples were taken from depths down to 2.5 m at eight places to determine the natural iodine content of the site. For this a Pürkhauser drill was used so that only an insignificant disturbance took place during the sample taking. These samples, like all other iodine-marked samples, after three days of air drying were milled, sifted and weighed in 5-g portions. These were shaken in 5 ml water until equilibrium occurred. Afterwards the solid matter was separated from the solution by a centrifuge. It was assumed that the solubility product of the KI was not reached in all cases, which indicated that the tracer substance was present in the liquid phase. Of this solution 0.3 ml was irradiated in a neutron flux of $3 \times 10^{12}$ n/cm$^2$/s in the Geesthacht reactor.

To get a calibration curve some standard iodine concentrations were similarly treated. This curve is shown in Fig. 2. It can be seen that the treatment of the samples has a certain but tolerable influence and that, on the whole, a good linearity of the method was obtained. For the evaluation the whole intensity of the photoline of $^{131}$I 0.45 MeV was used, which is a direct measure of the iodine concentration in the soil. To compare different activated samples the peak intensity of this $\gamma$-energy is calculated up to saturation activity from the end of the irradiation. The comparison of these induced activities of the prepared standard samples and the unmarked soil samples of the area results in a natural iodine concentration of 0.3 ppm. When measuring the induced and the standard activity two errors must be taken into consideration. One is caused by the count rate and the other arises at the determination of the $\gamma$-peak area. For instance, a peak intensity of $1.2 \times 10^6$ cpm is obtained at an iodine concentration of 2 $\mu$g after deducting the background. The error of the count-rate for this is 0.87%. A 10 times higher intensity is obtained from the peak area of a standard sample, which is irradiated at the same time with a standard error of 0.27%. On determining the ratio of both sample and standard, the error is therefore about 1% for a concentration of 2 $\mu$g.

With regard to the determination of the peak area the size of the error cannot be defined easily. In the case of the 0.45-MeV line of $^{131}$I its value is about 2-3%. Besides these possibilities of errors the following uncertainties must be considered:
(a) Weighing and volume determination: faults from this operation amount to 0.1%.

(b) The gradient of the neutron flux in the reactor: it amounts to 3.3%/cm in the position that is used in the reactor, and causes about a 3-4% inaccuracy.

(c) Neutron-flux depression: at elements of high absorption cross-section (potassium 8 = 2.07 b, iodine 8 = 7 b), the higher neutron absorption in the sample leads to an uneven activation. Therefore, the neutron flux is slightly reduced by a 15-mm sample charge. In our case this depression was very low and gave an error of only about 0.5%.

(d) In addition to these inaccuracies it must be borne in mind that a certain mutual influence on the soil stratifications by the drilling apparatus occurs. This error cannot be estimated, but a certain percentage should be considered for this as a source of error. On the basis of these inaccuracies the method is, on the whole, affected by an error of 10-15%.

FIG. 3. Plan of the field and sites where the samples were taken.

- Field marked with KI (10 x 10 m).
- X Unlabelled samples.
- O Labelled samples.

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EXPERIMENTAL RESULTS

In Fig. 3 the sample-taking positions are given. Because of the unknown spread conditions of iodine in the soil it was necessary to take into account that the iodine spread does not only take place within the marked area, but also in a certain horizontal direction. To determine this horizontal spread, 20 bore holes were drilled up to 22 m beyond the area. On the marked area itself three bore positions were used. On these positions the samples were taken down to 2.5 m (in 0.5-m distances) after 5, 10, 24, 72 and 1000 h. In Fig. 4, the measured spatial and time distribution of the iodine is shown. In this figure all values were connected which belonged to the same time. According to this, most of the iodine was found directly below the marked area to a depth of 2.5 m. Two metres from the marked area the iodine concentration is only a factor of two higher than the natural iodine content, while at 4 m and over from the field the iodine concentration for more than 70 samples is within a 0.3-ppm background. Obviously the "iodine cloud" only reaches
FIG. 5. Percolation velocity (from 0.5 to 1.5 m deep) as a function of the time after marking.

FIG. 6. Increase of the iodine concentration above the natural content after 40 min at a depth of 25 cm.
a maximal spread about 2 m from the area. The vertical distribution
of the marked solution under the marked area is dependent on local in-
fluences and changes with time. It is determined by the different local
situations, and chiefly by the soil stratification.

Because of the groundwater level at a depth of 2-2.25 m the iodine
movement here is also influenced by the groundwater. At a depth of about
1.3 m after 72 h and 1000 h a remarkable decrease of the concentration
was noticed. This may be caused by a retention layer, which, in ad-
dition causes the horizontal movement of the iodine at this depth. The
increase of the concentration at a distance of 2 m after 24, 72 and 1000 h
also indicates a movement from the area up to a maximum distance
close to the edge of the marked field. Figure 4 also shows the rela-
tively even distribution of the iodine after a 5-h percolation time at a
depth of about 2 m with a 50-ppm concentration. Above a 1.3-m depth
a slow concentration increase takes place, whereas below 1.3 m a de-
crease was measured. Therefore, a layer exists in which the iodine
content is remarkably constant. It is suspected that it is caused by a
bottom layer which acts as a dam. Such layers can be often found in
silt and fine sands. It could be also responsible for the horizontal spread,
which is detected at this depth. Below 2 m a slight increase of the iodine
concentration occurred, which is later de-enriched by the groundwater.

Between 0.25 and 1.25 m the vertical velocity with respect to the
percolation and to the change of ppm-values as a function of time could
be also obtained from Fig. 4 and is shown in Fig. 5. This velocity is
dependent on the concentration itself, the adhesive water, the capillarity
and the soil profile. All these influences on the percolation velocity are
within this time dependence. It is valid for curving lines and occurs
exponentially so that, as time goes on, smaller infiltration velocities
take place. Because of this dependence a velocity of about 33 cm/h
follows after 5 h. Before this the migration velocity must have values
of about 2-3 m/h and over, especially as it involves curving lines. There-
fore it can be explained that, at the latest after a few hours, iodine could
be found below the whole labelled area. If a velocity of only 33 cm/h,
with no respect to higher velocities is assumed, iodine must be detected
at a 0.25-m depth after 40 min above the natural content at the latest.
This corresponding point is shown in connection with the measured values
in Fig. 6.

By using the same percolation velocity one finds that the anion appears
at a depth of 2 m after 6 h. The measurement shows the entrance of iodine
already after 5 h at this depth, but in a lower concentration than that in
the layers above it. Also because of this a higher percolation velocity
is indicated so that the lower limit of the iodine movement in the soil is
about 30 cm/h. If one compares the iodine concentration of 10 ppm at a
2-m depth 5 h after starting, a de-enrichment factor of $4.5 \times 10^4$ results
during this time and for this depth.

With regard to the smallest detected iodine concentration of 0.8 ppm
at 2-m depth after 1000 h, a de-enrichment factor of $5 \times 10^5$ was measured.
This means a de-enrichment of the factor 4 for a 0.2-m thick soil layer
with an infinite spread and under natural weather conditions.

On the whole it can be concluded from the experiment that iodine,
as an anion, moves mainly vertically in the soil with a considerably
varying percolation velocity. The horizontal spread is not noticeable.
The slowest velocity is about 30 cm/h; it is probable that shortly after starting the experiment a velocity of a few metres per hour takes place directly below the soil surface. At a sufficiently high groundwater level this is reached by this anion after 5 h at the latest.

It was shown how during 1000 h different soil-weather conditions influence the movement of an anion which has a very long range in comparison with cations. The measurement methods described can also be applied to other anions whose movement and concentration in the soil under natural conditions should be examined.

DISCUSSION

M. J. FRISSEL (Chairman): In your paper you state that the natural iodine was activated by a neutron flux of $2-3 \times 10^{12}/cm^2 s$. Were these thermal neutrons?

W. K. G. KÜHN: Yes, they were.
STUDIES ON TAGGED CLAY MIGRATION DUE TO WATER MOVEMENT

H. W. SCHARPENSEEL
INSTITUT FÜR BODENKUNDE DER UNIVERSITÄT BONN,
AND
W. KERPEN
ARBEITSGRUPPE, INSTITUT FÜR LANDWIRTSCHAFT DER KFA JÜLICH,
FEDERAL REPUBLIC OF GERMANY

Abstract

STUDIES ON TAGGED CLAY MIGRATION DUE TO WATER MOVEMENT. $^{55}$Fe-tagged clay minerals, produced by hydrothermal synthesis, serve to clarify the question whether clay migration or clay formation in situ is the predominant mechanism in the $\delta$-development of Parabraunerde (sod brown leasitivity, grey brown podsol, haplufeit, derosol). They further indicate the possibilities of clay transportation caused by water percolation. Suitable experimental approaches, such as thin-layer chromatography and autoradiography, translocation tests in columns filled with monochromatic textural fractions or with undisturbed soil profiles, and synchronous hydrothermal treatment of $^{55}$Fe-containing material from different horizons of Parabraunerde, to reveal the specific readiness of the different profile zones for $^{55}$Fe-clay production, are described. The possibilities of clay percolation are discussed.

Although clay migration is traditionally considered to be the valid explanation for the phenomenon of horizons of clay accumulation, such as that in argids, alfisols and ultisols, this assumption is based on indirect evidence arising from the textural comparison of the horizons and micro-morphological thin-slide demonstration of plasmatic flow structures.

While the movement is certainly too slow to be detected by direct observation, one could expect to confirm or refute the clay migration concept from:

(1) Model experiments with columns of undisturbed soil profiles, or of different textural composition;
(2) Thin-layer chromatographic tests with layers of different grain-sizes;
(3) Trials to detect in-situ clay formation in the accumulation horizon as proof of an alternative mechanism;
(4) Chemical and physical comparison of the clay minerals in the $A_1$- and $A_2$-horizon with those along the plasmatic flow structures.

The methods connected with (1) - (3) require the use of tagged clay, which is distinguished by its radiation from the resident clay and mineral substance.

In earlier reports [1, 2] the production of $^{55}$Fe-labelled kaolinite and montmorillonite by hydrothermal synthesis in high-pressure autoclaves were explained.

A comparison of the constituents taking part in the synthesis of the clay minerals montmorillonite and kaolinite, with the partial substitution of $^{55}$Fe in isomorphic exchange for aluminium, is given in Table I.

1. COLUMN EXPERIMENTS

In studying tagged clay migration, the approach that is closest to natural field conditions is to administer $^{55}$Fe-tagged clay, placed in
TABLE I. CONSTITUENTS IN THE SYNTHESIS OF MONTMORILLONITE AND KAOLINITE

<table>
<thead>
<tr>
<th></th>
<th>Montmorillonite</th>
<th>Kaolinite</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>672.7 mg</td>
<td>491 mg</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>214.9 mg</td>
<td>475 mg</td>
</tr>
<tr>
<td>Mg-acetate</td>
<td>396 mg</td>
<td></td>
</tr>
<tr>
<td>KCl</td>
<td>88.9 mg</td>
<td></td>
</tr>
<tr>
<td>H₃Fe(OH)₃</td>
<td>35 mg</td>
<td>35 mg</td>
</tr>
<tr>
<td>H₂O</td>
<td>71 ml</td>
<td>71 ml</td>
</tr>
</tbody>
</table>

Treatment: 14 d, 300°C, 80 atm, or 42 d, 225°C, 50 atm. Autoclave 200 ml.

![Image of columns with well-defined soil texture-fractions; contemporary percolation by means of a dosis pump.](image)

Fig. 1. Columns with well-defined soil texture-fractions; contemporary percolation by means of a dosis pump.

1.50-m-long glass columns, in the upper zone of undisturbed soil profiles. By perfusion with known, sufficiently large amounts of water, and by activity scanning, the potential clay movement can be observed [3, 4]. Results so far obtained show little evidence of a clay migration, but rather an immobile storage of the tagged clay in a layer near the surface.

Since such experiments have not yet confirmed a measurable clay migration, a second perfusion method, in 50-cm columns filled with well-defined textural soil fractions, was carried out (Fig. 1).
The following fractions were singled out with the aid of sedimentation cylinders:

<table>
<thead>
<tr>
<th>Size Range</th>
<th>Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.002 - 0.02 mm</td>
<td>diam.</td>
</tr>
<tr>
<td>0.02 - 0.06 mm</td>
<td>diam.</td>
</tr>
<tr>
<td>0.06 - 0.2 mm</td>
<td>diam.</td>
</tr>
<tr>
<td>0.2 - 1 mm</td>
<td>diam.</td>
</tr>
<tr>
<td>1 - 2 mm</td>
<td>diam.</td>
</tr>
</tbody>
</table>

Incorporated in the upper 1-cm layer of the five columns were 150 mg of $^{59}$Fe-labelled montmorillonite with 6000 dpm/mg, suspended by ultrasonic treatment in 0.4N sodium pyrophosphate. Each percolation amounted to 1000 ml, equivalent to about 10000-mm precipitations. A thin inner coating of the columns with silicon oil prevents the water from forming preferential flow tracks along the glass walls. After the percolation the collected water was agitated and aliquots were tested for their activity. The activity rate in the liquid-scintillation spectrometer, minus the background (slightly increased), would express quantitatively the extent of eluted tagged clay.

![Image](image_url)

**FIG. 2.** Thin-layer chromatography with $^{59}$Fe-montmorillonite, the tagged compound remaining at the starting line.

Table II shows clay migration resulting from percolation with water only in the textural fractions, down to 0.06 mm diam. This occurs to a measurable extent only with coarse sand (2 - 0.2 mm diam.). In the columns with particle sizes of less than 0.06 mm diam. the whole tagged clay remained immobile in the top layer where it was administered.
TABLE II. MIGRATION OF TAGGED MONTMORILLONITE IN FIVE SOIL COLUMNS WITH DIFFERENT TEXTURAL FRACTIONS

<table>
<thead>
<tr>
<th>(mm diam.)</th>
<th>1st percolation (cpm/litre)</th>
<th>2nd percolation (cpm/litre)</th>
<th>3rd percolation (cpm/litre)</th>
<th>4th percolation (cpm/litre)</th>
<th>5th percolation (cpm/litre)</th>
<th>Total (cpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 2</td>
<td>516 210</td>
<td>387 230</td>
<td>386</td>
<td>-</td>
<td>-</td>
<td>903 828</td>
</tr>
<tr>
<td>0.2 - 1</td>
<td>204 118</td>
<td>318 050</td>
<td>821</td>
<td>-</td>
<td>-</td>
<td>522 989</td>
</tr>
<tr>
<td>0.06 - 0.2</td>
<td>-</td>
<td>217</td>
<td>557</td>
<td>-</td>
<td>-</td>
<td>774</td>
</tr>
<tr>
<td>0.02 - 0.06</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.02 - 0.002</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
2. THIN-LAYER CHROMATOGRAPHY

Thin-layer chromatography of plated soil/or clay/silica-gel/starch mixtures (13:15:2) is used to test migration and fixation processes of ions, humic matter or clay minerals in the soil [5].

FIG. 3. Set-up of high-pressure autoclaves in a tube-oven.

It can also be applied exclusively to a certain fraction of the soil-plus-starch binder either in conventional discontinuous partition chromatography or in continuous flow chromatography. Again, $^{55}$Fe-clay, well dispersed by ultrasonic treatment, is administered at a sequence of points on the starting line. Only with the coarse sand fraction was there observed a scanty clay translocation within the lower $B_t$-region (see Fig. 2).

3. HYDROTHERMAL TREATMENT

The general belief that the textural differences, i.e. higher concentrations of the clay fraction in the $B_t$-horizon (clay accumulation) of
lessevé-profiles, exist as a result of clay migration [6], is disputed. Model experiments in columns with undisturbed soil profiles indicate leaching and percolation of considerable quantities of colloidal SiO₂, aluminium and other required solvent associates, that might equally well form the excessive clay, wholly or in part, on the site of the B₁-horizon.

The potentialities of this alternative mechanism can be estimated by the comparative testing of newly formed clay-yields in the various profile horizons owing to mutual hydrothermal treatment in a high-pressure autoclave. As described in Figs.3 and 4 truncated cylinders with representative soil samples of the genetic horizons, previously mixed with finely ground ⁵⁷Fe(OH)₃ (20 g soil + 6 ml H₂O + 20 mg ⁵⁷Fe(OH)₃), were piled up in the autoclave (Fig.4) and treated hydrothermally for 42 d at 225°C and 50-atm steam pressure.

![Autoclave diagram](image)

**FIG. 4.** High-pressure autoclave filled with truncated cylinders containing soil of the different horizons.

The hydrothermally newly formed clay minerals, from the components available in the various horizons, were labelled with ⁵⁷Fe, i.e. incorporated in the clay minerals by isomorphic exchange for aluminium (see the basic constituents of clay synthesis, Table I). After hydrothermal treatment the soil samples were transferred into sedimentation cylinders. Only the clay fraction of less than 2 μm diam. is recovered and extracted with a dithionite-solution (40 ml 0.3 M Na-citrate-solution + 5 ml 1 M Na₂HCO₃-solution + 1 g Na-dithionite) so as to remove all the remaining free unbound ⁵⁷Fe. Finally the clay fractions were tested for their specific activity by suspension counting in a liquid-scintillation spectrometer. The specific activities measured were directly related to the clay-forming ability of the various genetic profile horizons.

Results so far available (Table III) consistently show that newly synthesized clay occurs more frequently in the A₁- and B/C-horizons. While, in the A₁-horizon, part of the ⁵⁷Fe might be tied up in stable clay-
humic acid-complexes with Fe-cation-bridge[7], the pronounced clay-forming predisposition in the B/C-horizon is genuine, and points to tendencies for clay to form in the transition zone between calcareous loess (C-horizon) and the decalcified, weathered loess-material of the B1-horizon. This, however, confirms the supposition that the higher clay content in the B1-horizon might at least partly stem from the development in loco because of the particularly favourable supply conditions with the required percolated structural components.

4. CHEMICAL AND PHYSICAL COMPARISON OF THE CLAY MINERALS IN THE A0- AND A1-HORIZON WITH THOSE ALONG THE PLASMATIC FLOW STRUCTURES

Studies are under way to compare the general clay fractions of the A0- and A1-horizons with the silicous-clayey substance, scraped off the plasmatic flow structures. Only if it is identical can the material from the plasmatic flow structures be considered to be translocated because of the clay-migration-mechanism. Appropriate methods are:
- X-ray diffraction analysis (control of background level due to amorphous matter);
- Differential-thermo-analysis;
- Electron-microscopy;
- Infra-red spectroscopy; and
- 26Si/28Si-29Si-isotope ratio measurement.

5. SUMMARY

The problem of whether or not in terrestrial soils, such as Parabraunerde, grey brown podsolic, sol brun lessivé, dernopodsoil and hapludalf, clay particles can be transported downwards with the flow of percolating water, is still open to question. So far the clay-migration concept is based on indirect evidence. Five different methods, mainly involving the use of tagged material, are described:

1. Tagged clay was found to remain concentrated in the upper layer when administered to large undisturbed soil-profile columns. Even after several years of repeated percolation this did not change.
2. 55Fe-labelled clay, administered to the upper layer of columns filled with varying soil fractions, showed a marked clay migration in the coarse-sand range of 2 - 0.2 mm diam., and a slight migration in the range down to 0.06 mm diam.
3. Thin-layer chromatography with different soil fractions reveals only a very slight clay migration and only in the coarse sandy soil fraction.
4. Hydrothermal treatment of material from all genetic horizons of Parabraunerde, mixed with 55Fe(OH)3, consistently yields the highest specific activity of the clay fractions in A0- and BC-horizon. The highest ability to produce clay seems to be associated with the transition zone of decalcification, superimposed on to the calcareous loess, in direct contact with the clay-accumulation zone (B1) above.

This at least points to a certain degree of new clay formation in or adjacent to the clay-accumulation horizon, apart from the clay migration alone claimed up to now.
### Table III. Specific Clay-Producing Ability of Different Horizons in Parabraunerde Profiles Below Forest and Field

<table>
<thead>
<tr>
<th>Genetic horizon</th>
<th>Depth (cm)</th>
<th>Sample depth (cm)</th>
<th>First run (dpm/g)</th>
<th>Second run (dpm/g)</th>
<th>Genetic horizon</th>
<th>Depth (cm)</th>
<th>Sample depth (cm)</th>
<th>First run (dpm/g)</th>
<th>Second run (dpm/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_b )</td>
<td>0 - 18</td>
<td>12 - 18</td>
<td>73000</td>
<td>106000</td>
<td>( A_b )</td>
<td>0 - 20</td>
<td>10 - 18</td>
<td>34000</td>
<td>62000</td>
</tr>
<tr>
<td>( A_t )</td>
<td>18 - 30</td>
<td>20 - 25</td>
<td>18000</td>
<td>44000</td>
<td>( A_t )</td>
<td>20 - 42</td>
<td>25 - 38</td>
<td>36000</td>
<td>58000</td>
</tr>
<tr>
<td>( B_t )</td>
<td>30 - 40</td>
<td>30 - 40</td>
<td>25000</td>
<td>44000</td>
<td>( B_t )</td>
<td>42 - 75</td>
<td>75 - 93</td>
<td>26000</td>
<td>34000</td>
</tr>
<tr>
<td>( B_z )</td>
<td>39 - 72</td>
<td>50 - 72</td>
<td>22000</td>
<td>45000</td>
<td>( B_z )</td>
<td>75 - 107</td>
<td>75 - 93</td>
<td>26000</td>
<td>34000</td>
</tr>
<tr>
<td>( B_tC_c )</td>
<td>72 - 80</td>
<td></td>
<td>53000</td>
<td>78000</td>
<td>( B_tC_c )</td>
<td>126 - 145</td>
<td>130 - 142</td>
<td>127000</td>
<td>22000</td>
</tr>
<tr>
<td>( B_tC_Cc )</td>
<td>80 - 110</td>
<td>90 - 100</td>
<td>78000</td>
<td></td>
<td>( B_tC_Cc )</td>
<td>145 - 155</td>
<td>145 - 150</td>
<td>46000</td>
<td>63000</td>
</tr>
</tbody>
</table>
(5) Comparative tests of the clay in the A_1- and A_2-horizons with the clayey material of the plasmatic flow-structures in the B_1-horizon must show identical characteristics, if the clay-migration concept is to be maintained. Experiments such as those done by X-ray diffraction tests, DTA, electron-microscopy, infra-red spectroscopy and {superscript}28Si/{superscript}30Si-isotope ratio measurement are being carried out.

REFERENCES


DISCUSSION

P. A. C. RAATS: Did you attempt in your column experiments to saturate the clays with any particular ion? The mobility of the clay would appear to depend strongly on the type of exchangeable ions present.

H. W. SCHARPENSEEL: Following synthesis the labelled montmorillonite is mainly calcium-saturated, but after washing with a solution of sodium citrate + sodium bicarbonate + sodium dithionite it is preferentially sodium-saturated. After it has been fed to the columns and percolated, the superficial cations are quickly equilibrated with the medium, in which Ca** constitute 70-80% of the exchange cations coating the clay minerals.

P. A. C. RAATS: The predominance of plasmatic flow structures on the walls of large pores, cracks and so on strongly suggest that these structures cannot be explained in terms of in-situ clay formation.

H. W. SCHARPENSEEL: The pores with plasmatic flow are not very large - some 25-60 μm in diameter - and clay formation from the downward-moving soil solution is quite feasible.

M. DE BOODT: Have you allowed for drying of the soil in your column experiments? One would expect the mechanical movement of the clays to occur through the fissures, which in Parabraunerde are sufficiently large (200 μm in diameter) when the water tension rises to 30 atm or more.

H. W. SCHARPENSEEL: For two days each month water is percolated through the soil columns. In the intervening period the soil dries until it reaches a condition somewhere between field capacity and the wilting
point. In view of the good water-holding capacity of loess, this procedure corresponds fairly well to field conditions.

M. DE BOODT: I should have thought it would be more logical to expect clay to form in the B1 rather than the B1/C horizon, the higher $^{55}$Fe activity in the latter being caused by the formation of iron phosphate or some other chemical with the ions present.

H. W. SCHARPENSEEL: The tendency for clay to form mainly in the B1/C horizon accords well with our experience of hydrothermal clay synthesis, from which we have come to expect maximum formation of montmorillonitic/lithic clay minerals in the region of maximum SiO$_2$ and Ca$^{++}$ availability. Iron phosphate formation does sound chemically feasible, but it is not substantiated by iron and phosphate values obtained by analysing the soil in different horizons.

W. KERPEN: I should like to amplify Mr. Scharpenseel's reply. Clay formation depends on the ratio of SiO$_2$ to bivalent cations. Since the availability of silicic acid is about the same in all horizons, the bivalent cations (particularly calcium) determine the extent of clay formation. The greatest availability of bivalent cations, together with a suitable amount of water, is in the B1/C horizon.

D. J. BROWN: Did you determine the mineral distribution throughout the soil columns before carrying out your tests? If so, was there any correlation between mineral content and clay formation?

W. KERPEN: The reasons for the concentration of clay enrichment in the B1 horizon can be extremely varied. For example, they can be genetic, that is to say, associated with clay migration or formation. Alternatively, they can be geological - associated with the stratification of substrata with different clay contents. We were interested in the former processes and accordingly used Parabraunerde (which is similar to the grey brown podsolics) for the column experiments. The initial material, Würman loess, was mineralogically uniform from the surface down to the subsoil, so that the formation of horizons with reduced and enhanced clay contents could be due only to clay migration and/or synthesis.

Nevertheless, we performed a wide range of soil analyses, including mineralogical, structural, radiographic, electron-optical, micromorphological and other physical studies.

Data on the correlation between mineral content and clay formation, obtained from hydrothermal synthesis studies, have been published in the following papers: Landw. Forsch. 17 Supplement (1963) 61, and Z. Pflanzenhr. Düng. Bodenk. 101 (1963) 122.

M. J. FRISSEL (Chairman): Many substances, such as DDT, are insoluble in water. Nevertheless these compounds are transported downwards. Some authors assume that they are adsorbed on and transported together with clay particles. Does your model allow for such a phenomenon?

H. W. SCHARPENSEEL: No, we did not attempt to study chelating processes. While podsoils would favour such processes the Parabraunerde would probably not, since the organic matter is inherently stable and the clay migration rate is too slow to allow direct observation.

O. TEODORU: In the literature opinions differ as to the role of different fractions in the microstructure of soils. In the light of your results, what influence do you think clay has on the formation of microaggregates?
H. W. SCHARPENSEEL: This question relates rather to paper SM-94/8, in which micromorphological and thin-section autoradiographic evaluation is the final aim of the protracted column percolation tests.

Unfortunately, it is impossible to answer the question at present, since the first series of Parabraunerde columns has only just reached (after four years of percolation and chemical measurements) the stage where thin sections are being prepared. The tagged clay that has been added will become visible within its micromorphological environment.

M. DE BOODT: The formation of microaggregates is completely dependent on the kind of cations absorbed on the clay minerals, on the concentration of the ions and on the speed and number of the wetting-drying cycles.

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1 KERPEN, W., SCHARPENSEEL, H. W., "Movement of ions and colloids in undisturbed soil and parent rock material columns", these Proceedings.
РАДИОАКТИВНЫЕ ИНДИКАТОРЫ ПРИ ИССЛЕДОВАНИИ СОВРЕМЕННЫХ ПРОБЛЕМ ГИДРОФИЗИКИ ПОЧВ

Н. Ф. БОНИДАРЕНКО и А. М. ГЛОБУС
АГРОФИЗИЧЕСКИЙ ИНСТИТУТ, ЛЕНИНГРАД,
СССР

Abstract — Аннотация

RADIOACTIVE TRACERS IN THE STUDY OF CONTEMPORARY PROBLEMS IN THE PHYSICAL HYDROLOGY OF SOILS. The principle of the isothermal movement of soil moisture departs appreciably from Darcy's law in a number of cases of practical importance. Here, the probable reasons for this deviation are reviewed. In non-isothermal transfer of moisture it is vital to determine the phase composition of the flow. Use of radioactive labelling can throw light on these questions, which are of prime importance in elaborating the physical bases of soil-moisture theory and in developing techniques for predicting and regulating soil-water cycles.

РАДИОАКТИВНЫЕ ИНДИКАТОРЫ ПРИ ИССЛЕДОВАНИИ СОВРЕМЕННЫХ ПРОБЛЕМ ГИДРОФИЗИКИ ПОЧВ. Закономерности изотермического передвижения почвенной влаги в ряде практически важных случаев существенно отличаются от закона Дарси. Рассматриваются вероятные причины этих отклонений. При неизотермическом переносе влаги существенным является определение фазового состава потока.

Применение радиоактивных меток может способствовать выяснению этих вопросов, весьма важных для разработки физически обоснованной теории почвенной влаги и создания методов прогноза и регулирования водного режима почв.

Быстрое развитие вычислительной техники в последние годы способствовало проведению большого количества расчетов по прогнозу процессов и состояний различных систем. Сравнение экспериментальных и расчетных данных позволило определить область справедливости различных физических моделей и математических зависимостей. В частности, было установлено, что закон Дарси, постулирующий линейную зависимость между скоростью потока жидкости в пористой среде и действующими силами, имеет верхний и нижний пределы. Верхний предел применимости зависимости Дарси определяется переходом ламинарного режима течения в турбулентный. Несколько неожиданными оказались опыты из которых следовало, что закон Дарси нарушается и при низких градиентах напора. Именно, было обнаружено непропорциональное уменьшение скорости фильтрации с уменьшением градиента напора и существование начальных градиентов напора, при которых фильтрация прекращалась.

Так как движение жидкости в пористых средах определяется геометрией пространства занятого жидкостью, интенсивностью действующих сил и геологическими свойствами жидкости, то можно указать на три группы факторов, обуславливающих отклонение фильтрационного потока от зависимости Дарси при низких градиентах напора.

1. В процессе опыта с возрастанием градиента напора изменяется геометрия порового пространства (разбухание или уплотнение системы).
2. В процессе опыта по обе стороны образца возникает разность концентрации растворенных веществ С, температуры Т или потенциала электрического поля Е. В этом случае наблюдаемые фильтрационные аномалии и начальные градиенты напора отражают существование двух противоположных потоков: одного — цваз控股股东ского, связанного с наличием градиента напора и другого — осмотического скольжения жид-
кости, вызываемого наличием градиентов С, T или E. Наблюдаются при этом начальные градиенты напора отражают квазинивновесие, объясняемое взаимной компенсацией противоположно направленных потоков.

3. Рейологические характеристики фильтрующейся жидкости не соответствуют ее принятой значимости.

В последнем случае жидкость может быть или неньютоновской или вязкокластической. Сващендреб (1) и Кутильек (2) предлагают две первой гипотезы. Выполненные в последние годы исследования (3) течения жидкостей в одиночных цилиндрических кварцевых и стеклянных капилярах показали, что течение жидкостей с межмолекулярными водородными связями (вода, этиловый спирт и др.) описывается уравнениями течения вязкокластичных систем, т.е. рейологическая характеристика данных жидкостей помимо вязкости включает некоторую величину предельного напряжения сдвига \( \tau_p \) порядка \( 10^{-2} \) \( \text{дин/см} \).

В то же время установлено, что рейологические свойства жидкостей без межмолекулярных связей (четыреххлористый углерод, ацетон, хлороформ и др.) характеризуются как истинные неньютоновские жидкости постоянной вязкостью.

Наличие в воде следов сдвигающейся прочности объясняет фильтрационные аномалии при низких градиентах напора (в том случае, когда исключается изменение геометрии порового пространства и интенсивности действующих сил). Выполненные расчеты дренажных систем (4) на основе зависимости Брукингса-Рейнера (вместо принятой до сих пор зависимости Дарси) показали, что при этом обеспечивается более обоснованное определение межденных расстояний.

Для почвенной гидрологии существенное значение имеет прогноз режима влажности в ненасыщенной зоне. Как известно, для скорости потока влаги в ненасыщенной зоне до настоящего времени принимался модифицированный закон Дарси, предложенный Ричардсом. Этот закон постулирует линейную связь между скоростью потока влаги в ненасыщенной среде и потенциалом влаги. В совокупности с уравнением неразрывности модифицированный закон Дарси приводит к дифференциальному уравнению типа диффузии. Выполненные на основе этого уравнения расчеты режима почвенной влаги в ненасыщенной зоне (5) показали, что в некоторых условиях расчет не совпадает с экспериментом даже в качественном отношении. В частности, в полном несоответствии с теоретиче- ской динамикой влаги к фронту испарения происходит в сторону большей влажности. Этот факт экспериментально наблюдался в работах (6–8).

Можно указать на три обстоятельства, позволяющие преодолеть кризис диффузионной теории:

1. Учет гистерезисных явлений, как показали Рубин (9) и Клайт (10), значительно сближает расчет и эксперимент.

2. Тот факт, что для воды скорее применима модель вязкокластичной системы, чем модель неньютоновской жидкости, означает, что гидравлическая проводимость, а, следовательно, и диффузивность являются функцией не только влажности, но и градиента влажности.

3. В случае заметной нестационарности процесс потенциальной влаги является функцией не только влажности, но и скорости изменения влажности в данной точке (11).

С учетом сказанного, модифицированный закон Дарси следует записать в виде:

\[
V = -K \left( \frac{\partial W}{\partial z} \right) \frac{\partial \Phi}{\partial t} \left( \frac{\partial W}{\partial z} \right)
\]
Здесь $V$ — скорость потока влаги, $K$ — гидравлическая проводимость, $W$ — влажность, $z$ — ордината, совпадающая с направлением потока, $\Phi$ — потенциал влаги, $t$ — время.

Подставляя эту зависимость в уравнение неразрывности

$$\frac{\partial W}{\partial t} = \text{div} V,$$

для одномерного случая найдем:

$$\frac{\partial W}{\partial t} = \frac{\partial}{\partial z} \left[ K \left( W_1, \frac{\partial W}{\partial z} \right) \frac{\partial \Phi}{\partial z} \left( W_1, \frac{\partial W}{\partial z} \right) \right]$$

или:

$$\frac{\partial W}{\partial t} = \frac{\partial}{\partial z} \left[ D \left( W_1, \frac{\partial W}{\partial z} \right) \frac{\partial W}{\partial z} + D_t \left( W_1, \frac{\partial W}{\partial z}, \frac{\partial W}{\partial t} \right) \right]$$

где:

$$D \left( W_1, \frac{\partial W}{\partial z} \right) = K \left( W_1, \frac{\partial W}{\partial z} \right) \frac{\partial \Phi}{\partial W}$$

$$D_t \left( W_1, \frac{\partial W}{\partial z}, \frac{\partial W}{\partial t} \right) = K \left( W_1, \frac{\partial W}{\partial z} \right) \frac{\partial \Phi}{\partial \left( \frac{\partial W}{\partial t} \right)}$$

Выполненные по уравнению (1) расчеты [12] с учетом некоторых допущений показали удовлетворительное совпадение теории и эксперимента в случае движения влаги к фронту испарения.

Из уравнения (1), кстати, следует тот факт, что метод нестационарного потока для определения $D$ по уравнению диффузии является не-пригодным — этот метод будет давать всегда завышенные значения.

Изложенная выше теория касалась изотермических условий передвижения почвенной влаги. Она с достаточным приближением применима к весеннему и осеннему времени года в умеренном климате, к проблемам фильтрации в предварительно смоченной тощее и к передвижению влаги в глубоких слоях грунта. Однако в целом ряде случаев, например таких, как движение влаги в пахотном горизонте летом, физическое испарение, инфильтрация в сухую почву и движение воды в промозглый грунте, условия переноса почвенной влаги являются существенно неизотермическими, и влияние температуры должно быть учтено в теории.

Одна из концепций неизотермического влагообмена в почве основана на идеях термодинамики необратимых процессов, согласно которым потоки тепла и влаги, неизбежно возникающие при наличии неоднородного температурного поля, влияют друг на друга. Это влияние, при соблюдении некоторых вполне реальных условий, учитывается перекрестными коэффициентами $L_{ij}$:

$$\frac{\partial W}{\partial t} = -L_{iw} \frac{\partial W}{\partial x} - L_{it} \frac{1}{T} \frac{d}{dx} \left( \frac{1}{T} \right),$$

(2)
где \( \mu \) — потенциальная почвенной влаги (относительная удельная парциальная свободная энергия Гиббса для воды в почве), \( T \) — абсолютная температура, \( L_{\text{мв}} \) — феноменологический коэффициент изотермического переноса, для которого может легко быть установлена связь с коэффициентом влагопроводности, \( L_{\text{вт}} \) — коэффициент неизотермической влагопроводности.

Любой из членов правой части (2) представляет, вообще говоря, как жидкостную, так и паровую составляющие потока, причем каждая из них может включать различные механизмы переноса [13]. Соотношение жидкостного и парового переноса в этих потоках оказывает существенное влияние на водный, химический и тепловой режим почвы. Так, перенос тепла движущейся влаги сильно зависит от фазового состояния, поскольку скрытая теплота парообразной влаги может значительно превышать конвективную и молекулярную составляющие теплопроводности газовой и жидкой фазы. На перераспределение элементов питания растений не-посредственное влияние оказывает только жидкостный поток. Изменение физических свойств почв — структуры и объемного веса — различным образом воздействует на жидкостную и паровую составляющие потока почвенной влаги.

Если в изотермических условиях роль парового переноса обычно не-значительна и становится существенной только в почвах, имеющих за-соленые горизонты, а также в самом верхнем слое почв, то при неизо-термическом режиме его роль при взаимодействии с жидкой фазой, воз-растает [14, 15] и требует специальных исследований.

Приведенный выше обзор проблем почвенной гидрофизики позволяет указать на три главные области, где применение радиоактивных индика-торов обещает дать и уже принесло полезные результаты. Эти области:

1) Изучение особенностей фильтрации воды при полном насыщении почв. Здесь наблюдения за распространением индикаторов позволяют уточнить пределы применимости закона Дарси и характер отклонений от него.

2) Исследование особенностей переноса влаги в ненасыщенных почвах, где применение радиоактивных меток может осветить сравнительную роль перечисленных выше факторов в нарушении закона диф- фузии.

3) Установление фазового состава потока влаги при неизотермиче- ском переносе, включая важнейший процесс испарения воды из верх- него горизонта почвы.

Основные преимущества радиоактивных индикаторов движения поч-венной влаги хорошо известны — это ничтожная, не влияющая на изуча-емую среду концентрация, достаточная для проведения исследований и легкость регистрации движения метки. Недостатки — радиационная опасность, большая стоимость оборудования и взаимодействие метки со средой, не исключающее даже при сорбирующих метках как следствие изотопного обмена.

Основными радиоактивными метками для гидрологических исследо-ваний сейчас служат сера-35, йод-131 и бром-82 в виде аннонов желто- ных солей серной и галоидводородных кислот, а также трийий, введен-ный в состав воды. Однако в ряде случаев эти соединения тоже не удовлетворяют требованиям, предъявленным к меткам как из-за хими-ческих свойств, так и из-за характера излучения указанных изотопов. Например, часто используемый изотоп серы в виде \((\text{S}^{35})_2\text{O}_3^-\) является мягким \(\beta\)-излучателем, поэтому при количественных измерениях тре-
буется либо извлечение его из образца почвы или грунта при помощи водной вытяжки, либо применение в качестве мишени всегда одинаковых навесок образца, что делает весь анализ более длительным и требующим особых мер предосторожности.

Кроме того, почвы и по отношению к анионам обла дают определенной емкостью обмена и поэтому частично поглощают ион $SO_4^{2-}$.

Распространенной меткой является йод-131, но для количественных исследований его можно применять только в присутствии носителя-йода, так как в противном случае значительная часть его (до 50%) теряется в результате реакции окисления, ведущей к образованию свободного йода. Это обстоятельство повышает требования техники безопасности при работе с йодом-131 и затрудняет применение его для получения количественных данных.

В последнее время в гидрологических исследованиях все чаще применяют радиоактивный изотоп водорода — тритий. Как метка он не пригоден для исследования таких вопросов почвенной гидрологии, в которых требуется различать передвижение жидкой и парообразной влаги, потому что тритий, входя в состав самой воды, будет вместе с ней испаряться и конденсироваться в отличие от других индикаторов. Меткой, аналогичной тритию, является дейтерий, входящий в состав тяжелой воды. При его реакции с высокоэнергетическими гамма-квантами выделяются нейтроны, по которым можно проследить путь распространения и концентрации метки [16].

В качестве меток воды пригодны также комплексные хелатные соединения, включающие радиоактивный катион [17]. Таким комплексообразователем является, например, этилендиаминтриетацетат натрия (трилон B), который с ионами металлов образует растворимые в воде и устойчивые в широком диапазоне pH внутрикомплексные соединения. В основе таких соединений металлы, будучи связаны внутри комплекса, не проявляют ионных свойств и не вступают в реакции обмена со средой при условии, что константа устойчивости данного хелатного комплекса выше, чем константы устойчивости комплексов с обменными катионами почвы и катионами почвенного раствора. Ряд таких катионов, как хром-51, сурьма-124, кобальт-60 по устойчивости их хелатных комплексов пригодны в качестве меток воды для обычных почвенных условий.

Нами в лабораторных условиях была проверена возможность использования хелата кобальта-60 в качестве водной метки. Кобальт-60, как известно, является жестким (1,33 мэв) γ-излучателем, что создает, например, возможность следить за передвижением почвенной влаги без извлечения образца из экспериментальной установки или толщи грунта, значительно расширяя возможности исследования.

Изотоп кобальта-60 для полевых опытов не всегда может быть применен из-за его сравнительно большого периода полураспада (5,24 года), в этих случаях можно воспользоваться другими изотопами кобальта кобальт-57 и кобальт-58, имеющими периоды полураспада соответственно 270 и 72 дня.

Само приготовление меченых хелатных комплексов является простым и заключается в прибавлении к водному раствору радиоактивной соли небольшого количества трилона Б.

Для выяснения пригодности хелата кобальт-60 в качестве метки нами были проведены две серии опытов. В первой из них к навескам по 2 г трех дерново-подзолистых почв разного механического состава
Таблица 1. Влияние трilonола Б на сорбцию кобальта-60 и (S^{58}O_4)^2- Тремя почвами

<table>
<thead>
<tr>
<th>Образец</th>
<th>Без трilonола Б</th>
<th>с трilonолом Б</th>
<th>Na_{2}(S^{58}O_4)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>имп. мин.·мл.</td>
<td>% сорбции</td>
<td>имп. мин.·мл.</td>
</tr>
<tr>
<td>Исходный раствор</td>
<td>38 400</td>
<td>100,0</td>
<td>-</td>
</tr>
<tr>
<td>Дерново-подзолистая</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>легкосуглинистая</td>
<td>5870</td>
<td>15,3</td>
<td>84,7</td>
</tr>
<tr>
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<td>91,9</td>
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<tr>
<td>Тоже, глееватая</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>легкосуглинистая</td>
<td></td>
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</tr>
</tbody>
</table>

(от лёгкого сулгикна до лёгкой глины) приливали 10 мл воды, содержащей 50 микрограм кобальта-60 (No_{2})_3 и 30 мл трilonола Б на 1 литр. В качестве контроля использовали раствор той же активности без трilonола. Пробирки с суспензией в течение двух часов встряхивали на роторе, центрифугировали 1 час, после чего из прозрачного отстоя отбирали пробу, в которой определяли радиоактивность натрия.

Все измерения проводили при помощи твердого сцинтиллятора-крystalла NaJ(Tl) и фотоумножителя, ФЭУ-13, установленных в массивной защите. Импульсы фотоумножителя поступали на дискриминатор с установленным порогом дискримиации 3 в, а оттуда на пересчетную схему. Такая установка может работать в спектрометрическом режиме и позволяет, в случае надобности, раздельно учитывать в одном образце активность от двух и более радиометров, отличающихся по характеристике излучения.

Результаты измерений, сопоставленные с активностью исходного раствора, приведены в табл.1, где для сравнения даны результаты таких же опытов с Na_{2}(S^{58}O_4).

Цифры табл.1 свидетельствуют о том, что связанный в хелатный комплекс кобальт-60 не сорбируется исследуемыми почвами и обнаруживает незначительную отрицательную адсорбцию, отличаясь от аниона (S^{58}O_4)^2-, который в известной мере (10—15%) удерживается в почве.

Полученные результаты подтверждены другой серией опытов, в которых через десятисантиметровые колонки воздушно-суходой почвы очень медленно (1 мл/час) фильтровали раствор с добавкой трilonола и без него. Удельную активность последовательных порций фильтрата сопоставляли с активностью исходного раствора. Результаты опыта показывают, что хелат кобальта свободно передвивается с водой, почти не сорбируется исследуемыми почвами.

При проведении длительных исследований существенным становится вопрос об устойчивости хелатного комплекса к биологическим и в особенности к микробиологическим воздействиям. Трилон Б является органическим азотосодержащим соединением, что увеличивает возможность его разрушения почвенной микрофлорой. Это затруднение, по-видимому, в меньшей степени относится к грунтам, более инертным в отношении
микрофлоры, а также к исследованиям по передвижению влаги при низкой температуре, которая тормозит жизнедеятельность микроорганизмов.

Методика применения радиоактивных индикаторов в первой из указанных областей гидрофизики почв достаточно подробно освещена в монографии [18]. Здесь следует особо выделить результаты, полученные авторами с помощью радиометров, и касающиеся характера движения воды в различных горизонтах торфяных залежей.

Мельникова и Заманурид [19], измеряли эффективные коэффициенты диффузии ^{03} в однородных и слоистых почвах, установили, что в различных почвах при одинаковых потенциалах влаги эти коэффициенты приблизительно одинаковы. Это позволяет предположить, что одинаковым потенциалом соответствует равная толщина водных пленок и что между потенциалом влаги и влагопроводностью ненасыщенных почв имеется фундаментальная связь.

При исследовании передвижения ненасыщенной влаги к горизонту испарения Чураевым и Гамазховым с сотрудниками [20, 21] широко использовался радиоактивный сульфат натрия.

В этих работах установлено существенное влияние возникающего при испарении градиента температуры на внутренний и внешний влагообмен в пористой среде. Показано, что на фоне общей потери влаги из сохнущей толщи имеет место сложная внутренняя циркуляция влаги в верхней части почвы, связанная с фазовыми переходами. Эти данные находятся в соответствии с полученными нами результатами по изотермическому влагообмену в закрытых системах.

Известно, что наблюдаемые при этом скорости передвижения влаги в сторону более низких температур в многих случаях превосходят скорость диффузии пара, вычисленную по уравнению Фика, модифицированном для пористой среды. Вместе с тем, нами показано, что, во-первых, скорость диффузии пара через сухую почву или гидрофобную прослойку хорошо совпадает с предвычисленной по Фику, и, во-вторых, что при более высоких, чем максимальная гигроскопическая, влажностях почвы часть движущейся влаги не приходит через гидрофобную прослойку, на- капливаясь перед ней.

Характер участия жидкой фазы в термопереносе влаги можно уточнить экспериментально при помощи метки жидкой фазы. Поэтому полученную на которой произошли опыт, доводили до заданной исходной влажности водой, содержащей 100 мкг/г Са^{60} и 50 мг/л трилона B. После окончания опыта (в ходе которого на конце колонки почвы поддерживали постоянную разность температур) колонку разбирали и в приблизительно одинаковых по весу образцах, помешанных в стандартные алюминиевые боксы, определяли конечную влажность почвы терmostatной сухой. Затем сухие образцы при помощи цилиндрического шомпона распределяли равномерным слоем в тех же боксах (одновременно разрушая комки) и измерили активность образца, помещая бокс непосредственно на кристалл сцинтилятора в специальную оправу, всегда одинаково фиксирующую бокс по отношению к кристаллу. Для проверки влияния расположения образца на свет, бокс после первого измерения поворачивали на 90° и активность измеряли вторично. Разность между такими измерениями не превосходила статистической ошибки счета. Предварительно была также выяснена зависимость измерений активности от веса образца; для этого в алюминиевый бокс помещали на весу влажную почву, высушивали в терmostatе, измеряли активность, добавляли к навеске новую порцию почвы той же удельной активности...
и после сушки снова производили измерение. Эту операцию повторяли несколько раз (табл. 2).

Из этой таблицы видно, что с увеличением веса образца наблюдается некоторое уменьшение регистрируемой удельной активности за счет самопоглощения и ухудшения геометрии; однако даже для количественных исследований может быть допущено рассождение в весе между сравнимыми навесками в 1–2 г. В случаях, когда к точности опыта предъявляются очень жесткие требования, желательно брать одинаковые навески, либо приводить результаты измерения к определенному весу образца при помощи предварительной калибровки, как это показано в таблице 2.

Колонка среднесуглинистой почвы в течение 96 часов подвергалась воздействию градиента температуры 1°/см. За время опыта средняя скорость передвижения влаги составила 4,4·10−7 г/см2 сек, тогда как теоретическая скорость диффузии пара для условий опыта равна 0,8·10−7 г/см2 сек. Если наблюдаемое превышение скорости потока влаги над пародиффузионной объясняется главным образом передвижением жидкой фазы, то общие тенденции перераспределения влажности и радиоактивной метки в ходе опыта должны быть одинаковыми. Этого, однако, не отмечается. Концентрация метки, обратно измеренная влажности, убывает на холодном и возрастает на горячем конце колонки, что объясняется, по-видимому, циркуляционными процессами, в ходе которых влажная, переохлажденная с холодного конца колонки термопотоком, движется обратно в виде жидкости под действием градиента влажности. Увеличение концентрации метки на горячем конце колонки, наблюдаемое даже при очень низкой исходной влажности почвы, связано, вероятно, с явлением термоосмоса.

В данных условиях, когда почва не насыщена влагой и последняя распределена главным образом в стиковых манжетах наиболее вероятный механизм термопередвижения влаги — это серия микропроцессов внутрьпорового испарения и конденсации с промежуточным перетеканием влаги по стиковым манжетам.

Эта внутренняя циркуляция влаги, происходящая в верхнем слое почвы под действием градиента температуры, может оказывать многоструктурное влияние на этот слой. В дневные часы при незатененной поверхности термоперенос влаги способствует образованию поверхностного мулу-слоя и сохранению запасов влаги. Этот же процесс способствует аккумуляции растворимых веществ на поверхности, а на некоторой (3–5 см) глубине. В незаселенных почвах эта аккумуляция способствует благоприятному развитию растений, но в заселенных почвах она усиливает накопление солей.
DISCUSSION

W. R. GARDNER: I should like to ask a question about the interpretation of the equations which you have used. From the earliest development of the diffusion equation it has been known that the equation is valid only if the relation between water content and water potential is known and (usually) unique. Studies such as that of M. Hallaire show only that water will move against a water content gradient; this can be explained by hysteresis. To test the validity of the form of the equation used by you, I think one must measure the water potential gradient. Did you make potential measurements?

It has been recognized since the work of W. H. Gardner in 1949 that capillary conductivity or diffusivity might depend on the potential gradient. The problem has been to determine the extent of this effect.

A. M. GLOBUS: Perhaps I can answer this question. The function $K'[\partial W/\partial Z]$, or $D[\partial W/\partial Z]$, stems from the fact that, to determine rate of flow in an unsaturated medium one should use an equation similar to the Buckingham-Reiner relation (if we accept that the Bingham-Shvedov model is applicable to water). This fact, i.e. that $K = K'[\partial S/\partial Z]$, was indeed taken into account; this is clear from the experiments.

Regarding the first part of your question, we observed in a number of cases the movement of moisture towards the evaporation front against the potential gradient measured by means of a tensiometer. This contradicts the modified Darcy law. Accordingly, to be able to use data on the water potential obtained by existing methods of describing moisture flow towards the evaporation front, it is reasonable to assume that $\varphi = \varphi'[\partial W/\partial t]$. Such a model explains the movement of moisture towards increasing values of $W$ or $\varphi$ and is in our opinion useful for that reason. As further experimental evidence is accumulated the picture will become clearer and a different model may prove to be preferable.

W. R. GARDNER: Equation (1) includes a term which depends upon the time rate of change of water content. This implies that the effects you are studying would not exist in a steady-state system. Do you find these effects experimentally in the transient state but not in the steady state? It seems to me that the Hallaire model should also apply to the steady state.

N. F. BONDARENKO: From Eq. (1) we derive a diffusion equation as a special case (for $\partial W/\partial t \to 0$ the second term on the right-hand side of Eq. (1) approaches zero).

W. H. GARDNER: I feel that we are not so much dealing with a simple diffusion problem as using diffusion mathematics to deal with a far more complicated problem. I should therefore like to return to the potential approach. Without fairly good measurements of matric potential I see little point, when describing flow with the help of potential equations (assuming that we confine our attention to assumed isothermal conditions), in including part of the uncertainties in the conductivity factor and part in the potential factor. I should therefore like to ask how your water
potentials are measured or inferred, and to request an explicit definition of the potential term you use.

N. F. BONDARENKO: In deriving Eq. (1) we assumed that the average values of the water potential $\varphi$, measured by means of appropriate instruments such as tensiometers, differed from the true values $\Phi$ at the point of measurement. As $\partial W/\partial t$ approaches zero, $\varphi \rightarrow \Phi$. Thus, if we learn to determine the potential $\Phi$ it will no longer be necessary to consider $\varphi$ as a function not only of the probability but also of the rate of moisture change.

A. M. GLOBUS: I should like to repeat that we have observed moisture flows against the potential gradient as measured by potentiometers.

W. H. GARDNER: I have no reason to doubt experimental evidence of moisture flow in any particular direction in a given experiment. Where disagreement may appear to exist is in the interpretation of the physical meaning of the data. To reach an understanding, therefore, it would be necessary to have explicit information on the experimental details, particularly with regard to the zero reference and to the possible existence of temperature gradients which are involved in flow but are not indicated by tensiometers. I hope that we shall in the future find ways of discussing such experiments in detail and under conditions where premises and definitions can be agreed upon. I am sure that we should find large areas of common understanding despite differences in approach.

P. A. C. RAATS: It is not difficult to see the qualitative implications of Hallaire's model. Have you measured the dependence of potential and hydraulic conductivity upon water content and time rate of change of water content? Have, to your knowledge, Hallaire's equations been solved for any definite boundary conditions, either by analytical or numerical methods?

N. F. BONDARENKO: We have not carried out any experiments to determine $\varphi$[W$_1$($\partial W/\partial t$)]. Equation (1) was solved numerically by making a number of assumptions regarding $D$ and $D_t$. The evaporating flow was considered as a known function of time.

P. A. C. RAATS: Hallaire's model is more complex than you suggest. The model implies a different relationship between $D$ and $W$ for each $\partial W/\partial t$ and a different relationship between $D_t$ and $\partial W/\partial t$ for each $W$.

N. F. BONDARENKO: We used a simplified model to avoid difficulties in solving the equation.

J. A. DAMAGNEZ: In experiments on the steady-state diffusion of water vapour in soil we have found that, in the case of a clayey soil, the experimental coefficient of permeability $K_s$ at normal temperature is twice the theoretical coefficient as defined by $K_s = \mu D/\sigma$, where $D$ is the coefficient of molecular diffusion, $\mu$ denotes porosity and $\tau$ tortuosity. In the case of a sandy soil the experimental and theoretical coefficients were identical.

I should like to add that, in the case of the clayey soil, the experimental coefficient of permeability declines as the temperature rises.
ETUDE, AU MOYEN DE L'EAU TRITIÉE, DE LA CIRCULATION DE L'EAU DANS UN SOL SABLEUX DU SENEGAL

C. CHARREAU ET L. JACQUINOT
INSTITUT DE RECHERCHES AGRONOMIQUES TROPICALES ET DES CULTURES VIVIERES, CENTRE DE RECHERCHES AGRONOMIQUES, BAMBEY, SENEGAL

Abstract — Résumé

THE USE OF TRITIATED WATER TO STUDY WATER CIRCULATION IN A SANDY SOIL IN SENEGAL.

The authors have carried out a study in Senegal on the behaviour, with respect to the soil solution, of a flow of water infiltrating a sandy soil under a constant head.

The experimental set-up consisted of a cylindrical lysimeter 2 m high and 3 m in diameter. The initial water content of the soil was increased to near field capacity. A sheet of tritiated water 3 cm deep was then maintained on the soil surface. The drainage water was collected in 5-litre amounts and the radioactivity measured in the laboratory.

The authors first compare the infiltration and drainage rates for dry and wet soil. From examination of the curve showing variations in the concentration of tritiated water in the drainage water as a function of the amount of drainage water it can be seen that the tritiated water begins to appear in the drainage water before the water initially in the soil has been completely replaced. The concentration then increases rapidly and approaches the original value. From the shape of the curve the authors conclude that the soil solution is not immediately displaced by the added water, even in very sandy soil; instead, there is an intermediate phase during which the two solutions present are progressively mixed. This phase involves a total of 105 mm of water, of which 42 mm is tritiated water. The mixing occurs within an 80-cm thick soil layer.

In conclusion, the authors discuss possible agronomic consequences of the processes studied.

ETUDE, AU MOYEN DE L'EAU TRITIÉE, DE LA CIRCULATION DE L'EAU DANS UN SOL SABLEUX DU SENEGAL. Le comportement vis-a-vis de la solution du sol d'un flux aqueux circulant per descensum sous l'effet d'une charge constante a été étudié dans un sol sableux du Sénégal.

Le dispositif expérimental consistait en un lysimètre cylindrique de 2 m de hauteur et 1 m de diamètre. Le stock d'eau du sol a été amené au voisinage de la capacité au champ. Une nappe d'eau tritiée a été ensuite maintenue sur une épaisseur constante de 3 cm au-dessus de la surface du sol. L'eau de drainage a été recueillie par fractions de 5 litres, dont la radioactivité a été mesurée ensuite au laboratoire.

Les auteurs comparèrent d'abord les débits d'infiltration et de drainage sur le sol sec et sur le sol humide. Ils examinèrent ensuite la courbe des variations de concentration d'eau tritiée dans l'eau de drainage en fonction des hauteurs d'eau éculées. De cet examen il ressort que l'eau tritiée commence à apparaître dans l'eau de drainage avant que le stock d'eau initial n'ait été complètement renouvelé. La concentration augmente ensuite rapidement jusqu'à approcher la valeur d'origine. De l'allure de la courbe les auteurs concluent que le déplacement intégral de la solution du sol par l'eau d'infiltration ("effet piston") ne s'opère pas immédiatement, même en sol très sableux, mais est précédé d'une phase intermédiaire correspondant au mélange progressif des deux solutions en présence. Dans l'expérience en question, cette phase intéresse une hauteur d'eau globale de 102 mm, dont 42 mm d'eau d'infiltration marquée au tritium. Le mélange s'opère dans une tranche de sol de 80 cm d'épaisseur.

En conclusion quelques conséquences agronomiques pouvant découler des processus précédemment étudiés sont évoquées.

1. INTRODUCTION

Une expérience a été conduite, en case lysimétrique, sur un sol sableux du Sénégal, dans le double but de
comparer les débits d’infiltration et de drainage sur un sol sec et sur le même sol préalablement humidifié au voisinage de la capacité de rétention,
- examiner le comportement de l’eau d’infiltration par rapport à la solution du sol préexistante et déceler dans quelle mesure il y a mélange entre les deux phases liquides.

2. DISPOSITIF EXPERIMENTAL

2.1. Le sol


La densité apparente varie entre 1,5 et 1,7 ; la porosité globale entre 36 et 43%. La stabilité de la structure est difficile à mesurer pour des sols aussi sableux : les valeurs de Iₐ (indice d’instabilité structurelle de Henin) sont de l’ordre de 0,5, ce qui laisserait supposer une stabilité assez bonne, alors que les observations de terrain sont en contradiction avec cette hypothèse.

TABLEAU I. PRINCIPALES CARACTERISTIQUES PHYSIQUES DU SOL DIOR

<table>
<thead>
<tr>
<th>Profondeur (cm)</th>
<th>Granulométrie (%)</th>
<th>Capacité au champ (%)</th>
<th>Humidité à pf (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sable grossier</td>
<td>Sable fin</td>
<td>Argile</td>
</tr>
<tr>
<td>0 - 5</td>
<td>22,3</td>
<td>73,7</td>
<td>2,0</td>
</tr>
<tr>
<td>5 - 10</td>
<td>21,1</td>
<td>74,9</td>
<td>1,5</td>
</tr>
<tr>
<td>10 - 20</td>
<td>22,6</td>
<td>72,4</td>
<td>1,0</td>
</tr>
<tr>
<td>20 - 40</td>
<td>21,9</td>
<td>71,7</td>
<td>2,5</td>
</tr>
<tr>
<td>40 - 60</td>
<td>25,0</td>
<td>66,9</td>
<td>1,0</td>
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<tr>
<td>60 - 80</td>
<td>22,4</td>
<td>70,1</td>
<td>2,0</td>
</tr>
<tr>
<td>80 - 100</td>
<td>24,9</td>
<td>68,1</td>
<td>3,0</td>
</tr>
<tr>
<td>100 - 120</td>
<td>24,3</td>
<td>68,7</td>
<td>1,5</td>
</tr>
<tr>
<td>120 - 140</td>
<td>25,5</td>
<td>71,5</td>
<td>1,5</td>
</tr>
<tr>
<td>140 - 160</td>
<td>22,9</td>
<td>71,6</td>
<td>1,0</td>
</tr>
<tr>
<td>160 - 180</td>
<td>25,2</td>
<td>67,8</td>
<td>2,0</td>
</tr>
<tr>
<td>180 - 200</td>
<td>25,6</td>
<td>67,9</td>
<td>1,0</td>
</tr>
</tbody>
</table>
Les teneurs en carbone sont très faibles et ne dépassent pas 3% en surface. La capacité d'échange est de l'ordre de 2 mèq/100 g avec un taux de saturation moyen de 50%. Les pH varient généralement entre 5 et 6.

2.2. Mode opératoire

Vingt-quatre lysimètres sont installés à Bambey, pour la mesure des bilans hydriques et minéraux annuels; nous avons utilisé l'un d'entre eux pour cette expérience. Il s'agit d'un lysimètre cylindrique de 2 m de hauteur et 1 m de diamètre.

![Diagramme de comparaison des hauteurs d'eau infiltrées et drainées en fonction du temps.](image)

**FIG. 1.** Comparaison des hauteurs d'eau infiltrées (-----) et drainées (-----) en fonction du temps.
A. Première mesure (eau pure).
B. Deuxième mesure (eau tritée).

Le remplissage du lysimètre a été effectué quatre ans avant l'expérience en question; le profil de sol Dior a été reconstitué horizon par horizon. La rotation suivante a été ensuite appliquée: mil - arachide - sorgho. L'expérience a été réalisée en mars 1964, c'est-à-dire en fin de saison sèche, la récolte du sorgho ayant été effectuée et les pailles enlevées au mois de décembre précédent.

Les opérations suivantes ont été effectuées:
- Arrosage par submersion du sol avec de l'eau pure (distillée) en maintenant une lame d'eau d'une épaisseur constante (3 cm) à la surface du sol; un volume de 370 litres d'eau a été utilisé, correspondant
à une hauteur d'eau de 452 mm. Au cours de cette opération les débits d'infiltration et de drainage ont été mesurés.

- Ressuyage du sol, sous couverture plastique, jusqu'à cessation complète du drainage, soit pendant deux jours.
- Préparation d'une solution d'eau tritée par mélange de 1,60 Ci d'eau tritée avec 242 litres d'eau pure (distillée).
- Arrosage par submersion du sol dans les mêmes conditions que précédemment avec mesure des débits d'infiltration et de drainage. Hauteur d'eau infiltrée: 302 mm.

![Graphique](image)

**FIG. 2.** Variations comparées de la vitesse d'infiltration de l'eau dans le sol et du débit de drainage en fonction du temps.

- ----- Infiltration de l'eau dans le sol; ----- drainage.
- A. Première mesure (eau pure).
- B. Deuxième mesure (eau tritée).

Prélèvement des eaux de drainage par fractions de 5 litres: détection de l'eau tritée d'après la méthode OMS-FAO (rapport technique FAO-OMS n° 173, Rome, 1959) au moyen d'un photomultiplicateur à cuve de quartz et scintillateur liquide.

Le mélange était le suivant: 1 ml d'échantillon, 10 ml d'éthanol absolu, 14 ml de toluène et 50 mg de paradiphényl-oxazol.

### 3. RESULTATS ET DISCUSSIONS

On examinera successivement
- la comparaison des débits d'infiltration et de drainage,
les relations entre eau d'infiltration et solution du sol préexistante, telles qu'on peut les déduire des variations de concentration de l'eau tritée dans les eaux de drainage.

3.1. Comparaison des débits d'infiltration et de drainage

Les résultats sont donnés aux figures 1, 2 et 3. La figure 1 permet de comparer les courbes d'infiltration et de drainage correspondant aux deux expériences successives: eau pure et eau tritée. La courbe D(T) est celle de l'eau tritée seule.

![Diagram showing infiltration and drainage rates](image)

**FIG.3.** Drainage cumulé (-----) et débit de drainage (----) en fonction du temps lors de la seconde mesure (eau tritée).

La figure 3 montre les courbes de drainage cumulé et de variation de débit du drainage établies au cours de la deuxième mesure: l'échelle a été agrandie de façon à préciser l'allure des variations de débit du drainage pendant les premières heures. Cela n'a pas été possible pour la première expérience, où nous ne disposions pas d'observations suffisamment rapprochées.

3.1.1. Hauteurs d'eau infiltrées et drainées

Au cours de la première mesure, pour une hauteur d'eau infiltrée de 452 mm, 292 mm ont été récupérés dans les eaux de drainage. La différence, soit 160 mm, représente la hauteur d'eau retenue par le sol. Si l'on admet que le stock d'eau restant dans le sol après drainage représente la capacité au champ, le chiffre de 160 mm représente donc le
déficit de rétention du sol jusqu'à 2 m de profondeur à cette époque de l'année. Or les mesures faites au champ indiquent suivant les années et les cultures des valeurs comprises entre 105 et 160 mm, tandis que la capacité de rétention se situe au voisinage de 180 mm pour le sol Dior jusqu'à 2 m de profondeur [1].

On a donc le choix entre deux hypothèses :
- ou bien on se trouvait, au moment de l'expérience, dans un cas extrême (mais possible) de dessèchement et le stock d'eau du sol avant submersion était très faible (de l'ordre de 20 mm);
- ou bien le stock d'eau restant dans le sol après drainage représente davantage que la capacité au champ.

Ainsi que de nombreuses études l'ont montré, cette valeur particulière est en effet difficile à saisir. Feodoroff et Betremieux [2], entre autres, ont mis en évidence l'influence des facteurs extérieurs au sol (intensité et dose d'arrosage) sur l'allure générale de la redistribution de l'humidité du sol et son évolution dans le temps. Il est possible que les conditions de submersion qui ont prévalu dans notre expérience, associant une forte dose d'arrosage à un débit d'infiltration élevé, aient conduit à un stockage d'eau dans le sol plus important que celui correspondant à la véritable capacité au champ. Ces points seront repris plus loin à l'occasion de l'examen des variations de concentration d'eau tritée dans les eaux de drainage.

Au cours de la deuxième mesure, la hauteur d'eau drainée (281 mm) a correspondu presque entièrement à la hauteur d'eau infiltrée (302 mm).

3.1.2. Comparaison de l'infiltration et du drainage en fonction du temps

L'allure des courbes d'infiltration et celle des courbes de drainage sont nettement différentes, l'amortissement avec le temps étant beaucoup plus marqué pour les secondes.

Dans la première expérience, 452 mm s'infiltrent en 4 h 28 min, soit un débit moyen de 101 mm/h ; 292 mm drainent en 42 h 45 min, soit un débit moyen de 6, 8 mm/h.

Dans la deuxième mesure, l'infiltration est de 302 mm en 4 h, soit 75, 5 mm/h en moyenne, et le drainage de 281 mm en 31 h 42 min, soit un débit moyen de 8, 9 mm/h.

Le débit de l'infiltration diminue d'une manière constante et assez rapide avec le temps : de 200 à 60 mm/h dans le cas du sol sec, de 90 à 35 mm/h dans le cas du sol préalablement humidifié. Les valeurs obtenues sont du même ordre de grandeur que celles qui ont été mesurées en plein champ par la méthode Muntz [1, 3] ; toutefois la décroissance des débits en fonction du temps paraît moins accusée en plein champ.

Le débit de drainage présente au contraire une courbe beaucoup moins régulière ; si l'on examine la figure 3 concernant le drainage lors de la deuxième expérience, on voit que la courbe des débits comporte quatre phases distinctes :
- une phase d'augmentation rapide pendant la première heure,
- un palier situé au niveau de 50 mm/h pendant la deuxième heure,
- une phase de décroissance rapide qui dure environ 5 h et amène les débits au niveau de 10 mm/h,
- une phase de décroissance lente qui se prolonge jusqu'à la fin du drainage.
Les débits du drainage sont toujours inférieurs à ceux de l'infiltration lors de la première mesure (sol sec); ils leur sont légèrement supérieurs, lors de la deuxième mesure, pendant la période qui correspond à la fin de l'infiltration et au début du drainage.

Le mouvement de descente de l'eau dans le sol sec est très rapide: le délai entre l'application d'eau à la surface du sol et l'apparition du drainage à 2 m de profondeur est de 3 h 43 min dans la première expérience, soit une vitesse de progression du front d'humidité de 54 cm/h. Cette valeur est nettement plus élevée que celles qui ont été observées dans les mêmes conditions d'humidité sur le sol en place et qui sont de l'ordre de 5 à 10 cm/h [1]. Elle est également plus forte que les valeurs théoriques maximales trouvées par Fedoroff [4] pour la progression du front d'humidité en sol sableux sec soumis à de fortes intensités d'arrosage (24 cm/h). Ces différences peuvent tenir aux conditions particulières de l'expérience (possibilité d'un cheminement préférentiel de l'eau le long des parois du lysimètre).

En ce qui concerne le sol préalablement humidifié au voisinage de la capacité au champ, le délai entre le début de la submersion et le début du drainage à 2 m de profondeur est de 2 h 21 min, soit une vitesse de transmission du mouvement dynamique de descente de l'eau de 85 cm/h. Mais les premières traces d'eau tritée ne sont décelées dans l'eau de drainage que 9 h 10 min après le début de la submersion. Les molécules de l'eau d'infiltration ne progressent donc dans le sol qu'à la vitesse maximale de 22 cm/h.

3.2. Relations entre l'eau d'infiltration et la solution du sol

Pour étudier ces relations, il est nécessaire que l'une ou l'autre des deux solutions soit marquée de façon que son déplacement et sa répartition puissent être suivis. La préférence a été donnée ici au marquage de l'eau d'infiltration. Le problème qui se pose ensuite est celui du choix du traceur.

3.2.1. Choix du traceur

Le traceur peut être un élément quelconque, radioactif ou non, pourvu qu'il soit absent du sol étudié ou, du moins, s'y trouve en quantité négligeable. Il doit également satisfaire aux deux exigences suivantes:
- la diffusion propre du traceur doit être négligeable, le traceur devant se déplacer avec sa solution,
- l'interaction du traceur avec le sol doit être la plus faible possible.

Un certain nombre d'études peuvent fournir des éléments de réponse à ces questions. Wang et al. [5] ont mesuré la diffusion de l'eau tritée dans l'eau pure et ont trouvé une valeur de $2,44 \cdot 10^{-5}$ cm$^2$/s.

Nakayama et Jackson [6] ont mesuré le coefficient apparent de diffusion de l'eau tritée dans divers matériaux (billes de verre, gel d'agar-agar) et dans différents sols. Les valeurs dans les sols s'étagent entre 0,87 et $1,14 \cdot 10^{-5}$ cm$^2$/s, lorsque le sol est saturé d'eau; elles peuvent toutefois être multipliées par 3 lorsque la teneur en eau du sol est faible. Rachinsky [7], étudiant les échanges isotopiques d'hydrogène dans le sol, dans des conditions statiques puis dans des conditions dynamiques, conclut que la sorption du tritium est peu importante et que
cet élément peut donc être utilisé comme indicateur d'eau dans les recherches sur les relations sol-eau; cependant la vitesse moyenne du mouvement d'eau marquée au tritium serait de 10% inférieure à la vitesse moyenne d'un courant d'eau dans le sol, à cause du processus de sorption d'isotopes échangeables. Corey et Kirkham [8] ont comparé, dans différentes conditions expérimentales, l'utilisation de solutions de nitrates et d'eau tritée en tant que traceurs. Dans toutes les expériences auxquelles ils ont procédé, et qui comportaient, après passage sur les sols des solutions de traceurs, le lessivage par un éluant, le tritium a été récupéré intégralement dans les eaux de drainage, ce qui n'a pas toujours été le cas pour le nitrate.

De toutes ces études il ressort que l'eau tritée paraît bien satisfaire aux conditions fixées plus haut et qu'elle constitue un traceur de choix pour l'étude des relations sol-eau. Par ailleurs, l'eau tritée présentait dans notre cas particulier un avantage supplémentaire: celui de sa neutralité vis-à-vis du sol, du point de vue physico-chimique; cela permettait, une fois l'expérience terminée, d'utiliser à nouveau le sol placé dans le lysimètre pour d'autres études (mesure des bilans hydriques et minéraux annuels).

3.2.2. Représentation théorique du phénomène

Le comportement de l'eau d'infiltration vis-à-vis de la solution du sol, lorsque celui-ci a été préalablement amené au voisinage de la capacité de rétention, peut s'imaginer de deux façons différentes, illustrées schématiquement de la manière suivante (voir fig.4):

![Diagramme de l'infiltration d'eau](image)

**FIG.4.** Représentation schématique de la distribution de l'eau d'infiltration dans le sol:
1) dans l'hypothèse de l'effet piston intégral;
2) dans l'hypothèse du mélange des phases.

- [] eau d'infiltration;
- [] solution du sol préexistante de l'horizon 0-h.

Soit $V$ un volume de solution du sol occupant une certaine fraction des pores du sol (correspondant à la capacité de rétention) sur une hauteur $h$ et une section $S$. 
Si l'on applique, en submersion, un même volume d'eau à la surface du sol, on peut trouver après infiltration deux types de distribution possibles pour l'eau d'infiltration dans la colonne de sol :

- ou bien cette eau d'infiltration a chassé devant elle, à la manière d'un piston, la solution du sol préexistante et a pris sa place dans le sol sur la hauteur h (en supposant que le taux d'humidité n'a pas varié);
- ou bien un mélange se produit entre les deux phases liquides et une partie de l'eau d'infiltration atteint une profondeur h supérieur à h.

FIG. 5. Représentation schématique des variations de concentration du traceur dans l'eau de drainage :
1) dans l'hypothèse de l'effet piston intégral ;
2) dans l'hypothèse du mélange des phases.

Pour étudier ce comportement, il est nécessaire d’arroser la colonne de terre avec de l’eau marquée. On peut ensuite, soit rechercher dans la colonne la répartition du traceur et celle de l’eau ou, s’il y a drainage, suivre les variations de concentration du traceur dans l’eau de drainage en fonction du temps, soit poursuivre l’arrosage avec un éluant et procéder comme précédemment. Beaucoup d’auteurs ont adopté la deuxième formule.

Pour des raisons de commodité, nous nous sommes arrêtés à la première, en étudiant les variations de concentration du tritium dans les eaux de drainage en fonction du temps, sans examiner sa répartition dans la colonne de terre.

Dans ce dernier cas, les représentations théoriques des variations de concentration du traceur dans l’eau de drainage en fonction des hauteurs d’eau drainées peuvent être schématisées comme le montre la figure 5. Sur ces modèles on a porté en ordonnée les valeurs du rapport \( C_1/C_0 \), où \( C_1 \) représente la concentration du traceur dans l’eau de drainage et \( C_0 \) la concentration dans la solution d’origine, et en abscisse les hauteurs d’eau drainées.

Dans l’hypothèse de l’effet piston intégral, le traceur apparaît brutalement dans les eaux de drainage avec sa concentration d’origine au moment précis où la hauteur d’eau écoulée correspond au stock d’eau initial \( S_0 \). La courbe des variations de concentration suit le trajet \( S_0 - A - B \).
Dans l'hypothèse du mélange des phases, le traceur apparaît dans l'eau de drainage avant que le stock d'eau initial n'ait été complètement renouvelé, soit en $S_1$. La concentration de l'eau de drainage est égale à celle de la solution d'origine. La courbe suit le trajet $S_1$-$C$-$B$.

Les surfaces $S_0$-ABE et $S_1$-CBE représentent respectivement les quantités de traceur trouvées dans les eaux de drainage, pour un même volume de drainage ($E$) dans la première et dans la seconde hypothèse.

Si l'on admet remplies les conditions suivantes: stock d'eau dans le sol identique avant et après drainage (voisin de la capacité de rétention), non-rétention du traceur par le sol, les concentrations de traceur dans les eaux de drainage doivent être égales à partir du moment où ces eaux ont la même concentration en traceur que la solution d'origine. En d'autres termes, les surfaces $S_0$-ABE et $S_1$-CBE doivent être équivalentes. Comme ces surfaces comportent une partie commune: $S_0$CBE, il s'ensuit que les aires hachurées $S_1$CS0 et ACB doivent être aussi égales.

En fait, il semble bien que le modèle 1 (effet piston intégral) doive être considéré comme purement théorique: si faible soit-elle, une certaine diffusion se produit inévitablement entre les deux phases liquides en présence.

C'est ce que montrent divers travaux utilisant des voies expérimentales très diverses: entre autres, les travaux anciens de Schlaeising cité par Demolon [9], et ceux plus récents de Feodoroff [4] et Corey et Kirkham [8]. Ces derniers auteurs ont opéré non seulement sur des sols mais aussi sur des matériaux inertes (billes de verre). Ils ont montré que, même dans ces conditions, il n'y avait pas d'effet piston intégral mais qu'un certain mélange entre les deux phases liquides se produisait au cours de l'infiltration.

Le modèle 2 (mélange des phases) représente donc le cas général. Mais, suivant les conditions expérimentales (nature du sol, humidité initiale, débit d'arrosage ou d'infiltration), les courbes $S_1$-CB pourront présenter des allures très diverses. Le mélange des phases sera d'autant plus important que l'écart entre $S_1$ et $S_0$ sera plus grand et que la courbe présentera une pente générale plus faible. En sens inverse, l'effet piston sera d'autant plus prononcé que l'écart entre $S_1$-CB se rapprochera davantage de la verticale.

La longueur du segment $S_1$E représente la hauteur d'eau intéressée par le mélange des phases, avant que l'eau d'infiltration n'ait remplacé la solution du sol. Connaissant la teneur en eau du sol, on peut faire correspondre à cette hauteur d'eau une profondeur de sol. Par le calcul de la surface $S_1$BE on peut connaître la quantité d'eau marquée intéressée par le mélange des phases.

3.2.3. Résultats expérimentaux (tableau II)

Comme on peut le constater, le traceur est apparu dans l'eau de drainage après qu'une hauteur d'eau de 194 mm eut été recueillie. La concentration augmente ensuite assez rapidement jusqu'à une valeur maximale de 70% de la concentration de la solution d'origine. Il est regrettable que les derniers prélèvements aient été trop espacés et que, pour ailleurs, la hauteur d'eau infiltrée ait été insuffisante pour retrouver la concentration originelle.
### TABLEAU II. RESULTATS DE MESURE DE RADIOACTIVITE SUR LES EAUX DE DRAINAGE

<table>
<thead>
<tr>
<th>N° de prélèvement</th>
<th>Fraction du drainage</th>
<th>Comptage net/30 s</th>
<th>Rapport $C_i/C_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>En volume (litres)</td>
<td>En hauteur d'eau (mm)</td>
<td></td>
</tr>
<tr>
<td>Solution d'origine</td>
<td>-</td>
<td>-</td>
<td>212 000</td>
</tr>
<tr>
<td>1</td>
<td>0 - 5</td>
<td>0 - 8</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>150 - 155</td>
<td>188 - 194</td>
<td>0</td>
</tr>
<tr>
<td>32</td>
<td>155 - 160</td>
<td>194 - 200</td>
<td>200</td>
</tr>
<tr>
<td>33</td>
<td>160 - 210</td>
<td>200 - 282</td>
<td>39 000</td>
</tr>
<tr>
<td>34</td>
<td>210 - 225</td>
<td>282 - 282</td>
<td>147 000</td>
</tr>
</tbody>
</table>

**FIG. 6.** Variations de concentration de l'eau tritiée dans l'eau de drainage en fonction des hauteurs d'eau écoulées.

Malgré ces imperfections expérimentales, il est possible, cependant, de tracer la courbe des variations de concentration relative de l'eau tritiée dans l'eau de drainage en fonction des hauteurs d'eau écoulées (fig. 6).

Cette courbe a été extrapolée jusqu'au point B où l'on doit, en principe, retrouver la concentration originelle. La courbe expérimentale ainsi obtenue offre une grande similitude avec la courbe théorique de l'hypothèse 2 (mélange des phases, fig. 5).

L'interprétation qui avait été proposée plus haut paraît pouvoir s'appliquer ici. Les deux conditions préalables semblent bien en effet remplies:
- le stock d'eau du sol n'a pratiquement pas varié entre le début de l'infiltration et la fin du drainage puisque la hauteur d'eau drainée est presque équivalente à la hauteur d'eau infiltrée;
- d'après les études citées plus haut il est fort peu probable qu'une quantité appréciable d'eau tritée correspondant au volume drainé ait été retenue par le sol dans les conditions où s'est déroulée l'expérimentation (débit important, temps très bref).

En recherchant la position du point $S_0$, stock d'eau initial, d'après les principes énoncés plus haut, c'est-à-dire de telle manière que les surfaces $S_1C_0$ et $ACB$ soient équivalentes, on trouve une valeur de 234 mm. Cette valeur est nettement supérieure à celle de 176 mm trouvée pour la capacité de rétention par mesure directe au champ sur le même sol. Les erreurs de mesure ne peuvent expliquer un écart aussi grand. On est ainsi conduit à admettre que le stock d'eau du sol après cessation du drainage se trouve être nettement supérieur à celui correspondant à la capacité au champ. Il s'agirait ici d'un état de pseudo-équilibre, consécutif à un débit d'infiltration très important. Cela rejoint les observations de Fedoroff [4] selon lesquelles le stock d'eau du sol augmente avec les débits d'arrosage, cela entraînant comme corollaire que la mesure de la capacité au champ ne peut se réaliser après application d'une seule dose d'irrigation.

Sur ces bases, le stock d'eau préexistant dans le sol avant l'expérience serait de 234 - 150 = 84 mm (150 mm représentant la hauteur d'eau retenue par le sol après la première mesure). Le déficit de rétention serait donc de 176 - 94 = 82 mm.

Cette dernière valeur est assez faible pour l'époque de l'année considérée, mais cependant plausible. Il est naturellement regrettable que les conditions particulières dans lesquelles s'est déroulée l'expérience n'aient pas permis d'effectuer une mesure in situ du déficit de rétention initial.

En ce qui concerne la distribution de l'eau d'infiltration dans le sol, on peut, sur les mêmes bases, calculer la hauteur d'eau correspondant au mélange des phases. Celle-ci se trouve être de 290 - 194 = 102 mm.

Si l'on admet que les 234 mm représentant le stock d'eau du sol sont répartis uniformément sur 2 m de profondeur, cette hauteur d'eau de 102 mm correspond à une tranche de sol de 80 cm d'épaisseur. Le calcul de la surface $S_1BE$ permet d'estimer à 42 mm la hauteur d'eau tritée mélangée à la solution du sol (soit 14% de l'eau tritée infiltrée).

On peut considérer que le fait d'avoir opéré sur un sol très sableux avec des débits d'infiltration importants favorisait pleinement la manifestation de l'effet piston et s'étonner de ce que les hauteurs d'eau et de sol intéressées par le mélange de phases soient aussi grandes. Cela rejoint pourtant les observations faites sur le même sol par Blondel [10] suivant en plein champ, à la suite d'application de pluies artificielles, la migration en profondeur de nitrates initialement apportés à la surface du sol. Cet auteur constate que, lorsque le sol a été préalablement humidifié au voisinage de la capacité de rétention, une pluie de 10 mm entraîne une partie des nitrates à plus de 20 cm de profondeur alors que si l'effet piston avait été intégral la totalité des nitrates aurait du rester dans l'horizon 0-10 cm. Bien que des calculs précis n'aient pas été effectués, on peut estimer à environ 40% la proportion de nitrates entraînés en dessous de la limite théorique.

Même en sol très sableux, les phénomènes de diffusion et de mélange des phases liquides seraient donc loin d'être négligeables.
4. CONCLUSIONS

Il n’est pas inintéressant pour l’agronome de pouvoir apprécier, après un arrosage naturel (pluie) ou artificiel (irrigation), la distribution de l’eau d’infiltration dans le sol et ses rapports avec la solution du sol préexistante. De cette appréciation dépend en effet pour une grande part celle de la migration des sols solubles et de leur répartition dans le profil après arrosage. On conçoit que cela revêt une certaine importance pour la nutrition minérale des plantes et son amélioration possible par le perfectionnement des techniques d’épandage d’engrais solubles (fractonnement, localisation, etc.).

Cette connaissance est également utile dans un autre domaine: celui de la mise en valeur des sols salés, qui occupent de vastes superficies au Sénégal. Dans le cas le plus répandu où lessivage et drainage du sol sont pratiquement impossibles à réaliser, la réussite de la culture dépend essentiellement du degré de dessalement par l’eau de pluie ou de ruissellement de l’horizon superficial du sol et de la possibilité de maintien, en superposition, de la lame d’eau douce sur la nappe salée. Il s’agit là encore du problème du rapport de deux phases liquides dans le sol. Dans le cas le plus favorable où le lessivage préalable est possible, il est important de prévoir dans quelle mesure et sur quelle profondeur la solution préexistante du sol aura été remplacée par l’eau d’arrosage.

C’est dans le but de tenter d’apporter une réponse à ces diverses questions que l’expérience décrite a été mise sur pied. Les résultats obtenus ne fournissent, bien sûr, qu’une réponse très partielle aux questions posées. Il serait nécessaire de corriger les insuffisances expérimentales et d’étudier systématiquement l’influence des principaux facteurs (nature du sol, taux d’humidité, débit d’arrosage) sur l’allure du phénomène.

Par sa facilité d’emploi, la commodité et la sensibilité de sa mesure, sa neutralité vis-à-vis du sol, l’eau tritiée paraît être le traceur de choix pour ce genre d’études.

REFERENCES


DISCUSSION

U. ZIMMERMANN: These experiments are very interesting and provide further proof of the layered water movement in soils. I think it would be useful to carry out a similar experiment with tritiated water in dry soil; this would produce rather interesting results, since the conditions would be extreme.

With regard to the molecular diffusion of water in soils, I cannot agree with the statement in Section 3.2.1 of your paper that the molecular diffusion coefficients of tritiated water are about three times higher in unsaturated than in saturated soils. The molecular diffusion coefficients in saturated soils are 20-30% smaller in saturated soils than in free water, because of the resistance caused by bottlenecks in the soil. In unsaturated soils one obtains about the same diffusion coefficient values as in saturated soils. But here we have different mechanism, the diffusion coefficient depending in this case on diffusion in the liquid phase, the absorbed phase and the gaseous phase. Moreover, the tortuosity of the pathways plays a role.

M. HAJDUKOVIĆ: I find your nitrogen leaching somewhat high in the light of results obtained by Broeckhart and Aleksić at the International Atomic Energy Agency's laboratory at Seibersdorf. They have found a high rate of nitrogen volatilization caused by intense micro-organism activity. I am surprised that, with the high temperatures dominating in your experiments, as much as 40% of the nitrogen was leached.

L. JACQUINOT: The results mentioned in the paper relate to an experiment performed during the very short wet season, when surface evaporation is virtually zero. We did not observe any nitrates emerging at the surface or, because of the short duration of the experiment, any nitrogen volatilization. The leaching of nitrates is a common phenomenon in these soils, particularly at the beginning of the rainy season.

J. MARCESSE: I should simply like to point out that the fact that drainage has ceased does not mean that the soil has attained field capacity. Observations in situ have shown that filtration occurs at an extremely slow rate below this value.
TRITIUM TAGGING OF SOIL MOISTURE: THE WATER BALANCE OF FOREST SOILS

H.P. BLUME
INSTITUT FÜR BODENKUNDE DER
LANDWIRTSCHAFTLICHEN HOCHSCHULE HOHENHEIM
AND
U. ZIMMERMANN AND K.O. MÜNNICH
II. PHYSIKALISCHES INSTITUT,
UNIVERSITY OF HEIDELBERG,
FEDERAL REPUBLIC OF GERMANY

Abstract

TRITIUM TAGGING OF SOIL MOISTURE: THE WATER BALANCE OF FOREST SOILS. A method of tagging soil moisture with tritium in order to measure water movement and groundwater recharge, and the results obtained by this method, were reported previously. The amount of tritium to be applied is evaluated. A new technique of labelling was tested. The soil was inoculated with tritiated water with a syringe to a depth of approximately 20 cm. This technique prevents the following effects occurring if the tracer remains for a longer time in the immediate neighbourhood of the soil surface:

1. High evaporation loss of the tracer,
2. Asymmetry of the tracer-concentration distribution,
3. Heavy rains overtaking the tracer peak if there are cracks in the upper soil layers.

The spatial distribution, both vertically and horizontally, of the tritium thus injected into a sandy soil was measured after artificial sprinkling. The influence of varying water content in the soil on the tracer-concentration distribution and the influence of a clay pan on the water movement were investigated. Also presented are results obtained in a forest soil tracer study at present being conducted over a two-year period. Two individual labellings at the same place, but six months apart, demonstrate the uptake of water by the roots between the two tracer marks.

INTRODUCTION

As has been shown in previous papers [1–4], the soil–water in the unsaturated zone moves downward layer by layer. This takes place because of lateral molecular diffusion, which mixes the percolating water with the stationary water present in the soil. This layered movement allows a simple determination of the groundwater recharge. An individual water layer in the soil is tagged with a (isotope) tracer and its movement is followed by repeated soil sampling with an auger. Rain, which afterwards falls on top of the soil, apparently pushes the older water ahead of it, and takes its place above the tracer mark. The average downward displacement of the tracer mark, therefore, only depends on the amount of water S (expressed in mm), which remains from the total amount of rain fallen R, and on the volume fraction of the soil that is occupied by this remaining water.

Tritiated water is used as a tracer in the present study in view of the fact that isotopic water molecules behave practically like normal water molecules [5]. The techniques used for extracting the water from the soil, and for measuring tritium have been described elsewhere [4, 6].
<table>
<thead>
<tr>
<th>Dimension (a)</th>
<th>Injection</th>
<th>( b^{9} ) soil volume (litres)</th>
<th>Water volume in litres (33% of ( b^{9} ))</th>
<th>( M )</th>
<th>Soil moisture m^a (ml)</th>
<th>Tritium concentration to be applied</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>plane</td>
<td>7.7</td>
<td>2.5</td>
<td>( 8 \times 10^{-3} ) µCi/dm^2</td>
<td>130</td>
<td>( 62 \times 10^{-9} ) µCi/l^a, ( 1.9 \times 10^{4} ) T.U.</td>
</tr>
<tr>
<td>2</td>
<td>line</td>
<td>59</td>
<td>19.5</td>
<td>( 62 \times 10^{-3} ) µCi/dm</td>
<td>41</td>
<td>( 1.5 ) µCi/l^b, ( 4.7 \times 10^{7} ) T.U.</td>
</tr>
<tr>
<td>3</td>
<td>point</td>
<td>455</td>
<td>150</td>
<td>0.48 µCi</td>
<td>10</td>
<td>( 48 ) µCi/l^b, ( 1.5 \times 10^{7} ) T.U.</td>
</tr>
</tbody>
</table>

^a m = amount of soil moisture naturally contained within ± 2 cm from the injection plane, line or point

^b 1 T.U. (tritium unit) is equivalent to a \([T]/[H]\) ratio of \(10^{-11}\) or to a specific activity of 3.24 pCi/l. The present environmental tritium level in the soil is between \(10^{7}\) and \(10^{9}\) T.U.
Evaluation of the amount of tracer to be applied

We shall now calculate how the tritium injected into the soil is
diluted by molecular diffusion with time; and attempt to discover what
are the minimum amounts or concentrations of tritium that can still be
identified as a tracer mark after a certain period. This, of course, de-
pends on the special way in which the tritium is applied. In principle,
the tracer can be applied to the soil uniformly, either in a horizontal
plane, or in a straight horizontal line, or at an individual point only. A
single-point injection will, of course, need a minimum amount of tracer,
but a relatively high tritium concentration to be injected into the water.
The \( n = 1^\text{st}, 2^\text{nd} \) and \( 3^\text{rd} \)-dimensional gaussian distribution of a tracer
concentration with minimum spatial extension at the start (plane-, line-,
point-distribution) and be universally represented by

\begin{equation}
c = c_{max} \cdot \exp(-r^2/2\sigma^2)
\end{equation}

where the square of the distance \( r \) from the centre of the distribution is
given by

\[
r^2 = \sum_{i=1}^{n} x_i^2 \quad n = 1, 2, 3
\]

and the mean square standard deviation is \( \sigma^2 = 2 \text{Dt} \) in all these cases.
\( D = \text{diffusion constant}, \ t = \text{time elapsed} \). \( c_{max} \) can also be represented by

\begin{equation}
c_{max} = \frac{M}{b^n} \quad n = 1, 2, 3
\end{equation}

where \( M \) is the total amount of tracer involved and \( b = \sigma \sqrt{2\pi} \) is the width
at any time \( t \) of an equivalent rectangular tracer distribution, having the
same maximum concentration and containing the same total amount of
tracer as the gaussian equation (1) (see, e.g., [7]). If we assume the
following parameters,
(a) Maximum time \( t \) after which the tracer should still be detectable = 1 yr,
(b) Moisture volume fraction = 33 vol. %,
(c) Detection sensitivity of the scintillation spectrometer
10\(^3\) T. U., \( \geq 3.2 \times 10^{-3} \) \( \mu Ci/1 \),
(d) Isotropic diffusion by molecular diffusion only, \( D = 1.5 \times 10^{-5} \text{ cm}^2/\text{s} \);
therefore \( \sigma \approx \sqrt{2\text{Dt}} \approx 3 \text{ dm after one year}, \)
(e) Virtually no loss by radioactive decay of the tracer,
we arrive at the tritium amounts to be applied for the different injection
methods shown in Table 1, column 3.

To be on the safe side as far as health and safety regulations are
concerned, one would like to keep the tracer concentration in the water
to be injected into the soil as low as possible. On the other hand, the
total amount of water that one would like to inject is also limited,
otherwise the natural moisture distribution in the soil is unduly altered.
As a basis for computing the maximum permissible amount of water to
be introduced artificially, we shall use the amount of soil moisture m
naturally contained within \( \pm 2 \text{ cm} \) distance from the injection plane, line
or point (see column 7 of Table 1).
Note that, with different soil-moisture volume fractions, the amount of water injected will be changed proportionally, while the specific tritium activity is maintained. All results obtained will then remain valid.

While the concentrations in cases \( n = 1 \) and \( 2 \) are considerably below the MPC value of 30 \( \mu \text{Ci}/\text{l} \) [8] suggested by the ICRP\(^1\) this is not so in case \( n = 3 \). It should be mentioned that the values calculated are the absolute minimum tracer amounts, which allow detection after one year. Experience shows that it is advisable to use amounts about ten times as high (\( \approx 5 \mu \text{Ci} \)). This is because we have not yet taken into account any tracer losses by evaporation, plant transpiration or horizontal movement. On the other hand, it should be noted that a higher detection sensitivity would not bring much, since the detection limit assumed under (c) above is approximately that of the environmental tritium background.

The question needs further consideration of whether it might be justified to abandon the chosen tracer concentration limit of the injected water on grounds that already, after one day, the tracer injected at a certain point will anyway appear to be distributed by molecular diffusion over a soil volume of approximately 65 cm\(^3\) and thus, in the above example, in the region of maximum concentration, appear to be diluted by 20 cm\(^3\) of soil water, or by 1.2 litres after one week, regardless of the concentration in the injected tracer solution.

Thus, if we injected the 5-\( \mu \text{Ci} \) tritium, proposed for this case, in a highly concentrated solution, the maximum concentration at the point of injection would be 250 \( \mu \text{Ci}/\text{l} \) equal to 8 times the MPC after one day, and 4 \( \mu \text{Ci}/\text{l} \) equalling 1/8 MPC after one week. We have not tried this to date, and it might possibly be difficult to convince people of the justification of this argument.

\(^{1}\) Should one exclusively drink water with 30 \( \mu \text{Ci} \) tritium/litre, the body tissues would eventually reach this specific tritium activity and a yearly internal dose-rate of 3 rem.
FIG. 2. Vertical distributions of the tracer during an experiment on a sandy brown earth under artificial sprinkling conditions. The tracer injection was on 6 March 1967. (Boundary of the shaded area = tritium concentration in 10-4 cpm/100 g; heavy line = moisture volume fraction.)

(a) Immediately before irrigation on 9 March 1967.
(b) 10 March 1967 (15 h after irrigation with 45 mm).
(c) Immediately before the second irrigation period on 20 March 1967 (natural rain between (b) and (c) 25 mm).
(d) 22 March 1967 (24 h after irrigation with 70 mm).

TABLE II. RESULTS OF A TRACER EXPERIMENT UNDER ARTIFICIAL SPRINKLING CONDITIONS (see also Fig. 2)

<table>
<thead>
<tr>
<th>Time interval</th>
<th>Amount of precipitation</th>
<th>Apparent groundwater recharge $S^a = S^b - S^c$</th>
<th>Depth of tracer maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_1 - t_2$</td>
<td>$R$ (mm)</td>
<td>($mm$)</td>
<td>$Z_1$ (cm) $Z_2$ (cm)</td>
</tr>
<tr>
<td>9.3.-10.3.67</td>
<td>45</td>
<td>22.5</td>
<td>16 25</td>
</tr>
<tr>
<td>10.3.-20.3.67</td>
<td>25</td>
<td>14</td>
<td>25 41</td>
</tr>
<tr>
<td>20.3.-22.3.67</td>
<td>70</td>
<td>35</td>
<td>41 60</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>80</td>
<td>41 100</td>
</tr>
</tbody>
</table>

$^a S^b$ and $S^c$ = amount of soil water per unit area between tracer maximum and soil surface at time $t_1$ and $t_2$ respectively.

In principle it is quite clear that there is no health and safety problem as long as one follows the above considerations. It is more a question of formalities. Another problem that we are most concerned with is a possible disturbance of the natural environmental tritium distribution. Owing to the very local nature of the proposed experiments, this danger is tolerable, although it would be desirable if institutions investigating natural and environmental (bomb) tritium would be notified of such...
experiments, if they are conducted somewhere where it is not anticipated. There are bad examples of, e.g. $^{14}$C disturbances, which are unnecessary [9].

**Experimental technique of tracer injection**

The technique of tracer application that we originally used was the irrigation of approximately 2×2 m² soil-surface area with tritiated water. This technique was abandoned in favour of a syringe-type injection into the soil. The injection instrument is shown in Fig.1. It allows the injection of a few millilitres of tracer solution to a depth of about 1 m. The hole in the soil, remaining after injection, is closed by inserting a 5-mm-diam. round wooden stick. In soils with a small hydraulic conductivity, e.g. clay-rich soils, holes are made with a steel bar, after which some millilitres of tracer solution are dropped in. An initial vertical spread of several centimetres of tracer has no effect on the determination of the tracer mark position after about six months.

Now we usually inject the tracer at individual points about 5–10 cm apart, along a straight horizontal line. The series of point injections only need tolerable tracer concentrations, and they will be practically indistinguishable from a true line injection after a few days.

This new technique avoids several disadvantages of the previous one. During the warm and dry season a large fraction of the tracer may be lost by evaporation from the soil surface [2,3], particularly owing to the fact that, under normal relative humidity in the air (~70%), the tracer evaporates three times as fast as the water. Besides this, the distribution may become asymmetric by diffusion if the tracer mark stayed for long right at the soil surface during a dry period after tracer input. If there are cracks and fissures present in the uppermost soil layer the mark will be unnecessarily broadened by dispersion effects or, if large rain intensities occur, it might even be possible that parts of the rain can overtake the tracer front, thus indicating too small a groundwater recharge. Furthermore, the injection along a straight line has the advantage over a plane injection that only a moderate number of punctures is necessary for a line, e.g. 2 m long, thus facilitating application.

Line and point injections easily show whether a horizontal movement of the tracer mark has possibly taken place. A first indication of this is automatically obtained, even with a single core, if the total amount of tracer is different from what had been expected for a given position of the core.
Fig. 4. Distortion of tracer distribution (boundary of shaded area) during passage through layers of varying moisture content (solid line).
(a) Theoretical distortion if dispersion effects are excluded.
(b) Measured distribution in several brown-earth pedons. The high moisture contents are caused by a clay-rich layer.

Experiments and evaluation of groundwater recharge

An experiment in a sandy brown earth under artificial sprinkling conditions demonstrates how the determination of the groundwater recharge is arrived at by watching the movement of the tracer mark. To check the usefulness of isotopic water molecules as soil-water tracers, we made this a double-tracer experiment, using tritium and deuterium as tracers.

On a vegetation-free horizontal proving ground, approximately 7x7 m², a line injection was made at 15 cm depth. Three days later the whole proving ground was sprinkled with 45 mm of tap-water for 6 h. A Melnor sprinkler, MTV 525 (Perrot-Regnerbau GmbH) was used. It was not possible to apply a higher rain intensity since, with that chosen, a large part was lost by surface run-off, owing to the insufficient permeability of the top soil layer (20-cm arable layer). Ten days later, the peak had moved to a depth of 41 cm because of natural rain (25 mm) and "sinking water", resulting from the relatively high water content in the upper soil layers after the artificial sprinkling. A second irrigation period, (70 mm during 16 h) showed different penetration depths from place to place. This may be due to the different permeability of the top soil layer because of partial clogging with fine material. The results of these experiments are shown in Fig. 2 and Table II. The greater the distance moved the more accurate were the results. It should be noted that all tracer concentration distributions shown in Fig. 2 were exclusively determined by molecular diffusion. Therefore, the constants of longitudinal and transverse dispersion were identical [10]. Figure 3 shows in two examples corresponding to those of Fig. 3(c) and (d), that there are practically no differences between the T- and D-concentration distributions. This means differences are not to be expected between isotope and normal water molecules.
FIG. 5. Influence of a clay pan on water movement (the abscissa is common to all three diagrams).

(a) Broken line (x) = measured depth position of the tracer maximum after 110 d. Heavy line = measured position of the boundaries of the clay pan. Water content in the clay-rich layer (shaded area) is 20-30 vol.%, and in the soil above it only 15-20 vol.%. 
(b) Apparent groundwater recharge 5° as deduced from the peak position in (a) and the moisture content above it. The broken horizontal line represents the total rain between tracer injection and soil sampling.
(c) Maximum tracer concentration found at the depth position (x) given in (a).

In general the question of whether mechanical dispersion had played a role in an individual case or not, cannot be answered directly in all natural cases because of the variation of water content with depth, which is often encountered. A tracer distribution can then be narrowed if it moves from a lower to an upper zone of higher soil-moisture volume fraction, i.e. from a larger to a smaller layer of smaller grain size. On the other hand the distribution will broaden if the sequence of soil layers is reversed. Figure 4(a) shows how a rectangular or a simplified gaussian tracer distribution is distorted if it moves through regions of varying moisture content. Figure 4(b) shows a few examples measured under natural conditions. However, a correction can be made for this influence if the moisture distribution in the soil is known.

Similar but more pronounced difficulties arise with the general lack of soil homogeneity encountered at many sites. Permeability variations from place to place, over distances too great for total molecular diffusion exchange [4], or lateral water movement along the surface of inclined clay pans, give varying groundwater recharge or evapotranspiration values from one place to another. In such cases only a number of parallel investigations will give an average representative value for the site.

The following example shows how a clay pan influences the water-movement pattern. If, after some time, it is found that the tracer
FIG. 6. Variation with depth of pore-size distribution (a), water conductivity as \( pK_w \) in \( \log \text{cm sec}^{-1} \) (b), \( w \) = horizontal conductivity, \( s \) = vertical conductivity, \( g \) = vertical conductivity if worm tubes are present) and grain-size distribution (c) of the Parabraunerden P, K and R. Methods of determination and explanation of the grain-size symbols are given in reference [11].
### TABLE III. DATA OF THE FOREST SOILS

<table>
<thead>
<tr>
<th>Symbol and location in southern Germany</th>
<th>Type of forest</th>
<th>Parent material</th>
<th>Soil type</th>
<th>Slope position</th>
<th>Date of tracer input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plieningen (near Stuttgart)</td>
<td>Old beech</td>
<td>Würm-Loess, underlain by</td>
<td>Parabraunerde (grey brown podsol soil)</td>
<td>1° SSE</td>
<td>30.11.64 = P1, 8.5.65 = P3</td>
</tr>
<tr>
<td>Kogen (near Stuttgart)</td>
<td>forest</td>
<td>Riss-Loess</td>
<td>above fossil B₂ horizon</td>
<td>0.5° SE</td>
<td>30.11.64 = K1, 8.5.65 = K3</td>
</tr>
<tr>
<td>Rast (near Lake Constance)</td>
<td>Old spruce forest</td>
<td>Riss-Moraine</td>
<td>Parabraunerde</td>
<td>3° SSW</td>
<td>8.5.65 = R1</td>
</tr>
</tbody>
</table>

---

* Further descriptions and analytical data are given in [12] (See also Fig. 6).
maximum is not exactly below the point of injection, it means that horizontal water movement took place. The experiment was done in a sandy soil with horizontal surface and a clay pan between approximately 60 and 100 cm deep. The surface of the pan was slightly rippled and had a maximum inclination of from about 5° to 10°. On 11 October 1966 a 10-ml tracer solution was injected at each of several points 10 cm apart along a straight line at a 20-cm depth. The total length of the injection line was 2 m. Two weeks later an almost uniform tracer distribution in both a horizontal and a vertical direction was found. After about 100 d the tracer mark reached the clay-rich layer. On 1 February 1967 several cores on the injection line and nearby were taken, so that the position of the clay pan could be reconstructed. The total rain between 11 October
and 1 February was 210 mm. Figure 5(a) shows the position of the clay pan and the position of the tritium maximum found in each individual core. Figure 5(b) shows the total amount of water found above the tracer maximum (apparent groundwater recharge $S^g$) compared with the total amount of rain fallen (dashed line). It can easily be seen that the apparent groundwater recharge varies greatly, and even exceeds the total rain, where the upper boundary of the clay pan has a depression. Obviously water moved along this boundary to its depression. In Figure 5(c) are shown the concentrations of the individual tracer maxima. It can be seen that the highest tracer concentration is not below the injection point. Obviously, water moved laterally to both sides from the "water divide" immediately below the injection line. The horizontal displacement is approximately 20-30 cm.
FIG. 9. Water balance of soil P (see Table IV).
(a) For P1 (tracer input 31 November 1964).
(b) For P3 (tracer inserted 8 May 1965).

FIG. 10. Water balance of soil K (see Table IV).
(a) For K1 (tracer input 31 November 1964).
(b) For K3 (tracer inserted 8 May 1965).
Water balance of forest soils

Tritium tracer experiments in forest soils were conducted for two years. Some of the results were reported previously [3]. Some soil data are summarized in Table III and Fig. 6. The data of individual tracer injections are also listed in the table. In all cases tracer application was by the older method of sprinkling a 2×2-m² surface area with tritiated water. From time to time cores were taken with an auger, and the tritium was measured at 10-cm intervals. Every fortnight the soil-moisture distribution was measured by a neutron probe down to a depth of 130 to 230 cm. The daily rain data for the open country were taken from the nearest station of the Deutsche Wetterdienst. The true water input at the site was measured directly by a rain gauge at the site itself. In Figs. 7 and 8 are shown all these data in water-content chronospliths and, in Figs. 6(b) and 7(b), in moisture chronospliths.

The water balance of forest soils is difficult to assess, owing to the considerable local variations of the rain distribution as well as to water removal by tree roots. Therefore, it would be desirable to take many parallel soil cores in order to obtain a representative average. However, if conducted over some time, this would soon result in a complete perforation of the site. Therefore, only spot samples were taken periodically. The vertical position of the tracer mark appeared to be remarkably uniform, especially after a longer period.

In the upper part the water input Figs. 9 to 11 show R as a function of time together with the total water contained in the soil between the tracer maximum and the soil surface. We shall call this quantity S* apparent groundwater recharge. The lower part of the figures gives the true depth position Z of the tracer maximum. Table IV shows the data of Figs. 9 to 11, if averaged over the same yearly intervals. It can be seen that the tracer moves relatively fast at the beginning (75–100 cm/yr), but nearly ceases later (compare P1, P3, K1, K3 for equal time intervals). This means that the apparent groundwater recharge decreases as the tracer maximum reaches a greater depth. We believe that the main reason for this behaviour is a penetration of the tagged soil layer by water flowing through the tree roots. The exchange with the tracer in the soil outside the roots is obviously minimized by a high flow velocity, large root cross-section, and a surface layer (cork) of low permeability. For this reason too high a groundwater recharge would be obtained for the time interval under consideration, as long as roots can suck water from below the tracer front.
TABLE IV. RESULTS OF THE FOREST SOIL TRACER STUDIES, IF AVERAGED FOR THE SAME YEARLY INTERVALS (see also Figs. 8-11)

<table>
<thead>
<tr>
<th>Time interval t1 - t2</th>
<th>Symbol of the proving ground</th>
<th>Water input R (mm)</th>
<th>Apparent ground-water recharge S^a = S^a - S^a  (mm)</th>
<th>Evapotranspiration ( \psi^a = R \cdot S^a ) (mm)</th>
<th>Depth of tracer maximum Z1 (cm)</th>
<th>Z2 (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1.65 - 31.12.65</td>
<td>P1</td>
<td>723</td>
<td>320</td>
<td>403</td>
<td>10</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td>K1</td>
<td>620</td>
<td>270</td>
<td>350</td>
<td>10</td>
<td>80</td>
</tr>
<tr>
<td>8.5.65 - 7.5.66</td>
<td>P1</td>
<td>675</td>
<td>225</td>
<td>450</td>
<td>50</td>
<td>98</td>
</tr>
<tr>
<td></td>
<td>P3</td>
<td>675</td>
<td>420</td>
<td>255</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>K1</td>
<td>598</td>
<td>240</td>
<td>288</td>
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<td>98</td>
</tr>
<tr>
<td></td>
<td>K3</td>
<td>598</td>
<td>290</td>
<td>238</td>
<td>0</td>
<td>76</td>
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<tr>
<td></td>
<td>R1</td>
<td>841</td>
<td>838</td>
<td>458</td>
<td>0</td>
<td>110</td>
</tr>
<tr>
<td>1.1.66 - 31.12.66</td>
<td>P1</td>
<td>598</td>
<td>40</td>
<td>468</td>
<td>95</td>
<td>117</td>
</tr>
<tr>
<td></td>
<td>P3</td>
<td>598</td>
<td>30</td>
<td>568</td>
<td>81</td>
<td>100</td>
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<tr>
<td></td>
<td>K1</td>
<td>504</td>
<td>60</td>
<td>444</td>
<td>80</td>
<td>102</td>
</tr>
<tr>
<td></td>
<td>K3</td>
<td>504</td>
<td>110</td>
<td>394</td>
<td>71</td>
<td>89</td>
</tr>
</tbody>
</table>

* S^a and S^a = amount of soil water per unit area between tracer maximum and soil surface at time t1 and t2 respectively.
The closing of draining pores in the clay-rich horizons of P and K, owing to increasing moisture swelling in winter 1965-66, possibly resulting in a lateral water movement, might also contribute to the decreasing tracer velocity. Finally, the capillary moisture rise during autumn 1966 might be of some influence.

For 1966 Table IV gives an average apparent groundwater recharge of 60 mm. During that period the tracer peaks were sufficiently deep for reliable results to be expected. In principle the true groundwater recharge $S^*$ is measured correctly only if there are no active roots below the tagged layer. Injection of tracer to a certain depth (e.g. 1 m) will improve the reliability of water balance deduced.

The moisture values obtained with the neutron gauge are corrected for the water tightly bound in clays, so that it is equivalent to the moisture content obtained by standard drying at 105°C. The tritium, however, does exchange to a large extent [13] with the tightly bound water and correction is necessary in principle. An example shows, however, that this correction is negligible in many cases. The maximum clay content in the soils studied here was 40% by weight or 25% by volume. The water loss after drying at 105°C was on the average 35 vol.%; the tightly bound water of the clay fraction would add another 1.4 vol.%. This means that the tightly bound water makes the apparent recharge value $S^*$ only 4% too low. This is an upper limit insofar as the exchange with the tightly bound water is much slower than with free water [13]. At present we are testing these effects with double-tracer experiments in clay-rich soils.

The tritium concentration distribution is nearly gaussian after two years, with an rms deviation somewhat less than that expected from molecular diffusion. This is because of the increasing moisture with depth (see Figs. 7 and 8). The total amount of tritium found in the peaks after 2 yr is only 1/5 of the amount initially injected. Of course, this is because the roots take up tritium during the passage of the tracer front.

ACKNOWLEDGEMENTS

The authors are indebted to C. Sonntag for his effort in developing the soil-water extraction and counting techniques. Part of the work reported was performed at the proving grounds of the Landwirtschaftliche Untersuchungs- und Forschungsanstalt, Speyer/Rh.; thanks are due to the director of this institution, Professor O. Siegel.

This work is supported by the Deutsche Forschungsgesellschaft, the Bundesministerium des Inneren and the Heidelberger Akademie der Wissenschaften.

REFERENCES

M. DE BOODT: Do you know the extent of tritium diffusion in the water that was already in the soil profile? I imagine such diffusion might be important in long experiments.

U. ZIMMERMANN: At first sight one might think that the accuracy of the tracer method decreases with time, due to spreading of the tracer. In reality, however, it is the other way round. The rms deviation $\sigma$ is proportional to $\sqrt{t}$, $\sigma = \sqrt{2D_t}$, whereas the distance moved by the tracer front is approximately proportional to $t$, so that in fact the accuracy in determining the distance $Z$ between tracer maximum and soil surface increases with time.

M.J. FRISSEL: If I may make an additional comment on this, it is true that tritium diffuses, just like deuterium. In general, however, it diffuses symmetrically, so that the location of the maximum concentration is not usually influenced. Errors arise only if diffusion is very asymmetric, which does not appear to have been the case in these experiments.

U. ZIMMERMANN: It is true that asymmetric diffusion of the tracer does cause difficulties in determining the exact position of the tracer maximum. Such asymmetry results in most cases from variations in the water content of the soil. Figure 4 shows how the tracer distribution is distorted when a tracer front moves through regions of varying water content. This effect can be corrected, however, if the moisture distribution in the soil is known.

L.E. DANFORS: What do you estimate to be the cost of a tritium determination using your laboratory facilities?

U. ZIMMERMANN: About $2.5$, if the activity in the sample is sufficiently high to be determined by the scintillation spectrometer with prior concentration.

L.E. DANFORS: With your techniques it would appear to be possible to estimate the time in which a water molecule passes through the different horizons of the soil. Can you give an example, for average precipitation conditions, of the number of times the water is exchanged during one year in the 0–20-cm soil layer of one of your profiles?
U. ZIMMERMANN: The transit time of a water molecule is proportional to $d^2/D$, $D$ being the molecular diffusion coefficient and $d$ the mean distance between stationary water and moving water. On a semi-macroscopic scale, corresponding to the size of the soil particles in question, the lateral molecular diffusion is so fast (i.e., water-molecule transit time is so short) that even in a coarse sand equilibrium is reached within a soil layer the thickness of which is about the same as the size of the sand particles. Most of the measurements we have made show that the spreading of the tracer front is not affected by mechanical dispersion; this is experimental proof of rapid lateral molecular exchange.

J.A. DAMAGNEZ: In Table IV the evapotranspiration value for 1965 (403 mm) is lower than that for 1966 (468 mm), whereas the water input in 1965 (723 mm) is greater than that in 1966 (508 mm). How do you explain this?

U. ZIMMERMANN: The evapotranspiration values for 1965 and 1966 cannot be compared, owing to differing root uptake of water below the tracer front and differences in rainfall.

In order to eliminate the influence of differences in rainfall one should compare P1 with P3 and K1 with K3 for the same time intervals.

H.W. SCHARPENSEEL: You suggest that notification should be given of all water tracer experiments in the field in order not to prejudice natural and environmental fall-out tritium investigations. Do you think that disturbances such as those reported by Olsson and Stenberg are attributable to contamination? Are they not more likely to result from uneven uptake of carbon-14 or tritium (due to the intrusion of tropical or polar air masses), the periods of maximum carbon-14 or tritium concentration coinciding with the sampling dates? I would mention in this connection that in 1958 we found plant material with unusually high fall-out carbon and tritium levels.

U. ZIMMERMANN: In 1958, the environmental concentration of fall-out carbon-14 in Central Europe was higher than the natural level by a factor 1.8. During the summer of 1965, Olsson and Stenberg found at Abisko, Sweden, a carbon-14 concentration 35 times higher than the natural level. This was undoubtedly caused by contamination.

In 1958, the environmental concentration of fall-out carbon-14 in Central Europe was higher than the natural level by a factor 1.2. If the carbon-14 concentrations found by you in plant material during this period were greatly in excess of this level, I imagine they were also caused by contamination.

---

1 Ref. [9]
SECTION IV
SOIL-WATER-PLANT RELATIONSHIPS
WATER UPTAKE AND SALT-DISTRIBUTION PATTERNS IN SALINE SOILS

W. R. GARDNER
UNIVERSITY OF WISCONSIN,
MADISON, WIS.,
UNITED STATES OF AMERICA

Abstract

WATER UPTAKE AND SALT DISTRIBUTION PATTERNS IN SALINE SOILS. There is an interaction between the pattern of water uptake from saline soils and the distribution of salts within the soil profile. To predict the response of a plant to the combined matric and osmotic components of the water potential, integrated over the entire root zone, it is necessary to solve the water-uptake and salt-leaching problems simultaneously. Data in the literature suggest that little saline water will be taken up so long as there is non-saline water at a higher potential within the root zone. The implications of this hypothesis with respect to salinity control in the field are discussed. Tentative conclusions concerning the re-use of saline water are also drawn.

INTRODUCTION

Isotope and radiation techniques are finding increasing use in soil-water and plant-water studies. One example is the neutron-moisture meter which has many advantages when water-content changes must be measured over large areas in the field [1]. Despite many recent experimental and theoretical advances in micrometry, the measurement of soil-water-content changes still gives one of the best measures of actual evaporation. However, this procedure has serious limitations, especially in saline soils. It is in just such soils that a precise estimate of evaporation is needed, since the amount of irrigation water applied must exceed the evaporation by a sufficient amount in order to ensure a satisfactory salt balance.

The difficulty in using water-content measurements to estimate water uptake and evaporation is that this procedure does not take into account movement of water into or out of the root zone across its lower boundary. The periodic changes in soil-water content, which occur at the soil surface tend to become damped out with depth so that water movement near the bottom of a reasonably deep root zone may average over several cycles of irrigation and drying and tend towards a steady-state condition [2]. Steady-state water uptake by the plant-root system obviously is not reflected in water-content changes.

There are a number of procedures whereby one can obtain a measure of the water flux across the lower boundary of the root zone but few of them offer much in the way of precision. The flux can be calculated from the product of hydraulic gradient and the capillary conductivity. While the hydraulic gradient measurement presents few difficulties in the

* Joint contribution from the US Department of Agriculture Salinity Laboratory, Riverside, California, and the Department of Soils, University of Wisconsin. Published with the permission of the Director of the Agricultural Experiment Station of the University of Wisconsin.

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tensiometer range, field methods of measuring the capillary conductivity are not in an advanced stage of development. The most suitable method is probably that used by Ogata and Richards [3], which has been analyzed in more detail by Rose et al. [4]. This method cannot be used, however, within a root zone from which plants are extracting water.

The direct measurement of the flux by means of an appropriate tracer appears to be the best solution to the problem. In a saline soil the concentration of the natural salts may yield the desired information. In other cases it may be necessary to introduce a special isotope. It is the purpose of this paper to consider a few of the problems involved in the interpretation of water movement and soluble ion concentration in the plant-root zone.

MATHEMATICAL ANALYSIS

The principle complication due to the presence of the plant-root system is the ability of the plant to take up water and ions differentially. Thus, changes in the ion concentration at any point in the soil may be due to ion uptake, water uptake, or water movement. To sort out the separate effects several different measurements may be required.

In the following simplified mathematical analysis only the major phenomena involved in the transport of soluble ions will be taken into account. Where simplifying assumptions are made for illustrative purposes it should be noted that a more exact treatment is often possible, it merely requiring a bit more work. The phenomena of diffusion and dispersion will not be taken into account explicitly, though this could be done.

We assume that the ions move with the same average velocity, v, as the water. The water flux density, q, is then equal to \( \theta v \), where \( \theta \) is the volumetric water content of the soil. The ion-flux density is \( qC \) where C is the concentration of ions in solution. It is assumed that there is no interaction between the ions and the soil. The equation of continuity or conservation of matter for the ions is, in one dimension:

\[
(\partial C/\partial t) = -\partial(qC)/\partial z - F
\]  

(1)

where \( z \) is the depth below the soil surface, \( F \) is the rate of ion uptake by the plant, per unit volume of soil, and the flux density \( q \) is positive in the downward direction. The major problem in interpreting soil-water-content data arises from the steady-state aspects of the problem. We will examine the steady-state solution of equation (1) by setting \( \partial C/\partial t = 0 \) and integrating to get:

\[
qC = IC_0 \int F \, dz
\]  

(2)

We have evaluated the constant of integration by assuming that water of concentration \( C_0 \) is being continuously introduced into the soil at \( z = \theta \) at a rate I.
The flux density $q$ must satisfy the continuity equation for water flow

$$\frac{\partial q}{\partial t} = -\frac{\partial q}{\partial z} - w$$  \hspace{1cm} (3)$$

where $w$ is the rate of water uptake by the plant roots per unit volume of soil. If the ion in question is completely, or nearly completely excluded by the plant roots $F = 0$ and the dependence of $C$ upon $z$ is given by

$$C = IC_0/q(z)$$  \hspace{1cm} (4)$$

Setting $\frac{\partial q}{\partial t} = 0$ in equation (3) and combining with equation (4) gives

$$-\frac{dq}{dz} = w = (IC_0/C^2) \frac{dC}{dz}$$  \hspace{1cm} (5)$$

Equation (5) gives us a relation between the water-uptake pattern with depth and the concentration distribution. Since it is easier to measure the concentration than to measure the flux directly, the concentration gradient may give a better measure of $w$ than the divergence of the flux density. Furthermore, the lower limit of the water uptake can be ascertained from the depth at which the concentration becomes constant.

Rather than introduce an ion continuously at the soil surface one might introduce narrow bands at regular intervals. These would move down through the soil a constant distance apart if the velocity were constant and uniform. However, water uptake by the plant would cause them to move at different rates in different parts of the root zone, from which the divergence of the flux could be estimated. This can be written

$$-w = \frac{dq}{dz} = v \frac{d\theta}{dz} + \theta \frac{dv}{dz}$$  \hspace{1cm} (6)$$

A problem which enters here, though it is not insurmountable, is the tendency of diffusion and dispersion to spread out such a band. It would be necessary to follow the peak or maximum concentration rather than the leading edge of the band.

**Low ion concentration**

Many ions are taken up by plant roots, especially when they are present at low concentrations in the soil solution. When this is the case $F$ is not zero in equation (1). One situation of possible interest is that in which the rate of ion uptake is proportional to the concentration. We then replace $F$ by $KC$ in equation (1) where $K$ is a constant. We must know $q$ as a function of $z$ in order to perform the integration. In some circumstances the water-uptake pattern appears to be fairly uniform when averaged over time for at least part of the root zone. In this case $q = (I-wz)$. Equation (1) then becomes

$$\frac{1}{C} dC = (w-K) dz / (I-wz)$$  \hspace{1cm} (7)$$
which integrates to give

$$\frac{C}{C_0} = \frac{1}{(1-wz)^{(w-K)/w}}$$  \hspace{1cm} (8)$$

One circumstance which might lead to the relation $F = KC$ is that in which ion uptake is limited by the rate of movement of ions to the plant roots. This movement will be the result of diffusion plus mass transport in the water. Unless the rate of water uptake is much greater than the diffusion rate, the two processes are nearly additive [5] so that $F = wC + 2\pi D L C / (\log b/a)$. $L$ is the length of roots per unit volume of soil, $a$ is the root diameter, $2b$ the average distance between roots, and $D$ is the diffusion coefficient. $D$ is not the true diffusion coefficient but an apparent coefficient which may be several times larger than the actual coefficient owing to dispersion [5]. For a uniform root-system equation (7) would then be rearranged to give

$$q \frac{dC}{dz} = -2\pi D L C / \ln(b/a)$$  \hspace{1cm} (9)$$

The concentration distribution in the root zone should then give a fair estimate of the root distribution since $D$ and the logarithmic term in (9) should not be difficult to estimate to a reasonable degree of precision. If the root distribution is uniform then (9) integrates to give:

$$C = C_0 (1-wz)^{2\pi D L / \ln(b/a)}$$  \hspace{1cm} (10)$$

The chief limitation to this procedure could well be the difficulty in achieving steady-state distribution in a dynamic root system.

**High ion concentration**

If the concentration of ions becomes high enough that a significant fraction of them are excluded by the plant-root membranes their osmotic effect will then tend to restrict water uptake. The rate of water uptake is presumed to depend upon the difference between the potential energy of the water in the root system and that of the water in the soil. If we assume a simple linear system we can write

$$w = (\psi_p - \psi_m - \psi_c - \rho g z) / R$$  \hspace{1cm} (11)$$

where $\psi_p$ is the water potential in the plant, $\psi_m$ is the matric potential in the soil, $\psi_c$ is the osmotic potential in the soil, and $\rho g z$ represents the gravitational potential. $R$ represents the combined resistance to water movement through the soil and the plant and is probably a very complex function of the plant-root system and the soil properties. It is extremely difficult to obtain direct information concerning $R$ and even more difficult to measure $\psi_p$ directly within the plant-root system. Thus, most information concerning the functioning of the plant-root system with respect to water uptake must be obtained by indirect means. The manner in
which the plant-root system integrates over a non-uniform salt distribution depends to a great extent upon \( R \). For example, if the resistance to water movement were relatively low in the upper, less saline, portion of the root zone, relatively little water will be extracted from the lower, more saline portions unless the matric potential in the upper part were of the same order of magnitude as the osmotic potential in the lower. There are relatively few reported experiments on water uptake from differentially salinized root systems and much more information is needed before the nature of \( R \) can be specified with any degree of confidence for any particular root system. When combined with equation (5) equation (11) gives

\[
w = (\psi_p - \psi_m - \psi_c - \rho gh)/R = \frac{1C_0}{c^2} \frac{dc}{dz}
\]  

where \( C_0 \) is the concentration at \( z = 0 \) and \( \psi_p \) is the plant-root potential at the same elevation. Thus, to the extent that the actual periodic variations in potential oscillate about the steady-state average, the salt distribution can be used to give a measure of \( R \) as a function of \( z \). Altering the uptake rate by changing the transpiration rate or the value of \( C_0 \) should then give information on whether lumping all the resistance into a single resistance term is a valid assumption. In this case in particular, thin bands of radioisotopes of the same ion would be interesting to follow in order to evaluate the importance of the non-steady-state nature of the actual uptake process in influencing the uptake patterns. It should be noted that under steady-state conditions the same results would be obtained for ions which are adsorbed by the soil particles.

**DISCUSSION AND CONCLUSIONS**

It is important to understand the conditions throughout a saline root zone in order to manage such systems efficiently and obtain maximum use of the saline water. Some plants will tolerate rather low osmotic potentials, of around minus several bars. However, to concentrate an only slightly saline water to such minimum allowable osmotic potential, it may be necessary to allow the matric potential in the upper part of the root zone to drop to a value which in itself would result in a yield reduction. In such circumstances it would be more efficient to allow the water to concentrate less than the maximum amount during first use and then re-use the more saline drainage water. However, to assess the economic feasibility of such a procedure we must have much more data on plant response to saline root zones. It is essential that this data include information on water-uptake patterns and salt distribution. Since direct measurement of ion and water uptake as a function of position within the root zone is virtually impossible, the use of tracer techniques combined with a valid mathematical analysis seems to offer the best hope for acquiring a quantitative understanding of the behaviour of plant-root systems under saline conditions.
REFERENCES


DISCUSSION

U. ZIMMERMANN: You mentioned in your oral presentation that separation occurs when salt water is taken up by plant roots. I should like to point out that this does not apply to the isotopic water molecules.

W. R. GARDNER: Since there has been speculation in the past as to whether deuterium or tritium might somehow be discriminated by the plant, it is good to know that such a separation does not occur, or is too small to be measurable, and thus presents no problems in the interpretation of data.

J. A. DAMAGNEZ: At low ion concentrations you assume that the rate of ion uptake is proportional to the concentration in the soil solution. For this assumption to hold, the ion concentration in the root system would have to be zero, or very low, and constant throughout the root system. Do you not think that your assumption might lead to an erroneous interpretation of the ion flux in the soil?

W. R. GARDNER: The assumption that uptake occurs as rapidly as ions can move to the plant roots is only one of many possibilities and was used as an illustration. By varying C_{0} one might be able to ascertain the proper function to describe the uptake. It probably depends on the level of ions in the plant and on a number of other factors.

A. M. GLOBUS: Not only do water and salts move towards the root system, the roots also move towards sources of water and nutrition. In many cases the relative importance of the two processes is of no significance; if, however, the equations proposed by you are used to find quantities such as K, the results will be greatly affected by the relationship between them.

W. R. GARDNER: I entirely agree. We have derived equations for dealing with this problem and will present them in a paper later this year.

C. E. MAERTENS: I should like to point out that the concentrations in the immediate vicinity of the roots differ considerably from the mean concentrations in the soil. For example, the calcium concentrations are much higher near the roots, whereas the potassium concentrations are much lower.

H. KICK: We found in our pot experiments with different kinds of saline water that yields were somewhat depressed when we introduced the saline water at the beginning of the experiments. When we introduced the saline water later in the experiments there was less or no depression of the yields, depending on the type of crop and its stage of growth.
W. R. GARDNER: My colleagues at the United States Salinity Laboratory have often noted a stimulation of growth at low salinity levels caused by the application of salt. This is a function of light level, being most pronounced at low light intensity but very small at full sunlight.

N. F. BONDARENKO: In considering the steady state one can avoid difficulties associated with the adsorption and desorption of ions along the flow path. Do you think that by introducing $\psi_m$ one can avoid difficulties connected with capillary osmotic flow? The behaviour of the osmotic flow and that of the flow induced by $\psi_p$ differ considerably.

W. R. GARDNER: The osmotic potential is used only to describe the passage of ions through the root membranes. Concentration gradients might well exist near the plant root and would have to be taken into account. The influence of the concentration gradient on water movement within the soil is probably negligible. To be more exact, one should also take into account diffusion of ions caused by the concentration. This can be done, and the equations are given in one of the references.
PRODUCTION DE MATIERE SECHE DES CULTURES IRRIGUEES EN ZONE MEDITERRANEENNE ARIDE

J.A. DAMAGNEZ
INRA, CENTRE DE RECHERCHES AGRONOMIQUES DU SUD-EST,
MONTFAVET, AVIGNON, FRANCE

Abstract — Résumé

DRY-MATTER PRODUCTION IN IRRIGATED CROPS IN THE ARID MEDITERRANEAN ZONE. The water-balance equation for crops is applied to research on the water requirements of crops in the arid Mediterranean zone and the effectiveness of the water according to the season.

The neutron probe is used to determine variations in the groundwater reserve. The method used results in an error in estimation of the term $\Delta R$ (variations in groundwater reserves in the zone penetrated by the roots) not exceeding 10 mm of water.

For fodder crops which undergo successive cuttings (sorghum, lucerne) the method used disclosed some outstanding facts, which may be confirmed by theoretical study of the equation for the production of dry matter. These results show in particular that:

- There is in fact a simple relationship between the yield and the ETR water consumption (true evapotranspiration);
- Nevertheless, for a given quantity of water added to the soil (rainfall + drainage), the demand made by the crop on the groundwater reserves varies in particular with the level of these reserves and with the root development;
- An important finding is that the maximum yield, obtained when $ETR = ETP$ (potential evapotranspiration), decreases as the ETP values increase. For large ETP values, when the light factor does not limit photosynthesis, the product $ETP \times yield$ is relatively constant.

Therefore, high potential evapotranspiration values appear to be an important limiting factor in the production of dry matter in the arid Mediterranean zone.

The paper concludes by suggesting a number of agronomic solutions.
1. INTRODUCTION

Le déficit d'eau est le facteur limitant essentiel du rendement des cultures, non seulement dans les régions arides, mais bien souvent également sous les climats tempérés.

Jusqu'à une époque récente, l'irrigation avait pour but essentiel de compenser le déficit pluviométrique et de maintenir ainsi l'humidité du sol à un niveau satisfaisant.

A cette notion statique de besoin en eau des cultures s'est ajouté récemment un concept dynamique qui fait apparaître la notion d'évapotranspiration potentielle, non seulement comme un facteur quantitatif qui fixe l'enveloppe du besoin en eau des plantes, mais également comme un concept dynamique dont l'intensité peut devenir un facteur limitant de la production.

On constate en effet que les végétaux apparemment situés dans les meilleures conditions d'alimentation hydrique souffrent souvent, sans flétrissement apparent, d'un déséquilibre quotidien qui résulte de l'inadaptation du couvert végétal à des exigences climatiques sévères. Ce déséquilibre contribue fortement à limiter le niveau de production des cultures [1-3]. Quand le facteur eau n'est pas limitant de la consommation d'eau, l'évapotranspiration réelle des cultures, ETR, est sous la dépendance étroite des facteurs du climat. L'évapotranspiration potentielle, ETP, traduit alors la consommation d'eau maximale, ETR_max du couvert végétal.

Si, au cours d'intervalles de temps même réduits, les quantités d'eau apportées par les pluies, P, et les irrigations, I, sont inférieures à ETP, la culture prélevera une fraction ΔR de ses besoins dans les réserves d'eau du sol. Selon que la contribution du sol définie par

\[
q_{\text{th}} = \left( \frac{1}{n} \sum_{i=0}^{n} \text{ETP} - \frac{1}{n} \sum_{i=0}^{n} (I + P) \right) \text{ et } \Delta R \text{ théorique} = q_{\text{th}} \cdot n
\]

(n = intervalle en jours séparant deux bilans) est satisfait ou non, l'évapotranspiration réelle ETR sera potentielle, ETR = ETP, ou réduite, ETR < ETP. L'équation générale du bilan d'eau s'écrit alors:

\[
ETR = P + I \pm \Delta R + D
\]

dans laquelle

ETR = consommation d'eau réelle de la culture (ETR < ETP)
P = quantité d'eau apportée par les pluies
I = quantité d'eau apportée par l'irrigation
ΔR = variation des réserves en eau du sol dans la zone exploité par les racines, ΔR < ΔR théorique
D = eau éliminée par drainage.

Si les apports d'eau sont fractionnés de telle sorte que la tranche de sol humectée n'excède pas la profondeur exploitée par les racines, le terme de drainage peut être négligé en première approximation.

Quand les apports d'eau sont réduits, I + P < ETP, l'aptitude de la culture à exploiter les réserves d'eau du sol varie en fonction du niveau
mème de ces réserves, mais aussi en fonction des cultures, de leur enracinement notamment.

2. METHODE EXPERIMENTALE

Les résultats d’expériences relatés ici ont tous été obtenus sur la même parcelle expérimentale, suivant un dispositif statistique en blocs (5 traitements x 4 répétitions); le même dispositif a été conservé tout au long des essais afin de suivre parallèlement l’évolution pédologique du sol, un limon argileux homogène, sous irrigation [4]. Les irrigations étaient pratiquées à l’eau douce (extrait sec 0,2 g/l).

Le même dispositif a été mis en place sur un parcelle voisine, dont le sol était de même nature. Dans cette deuxième série d’essais l’irrigation était pratiquée avec une eau salée (extrait sec 2,7 g/l). La comparaison des résultats obtenus à l’eau douce et à l’eau salée a déjà fait l’objet de précédentes publications [4-6].

Deux autres parcelles contiguës, aménagées selon un dispositif en carré latin, ont été consacrées à des cultures arbustives (oranger, olivier). Le protocole expérimental appliqué était en tous points analogue au dispositif retenu pour les cultures annuelles.

La succession des cultures est résumée au tableau I.

2.1. Paramètre d’irrigation

Tout au long de l’expérimentation, l’évapotranspiration potentielle a été mesurée sur gazon de Kikuyu (Pennisetum clandestinum) suivant un dispositif classique [7].

Pour une période considérée de n jours, les besoins d’eau maximaux de la culture sont définis par l’évapotranspiration potentielle. La couverture intégrale de ces besoins peut être assurée, soit par les apports d’eau représentés par l’irrigation ou la pluie, soit par l’exploitation de réserves en eau du sol dont le déficit théorique doit varier de $\Delta R_{th}$.

\[
ETR_{max} = ETP = I + P + \Delta R_{th}
\]  

(3)

La contribution du sol à l’alimentation en eau maximale de la culture est alors:

\[
\Delta R_{th} = ETP - (I + P)
\]  

(4)

La dose d’irrigation maximale est celle qui assure l’intégralité du besoin d’eau maximal de la culture:

\[
I_{max} = ETP - P
\]  

(5)

Dans ces conditions, on doit sensiblement vérifier que $\Delta R_{th} = 0$.

Si l’on réduit l’importance des irrigations, corrélativement la contribution théorique du sol augmente. Généralement, la culture ne peut cependant pas prélever dans le sol les quantités d’eau correspondantes; la contribution réelle du sol, $\Delta R$, est inférieure à la contribution
### TABLEAU I. TABLEAU SYNOPTIQUE DES CULTURES EXPERIMENTEEES

Centre d'étude de l'eau, Tunis

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<td>Coton (Pyma 67)</td>
<td>Blé (Florence X Aurore)</td>
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### TABLEAU II. CALCUL THEORIQUE DES DOSES D'IRRIGATION

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<tr>
<td>Contribution théorique du sol (mm/j)</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>(1+P)</td>
<td>(ETP)$_n$</td>
<td>(ETP)$_n$ - n</td>
<td>(ETP)$_n$ - 2n</td>
<td>(ETP)$_n$ - 4n</td>
<td>(ETP)$_n$ - 6n</td>
</tr>
</tbody>
</table>

*Note: cultures annuelles n = 7; cultures arbustives n = 14.*
théorique fixée et la consommation d'eau effective ou évapotranspiration réelle, ETR, reste inférieure à ETP.

\[ \text{ETR} = 1 + P + \Delta R \]  

(6)

Pour chacun des cinq traitements retenus, les doses d'irrigation, appliquées tous les 7 jours pour les cultures annuelles et tous les 14 jours pour les cultures arbustives, ont été ainsi calculées par référence à l'évapotranspiration potentielle mesurée depuis la dernière irrigation et en imposant au sol des contributions croissantes (tableau II).

2.2. Détermination du bilan d'eau

L'expression du bilan d'eau \( \text{ETR} = 1 + P + \Delta R \) a été appliquée à la détermination du champ de l'évapotranspiration réelle des cultures.

La dose d'irrigation \( I \) étant fixée par le protocole expérimental, \( I \) et \( P \) ont été exactement mesurées. Les variations de stock d'eau du sol \( \Delta R \) ont été déterminées, soit par la méthode gravimétrique, soit au moyen de la sonde à neutrons. Au cours de certaines expériences, les deux méthodes ont été appliquées simultanément [8].

Les courbes d'étalonnage de la sonde à neutrons (sonde CEA HP 110) de sols de composition minéralogique voisine, mais de densité apparente ou de equivalents en eau du sol sec différents, appartiennent toutes en première approximation à une famille de droites parallèles. Ainsi, pour une position déterminée de la sonde dans le milieu modérateur, une certaine variation \( \Delta N \) du taux de comptage correspond toujours, quelle que soit la courbe d'étalonnage et par conséquent quel que soit le milieu modérateur, à une même variation du taux d'humidité volumique \( \Delta N_v \). Même si la valeur exacte du taux d'humidité est indéterminée, la comparaison de deux mesures successives reste alors valable et utile pour l'établissement d'un bilan hydrique.

La sonde à neutrons réduit l'écart d'estimation sur les variations de stock d'eau du sol: pour quatre répétitions il était de l'ordre de 40 mm dans le cas des mesures gravimétriques; il n'est plus que de l'ordre de 10 mm au maximum avec la sonde à neutrons pour une tranche de sol explorée de 1,50 à 2,00 m de profondeur.

3. CONTRIBUTION DU SOL AU BILAN D'EAU ET RENDEMENT DES CULTURES

La réserve d'eau utile du sol (RU) est définie en première approximation par les paramètres hydriques du sol: capacité de rétention et point de flétrissement permanent, et par la profondeur utile. La limitation en profondeur du réservoir dépend, soit de la profondeur moyenne d'enracinement, qui est caractéristique de la culture mais aussi des techniques de l'irrigation, soit de facteurs pédologiques quand ceux-ci limitent la pénétration en profondeur du système radiculaire (encroûtement, nappe phréatique, ...).

En fait, la réserve facilement utilisable (RFU) varie entre des limites importantes. Hallaire [9] a montré que la RFU ne pouvait pas être déterminée a priori pour chaque sol, mais qu'elle était sous la
dépendance étroite de la dynamique d'exploitation des réserves; elle dépend en particulier du volume de sol exploité par les racines – profondeur et densité du système radical – et de la vitesse de dessèchement du sol dH/dt, qui fait intervenir des facteurs climatiques tels que ETP.

Cette aptitude plus ou moins grande à utiliser les réserves d'eau du sol se traduit, pour des apports d'eau (I+P) identiques, par une consommation d'eau plus ou moins élevée. Sur le même sol et sous le même climat, ces consommations d'eau différentes traduisent les aptitudes de chacune des cultures à utiliser les réserves d'eau du sol.

Les résultats obtenus sur différentes cultures sont résumés sur la figure 1. En abscisse, les apports d'eau sont définis en valeur relative par le rapport \( \frac{\text{ETP} - (I+P)}{\text{ETP}} \). La valeur de ce rapport est égale à 100 si I+P = 0 et à 0 si I+P = ETP. En ordonnée sont portées les consommations d'eau relatives, définies par le rapport ETR/ETP.

Si la contribution du sol à l'alimentation en eau de la culture est nulle, soit parce que les réserves d'eau du sol sont épuisées, soit parce que l'enracinement est superficiel, le rapport ETR/ETP suivra la droite ETR = I+P. Au contraire, si les réserves d'eau du sol sont bien reconstituées et si l'enracinement est suffisant, la courbe théorique est définie par la droite parallèle à l'axe des abscisses, ETR = ETP. Les courbes expérimentales se situent toutes entre ces deux valeurs extrêmes théoriques.

Ainsi pour une valeur donnée de (I+P) – 50% de ETP par exemple – la consommation d'eau réelle d'une culture d'orangers plantés à l'écartement de 4 × 4 m s'établit à 55% de ETP, la contribution du sol, ΔR,
représente seulement 5% de ETP, bien que dès 1,25 m, les réserves d'eau du sol à la veille d'une irrigation se situent à un niveau très voisin de la capacité de rétention. Au contraire, dans le cas du sorgho la contribution du sol est importante: pour une même valeur des apports (I + P = 50% ETP) la contribution du sol atteint près de 30% de ETP et le rapport ETR/ETP s'établit alors à près de 80%. Pour différentes cultures (maïs, luzerne, coton) la contribution du sol se situe à des valeurs intermédiaires.

![Figure 2](image)

**FIG. 2.** Influence de la réserve en eau du sol sur la contribution réelle du sol à l'alimentation en eau d'une culture de luzerne (Tunis, 1968).

En fait, les courbes obtenues représentent des valeurs moyennes prises sur l'ensemble de la période d'irrigation, du printemps à l'automne. Pour la luzerne en particulier, plante pérenne, le système radical est déjà bien établi en début de saison et la contribution du sol varie dans le temps au fur et à mesure que les réserves d'eau du sol s'épuisent (fig. 2). Pour une même valeur des apports d'eau - I + P = 50% de ETP - la contribution du sol, qui est de 40% pour la première coupe, diminue rapidement pour être nulle en fin de saison.

Ces résultats sont illustrés sur la figure 3 où les pourcentages de contribution du sol, horizon par horizon, sur les parcelles les moins irriguées ont été portés pour chaque culture. L'enracinement puissant du sorgho et de la luzerne exploite un volume de sol important, cependant que l'enracinement superficiel de l'oranger ne permet pas une exploitation des réserves d'eau du sol au-delà de 1 m pour des apports (I + P) qui ne représentent pourtant que 20% seulement de ETP.

Ces résultats permettent d'apporter des éléments de réponse au choix du régime des irrigations pour différentes cultures. Toutes les conditions de sol étant égales, une culture dont l'enracinement est dense et profond...
pourra se contenter de doses relativement élevées apportées à intervalles de temps espacés, cependant que le fractionnement des apports sera préférable dans le cas de cultures telles que l'oranger.

4. **ÉVAPOTRANSPIRATION POTENTIELLE ET RENDEMENT DES CULTURES**

L'expression générale de la photosynthèse [10] en fonction des différents paramètres — diffusion gazeuse du CO₂ ou réaction biochimique — est de la forme:

\[ -P^2(R_a + R_t + R_m) + (R_a + R_t + R_m + R_c) \sigma \text{EP} + CP - C\sigma E = 0 \]  

(7)

dans laquelle

- \( P \) = intensité de la photosynthèse par unité de surface de feuille
- \( E \) = énergie absorbée dans le visible (0,4 à 0,7 \( \mu \)m).
- \( C \) = concentration en gaz carbonique de l'air
- \( R_a \) = résistance à la diffusion du CO₂ dans l'air
- \( R_t \) = résistance à la diffusion du CO₂ à travers les stomates et la cuticule
- \( R_m \) = résistance à la diffusion du CO₂ à travers les tissus
- \( R_c \) = résistance à la carboxylation qui traduit l'ensemble des résistances de nature biochimique
- \( \sigma \) = rendement lumineux maximal, qui dépend entre autres de la composition spectrale de la lumière.

L'expression graphique de cette équation générale (fig. 4) en fonction de l'éclairement \( E \) fait apparaître des courbes dont le piblier correspond à la photosynthèse maximale et dont l'équation est

\[ P_{\text{max}} = \frac{C}{R_a + R_t + R_m + R_c} \]  

(8)
FIG. 4. Famille de courbes exprimant l'intensité de la photosynthèse en fonction de l'éclairement (trait fin) et effet dépresseur sur l'assimilation d'un éclairage énergétique déclenchant une régulation stomatique (trait gras) (d'après [10]).

FIG. 5. Influence de l'évapotranspiration potentielle et de l'évaporation réelle sur le rendement d'une culture de luzerne (Gabelle, 1961-1962).

--- Δ du 3.6 au 30.6.1961
--- ▽ du 30.6 au 29.7.1961
--- ▲ du 29.7 au 31.8.1961
--- ○ du 34.4 au 26.5.1962
--- + du 26.5 au 23.6.1962
--- * du 23.6 au 21.7.1962
--- ◦ du 21.7 au 18.8.1962
--- ▼ du 18.8 au 24.9.1962
--- □ du 24.9 au 20.10.1962.
Ainsi, la photosynthèse est une fonction décroissante de l'une quelconque des résistances $R_3$, $R_4$, $R_m$, ou $R_e$. Elle sera en particulier fonction décroissante de $R_4$ et $R_m$, respectivement résistances à la diffusion du CO$_2$ dans l'air et à travers les stomates. Ces résistances sont, aux coefficients de diffusion près, les mêmes que les résistances à la diffusion de la vapeur d'eau.

Par ailleurs, la circulation de l'eau du sol vers l'atmosphère résulte d'un équilibre entre la demande extérieure déterminée par l'évapotranspiration potentielle et le flux d'eau liquide dans le sol et dans la plante. Ce débit liquide est en particulier fonction de l'humidité du sol, du volume et de la densité des racines.

![Graphique](image.png)

**FIG. 6.** Influence de l'évapotranspiration potentielle et de l'évapotranspiration réelle sur le rendement d'une culture de sorgho (Auge grass) (Tunis, 1959).

Afin de prévenir un flétrissement de la plante, la régulation stomatique intervient alors pour ajuster la transpiration à la quantité d'eau puisée par la plante dans le sol. Le phénomène de régulation stomatique intervient non seulement quand le déficit d'eau du sol est appreciable, mais se manifeste également sur des plantes bien alimentées en eau quand l'évapotranspiration potentielle devient trop importante [11].

Par suite du parallélisme entre l'éclairage $E$ et le rayonnement solaire $R_g$ d'une part, et de ce dernier avec l'évapotranspiration potentielle $ETP$, les hautes valeurs de l'éclairage sont, dans les conditions naturelles, associées à des valeurs d'ETP élevées qui provoquent une augmentation de la résistance stomatique. Il apparaît ainsi un niveau d'éclairage optimal pour lequel la photosynthèse est maximale. Au-delà de cet optimum $ETP$, par suite du jeu de la régulation stomatique, devient un facteur limitant de la production de matière sèche.

La vérification expérimentale de cet effet dépressif de l'ETP a été mis en évidence globalement sur luzerne et sur sorgho (Auge grass) en analysant les rendements de coupes successives.
Sur les graphiques des figures 5 et 6, la production de matière sèche, exprimée en qx mat. sèche/ha-j, obtenue au cours de coupes successives de luzerne (fig. 5) et de sorgo (fig. 6), a été portée en fonction de la consommation d'eau, ETR, déterminée au champ par la méthode du bilan hydrique.

Les différentes courbes obtenues pour chacune des récoltes traduisent bien la relation de proportionnalité qui existe entre le rendement et la consommation d'eau, ETR, mais, fait plus remarquable, le rendement maximal obtenu quand ETR = ETP décroit quand les valeurs de l'évapotranspiration potentielle augmentent.

Dans le cas de la luzerne, le rendement maximal est réduit de moitié (1,2 à 0,6 qx mat. sèche/ha-j) quand l'ETP passe de 4 à 8 mm/j. Ce résultat fait ainsi apparaître en été une réduction dans le rapport de 1 à 4 de l'efficience de l'eau consommée par la luzerne.

Les résultats obtenus sur sorgo, bien qu'ils ne portent que sur deux coupes, sont tout à fait comparables (fig. 6).

Il est vraisemblable que la même expérience répétée sous des latitudes différentes conduirait à des résultats sensiblement différents car le critère d'intensité de l'ETP retenu ici était celui du ETP journalière qui peut en fait correspondre, pour une même valeur journalière, à des intensités maximales de l'évaporation potentielle assez différentes en fonction de la durée du jour.

Ainsi, l'efficience de l'eau est limitée par les valeurs de l'évapotranspiration potentielle instantanée, supérieures aux possibilités offertes par la culture.

L'accroissement de rendement obtenu par l'irrigation n'est pas une relation simple de la quantité d'eau consommée. Le rendement maximal serait atteint s'il était à chaque instant possible de faire coïncider le débit maximal que peut assurer le système sol-plante avec les exigences climatiques.

Parallèlement à l'irrigation, il sera donc souvent tout aussi profitable, soit de rechercher les moyens de réduire les valeurs trop élevées de l'ETP = brise-vent, culture associée =, soit d'augmenter le débit maximal que peut assurer le système sol-plante en réduisant les résistances à la circulation de l'eau du sol à l'atmosphère. Parmi les facteurs susceptibles de réduire ces résistances on peut citer:

- des caractéristiques morphologiques de la culture: surface foliaire, enracinement, densité de plantation, …
- des caractéristiques du sol: l'eau du sol effectivement disponible pour la plante dépend non seulement de l'énergie avec laquelle elle est retenue par celui-ci mais également de la vitesse de dessèchement, c'est-à-dire à la fois de la dimension du «réservoir» qui constitue le sol et de la «demande en eau» déterminée par le climat.

5. CONCLUSIONS

L'ensemble des résultats obtenus au cours de ces six années d'expérimentation a permis de vérifier qu'il existait bien des relations simples entre le rendement et la consommation d'eau des cultures, mais que cependant le rendement maximal obtenu était, au-delà d'un certain seuil de ETP, fonction inverse de l'intensité de ce facteur qui apparaît alors, au même titre que le déficit pluviométrique, comme un facteur limitant essentiel de la production végétale dans des régions arides.
Parallèlement à l'irrigation, un certain nombre d'hypothèses peuvent être émises et des techniques culturales proposées, pour accroître les potentialités de rendement des cultures.

Le déséquilibre observé au niveau d'échange feuille-atmosphère et dont la régulation stomatique est une des conséquences peut-être atténué par les moyens suivants:

Dans l'atmosphère, par une réduction de l'ETP au moyen des brise-vent, par l'utilisation des associations végétales dont l'oasis ne représente d'ailleurs qu'un cas particulier, par effet d'ombrage.

Le brise-vent peut en effet avoir une action favorable sur le rendement en réduisant les apports advectifs d'énergie. Toutefois, dans les régions arides on devra distinguer dans leurs conséquences sur l'action des brise-vent, les vents à caractère dynamique (type Mistral) ou thermique (type Sirocco).

La culture associée [12], dont l'oasis représente un type particulièremment perfectionné, doit finalement conduire à une amélioration de l'efficience de l'eau. Au niveau des étages herbacés, l'évapotranspiration potentielle locale est réduite, si bien que des cultures sensibles à un déséquilibre d'alimentation hydrique s'y trouvent placées dans des conditions d'évapotranspiration potentielle favorables. Dans le même sens, les recherches sur les cultures ombragées peuvent être justifiées.

Au niveau de la plante, en recherchant par une réduction des résistances à la circulation de l'eau du sol à l'atmosphère un accroissement du débit maximal de la culture.

Pour des conditions de sol et de climat identiques, l'aptitude des cultures à utiliser les réserves d'eau du sol est différente. Pour un volume d'eau déterminé le calcul des doses et des fréquences devra prendre en considération, non seulement les caractéristiques pédologiques et hydrodynamiques des sols, mais également la puissance de l'enracinement sur la densité du chevelu radiculaire qui détermine l'importance de la contribution des réserves du sol à l'alimentation en eau de la culture.

D'un point de vue pratique ces résultats expliquent les échecs souvent constatés en zone aride dans la recherche, par une irrigation intensive, de rendements élevés. Ils suggèrent également pour les régions à hivers doux de favoriser l'irrigation intensive au printemps et à l'automne, alors que l'efficience de l'eau est maximale. Partout où les quantités d'eau disponibles pour l'irrigation sont limitées, la productivité du mètre cube d'eau consommée pourrait ainsi être accrue.

REFERENCES


DISCUSSION

L.E. DANFORS: I feel that drainage D in Eq. (2) should be a negative term.

J.A. DAMAGNEZ: You are probably right, although the moisture of the deeper soil layers was always less than the field capacity, so that one had downward capillary diffusion in a non-saturated medium rather than upward movement (compare results obtained by De Boodt). However, the error is unlikely to affect the value of the results since the moisture gradient at the lower levels, beyond the zone tapped by the roots, was the same throughout our experiments and for all irrigation treatments.

L.E. DANFORS: Are you familiar with H.L. Penman's method of relating crop growth to adjusted potential transpiration $E_T(A)$ calculated as the sum of the $E_T$ that occurs during days when the soil moisture is above a critical minimum value? Linear relationships are obtained where the slope is found to be a function of the crop type and the soil type. Have you any comments on this method?

J.A. DAMAGNEZ: I do not think there is any contradiction between our results and those of Penman, which I believe correspond to the dotted curve in Fig. 5 of our paper and to relatively low ETP values, whereas our results relate to ETP values above a certain threshold that is exceeded only during exceptional days in the United Kingdom.
It is therefore likely that, for a given daily ETP reference value, the height of the threshold beyond which ETP becomes a limiting factor in the production of dry matter will vary directly with the length of the day. Strictly speaking, it is the rate of evaporation (mm h⁻¹) which should be considered, as can be seen from Fig. 1, where daily ETP in lower latitudes is represented by the curve λ₁ and that in higher latitudes by the curve λ₂.

M. DAGG: ETP is defined with respect to complete vegetative cover. Do the water-use data of the crops mentioned in Fig. 1 in the paper refer to full cover? Did the orange crop in particular cover the ground or was there an appreciable amount of bare soil between trees?

J. A. DAMAGNEZ: In these experiments the water-balance determinations were carried out when the vegetative cover was sufficient for complete vegetative cover to be assumed. The orange trees in particular were planted close together, at a distance of 4 X 4 m, so that we could assume complete vegetative cover. This can easily be verified by following the maximum water consumption by the crop from the time of planting to the first year of our experiments.
EVAPOTRANSPIRATION STUDIES ON MAIZE IN GIZA, UNITED ARAB REPUBLIC

A. ZEIN EL ABEDINE, M.M. ABDALLA AND Sh. I. ABDEL-AL
MIDDLE EASTERN REGIONAL RADIOISOTOPE CENTRE FOR THE ARAB COUNTRIES IN CO-OPERATION WITH THE IAEA, DOKKI, CAIRO, UNITED ARAB REPUBLIC

Presented by M. Dagg

Abstract

EVAPOTRANSPIRATION STUDIES ON MAIZE IN GIZA, UNITED ARAB REPUBLIC. Evapotranspiration studies of main crops are very important to the development of crop production in countries with limited water resources. Through these studies sound and efficient water-use policies can be planned so as to achieve the best use of water resources.

In this work, which was carried out in the Experimental Farm Station of the Cairo University, three methods of measuring evapotranspiration of maize were used: (1) Direct measurement through the daily weighing of hydraulic lysimeters; (2) Indirect, by measuring the moisture changes in the profiles with neutron-moisture meter; and (3) computing the potential evapotranspiration after Penman from climatological data.

Two levels of irrigation were used: (a) To irrigate to field capacity once 0.4 of the available moisture in the root zone is depleted, and (b) to irrigate to field capacity when 0.7 of the available moisture is depleted. One hydraulic lysimeter and five plots were used for each treatment. The results show that for the whole growing season the evapotranspiration from Penman agrees well with that obtained from the lysimeters.

But the Penman E.T. was higher at the beginning of the growing season, lower in the middle, and about the same at the end. The E.T. measured by the neutron-moisture meter also agreed well with the actual one. The neutron-meter measurements were 0.93 of the actual E.T. in both lysimeters. The data obtained from plots indicate that a considerable amount of water was used by the plants from the fringe of the water table.

The growth and yield of maize were affected by the two levels of irrigation; the greater depletion produced crops 13 to 19% less than that of the other treatment. Thus the Penman E.T. and moisture measurements by the neutron-moisture meter can be used after special corrections, at least under conditions similar to those of the experimental site.

INTRODUCTION

Studies on evapotranspiration of main crops are very important for the development of crop production in countries with limited water resources. Through these studies sound water-use policies could be planned so as to achieve the best use of water resources.

Several methods are used to determine water losses through evapotranspiration by crops. The main purpose of this study was to obtain evapotranspiration data under Egypt's climatic conditions so as to gain additional knowledge on an international scale concerning water-use efficiency.

* Delegated to the Centre from Soils Department, Faculty of Agriculture, Cairo University.
The evapotranspiration of maize is measured in the following ways:
(a) Directly through the daily weighing of hydraulic lysimeters;
(b) Indirectly through following the changes of moisture content in
the soil profile with a neutron-moisture meter;
(c) By computing the potential evapotranspiration after Penman.
It is hoped that these data will make it possible to estimate the actual
evapotranspiration by using neutron-moisture meters, or the potential
evapotranspiration after Penman once appropriate correction factors have
been applied.

EXPERIMENTAL AND RESULTS

1. Site, soil, and irrigation water

The experiment was carried out on the Experimental Farm Station
of the Faculty of Agriculture, Cairo University, Giza. This farm lies few
kilometres west of the Nile opposite Cairo, and has most of the soil types
of Middle Egypt.

The soil is clay loam from the surface down to 80 cm, with an under-
layer of loam passing to sandy loam at 200 cm. The topography is flat
and the soil is drained naturally. For most of the time during the experi-
ment the water table was about 2.8 m below the surface. During September
and October it rose to about 2.0 m from the surface. The mechanical
composition of the profile layers is presented in Table I.

The lysimeters were filled from the same soil as that of the experi-
mental field in the same layer order so as to resemble the experimental
plots.

2. Irrigation treatments

Two levels of irrigation treatments were used:
(1) The first treatment was irrigated when the depletion of moisture
in the root zone reached 0.4 of the available moisture calculated as:

\[(F.C. - W.P.) Z_r\]

where F.C. = field capacity by volume,
W.P. = wilting point by volume,
\(Z_r\) = depth of root zone in metres.

(2) The second treatment was irrigated when the depletion reached
0.7 of the available moisture in the root zone.

Each time irrigation water was given in sufficient amounts to raise the
moisture to the field capacity.

Both treatments received a pre-irrigation of 1.3 \((F.C. - M) Z\)

where \(M\) = average moisture in profile by volume,
\(Z\) = depth of profile in metres.

Thus, the first treatment received seven irrigation applications and
the second treatment received five. The amounts and dates of the irrigation
TABLE I. MECHANICAL COMPOSITION OF SOIL PROFILE
Per cent of dry weight

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Ca CO₃ (%)</th>
<th>%</th>
<th>Coarse sand</th>
<th>Fine sand</th>
<th>Silt</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 20</td>
<td>2.92</td>
<td>1.86</td>
<td>40.73</td>
<td>17.73</td>
<td>31.82</td>
<td>3.04</td>
</tr>
<tr>
<td>20 - 40</td>
<td>2.81</td>
<td>1.94</td>
<td>42.23</td>
<td>20.45</td>
<td>30.16</td>
<td>2.92</td>
</tr>
<tr>
<td>40 - 60</td>
<td>3.00</td>
<td>1.18</td>
<td>43.54</td>
<td>22.62</td>
<td>29.37</td>
<td>3.01</td>
</tr>
<tr>
<td>60 - 80</td>
<td>2.93</td>
<td>0.40</td>
<td>53.46</td>
<td>14.72</td>
<td>25.15</td>
<td>2.34</td>
</tr>
<tr>
<td>80 - 100</td>
<td>2.86</td>
<td>0.20</td>
<td>81.46</td>
<td>5.40</td>
<td>5.20</td>
<td>1.82</td>
</tr>
</tbody>
</table>

TABLE II. DATES, AMOUNTS, AND ELECTRICAL CONDUCTIVITY OF IRRIGATION WATER

<table>
<thead>
<tr>
<th>Treatment 1</th>
<th>Treatment 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>Water (mm)</td>
</tr>
<tr>
<td>24 July 1966</td>
<td>115</td>
</tr>
<tr>
<td>2 August</td>
<td>32</td>
</tr>
<tr>
<td>10</td>
<td>40</td>
</tr>
<tr>
<td>20</td>
<td>43</td>
</tr>
<tr>
<td>6 September</td>
<td>86</td>
</tr>
<tr>
<td>18</td>
<td>96</td>
</tr>
<tr>
<td>2 October</td>
<td>109</td>
</tr>
<tr>
<td>12</td>
<td>92</td>
</tr>
<tr>
<td>Total</td>
<td>613</td>
</tr>
</tbody>
</table>

The chemical analyses of the soil solution and those of the irrigation water are given in Table III.

Water are given in Table II, where the electrical conductivities of the water used also appear alongside the growing season.

Each treatment necessitated one weighable lysimeter surrounded by five plots of the same 2 x 2-m surface area receiving the same levels of water. The whole experiment was surrounded by a maize field of about one hectare.

The soil/water characteristics of all the layers of the profile representing the soil of the experiments are given in Table IV. The bulk
TABLE III. CHEMICAL ANALYSES OF SOIL SOLUTION AND IRRIGATION WATER (meq/1)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Total soluble salts (ppm)</th>
<th>Ca</th>
<th>Mg</th>
<th>Na</th>
<th>K</th>
<th>CO₃</th>
<th>HCO₃</th>
<th>SO₄</th>
<th>Cl</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil paste</td>
<td></td>
<td>0.14</td>
<td>0.65</td>
<td>0.38</td>
<td>0.04</td>
<td>0.00</td>
<td>0.24</td>
<td>0.01</td>
<td>0.39</td>
</tr>
<tr>
<td>Irrigation water</td>
<td></td>
<td>170</td>
<td>1.17</td>
<td>0.73</td>
<td>1.20</td>
<td>0.14</td>
<td>0.50</td>
<td>0.21</td>
<td>0.27</td>
</tr>
<tr>
<td>July 1966</td>
<td></td>
<td>157</td>
<td>1.38</td>
<td>0.74</td>
<td>0.64</td>
<td>0.10</td>
<td>2.16</td>
<td>0.25</td>
<td>0.25</td>
</tr>
</tbody>
</table>

TABLE IV. SOIL-WATER RELATIONS OF SOIL-PHILE LYSIMETERS AND PLOTS (wt. %)

<table>
<thead>
<tr>
<th>Moisture at:</th>
<th>Profile layers 0-20</th>
<th>20-40</th>
<th>40-60</th>
<th>60-80</th>
<th>80-100</th>
<th>100-140</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH 0.00</td>
<td>46.0</td>
<td>43.6</td>
<td>41.1</td>
<td>37.0</td>
<td>34.5</td>
<td>32.0</td>
</tr>
<tr>
<td>pH 2.00</td>
<td>33.2</td>
<td>30.7</td>
<td>29.4</td>
<td>26.5</td>
<td>24.5</td>
<td>22.8</td>
</tr>
<tr>
<td>pH 2.48</td>
<td>29.2</td>
<td>26.6</td>
<td>24.8</td>
<td>21.5</td>
<td>20.0</td>
<td>18.9</td>
</tr>
<tr>
<td>pH 2.70</td>
<td>24.8</td>
<td>21.5</td>
<td>18.4</td>
<td>16.5</td>
<td>14.5</td>
<td>13.5</td>
</tr>
<tr>
<td>pH 2.90</td>
<td>21.0</td>
<td>19.5</td>
<td>16.0</td>
<td>13.0</td>
<td>12.0</td>
<td>11.7</td>
</tr>
<tr>
<td>Determined field capacity</td>
<td>30.5</td>
<td>28.8</td>
<td>28.8</td>
<td>22.1</td>
<td>21.5</td>
<td>17.8</td>
</tr>
<tr>
<td>Determined wilting point</td>
<td>16.3</td>
<td>14.3</td>
<td>12.3</td>
<td>11.0</td>
<td>10.7</td>
<td>10.3</td>
</tr>
<tr>
<td>Wilting point vol. %</td>
<td>19.6</td>
<td>17.4</td>
<td>16.1</td>
<td>14.5</td>
<td>14.6</td>
<td>14.3</td>
</tr>
</tbody>
</table>

densities of the profile layers were determined by calibrated soil tubes at high and low moisture contents, and the data obtained appear in Table V.

3. Management

The soil of the entire experiment area was ploughed and prepared for for sowing maize during the last week of June 1966. Superphosphate of calcium and sulphate of potassium were applied before ploughing, at 40 and 50 kg/ha of \( P_2 O_5 \) and \( K_2 O \) respectively.

The first dressing of nitrogen was applied on 24 July, and the second on on 10 August in treatment 1, and on 8 August in treatment 2. The total nitrogen given as ammonium sulphate amounted to 100 kg/ha. The nitrogen side dressing was carried out at 15 cm to one side of the maize row at 6 cm deep. No trace elements were applied.
TABLE V. BULK DENSITIES OF PROFILE LAYERS AT HIGH AND LOW MOISTURE CONTENTS

<table>
<thead>
<tr>
<th>Layers (cm)</th>
<th>High moisture (%)</th>
<th>Low moisture (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Moisture (vol.%)</td>
<td>Moisture (wt.%)</td>
</tr>
<tr>
<td>0-20</td>
<td>23.8</td>
<td>22.4</td>
</tr>
<tr>
<td>20-40</td>
<td>21.4</td>
<td>18.9</td>
</tr>
<tr>
<td>40-60</td>
<td>18.9</td>
<td>15.9</td>
</tr>
<tr>
<td>60-80</td>
<td>20.5</td>
<td>15.9</td>
</tr>
<tr>
<td>80-100</td>
<td>23.0</td>
<td>17.4</td>
</tr>
<tr>
<td>100-140</td>
<td>25.4</td>
<td>18.8</td>
</tr>
</tbody>
</table>

4. Plants

The "early American" maize variety was used in the experiment. Planting took place on 24 July 1966, and the crop was harvested on 11 November. The number of plants harvested, weight of dry grain, moisture content of the grain, and the weight of fresh stalk at maturity are given in Table VI. The average heights of plants for lysimeters and plots throughout the growing season are given in Table VII. The emergence of seeds in plots and lysimeters took place four to five days after sowing and irrigation.

5. Evapotranspiration

The direct measurements of the actual evapotranspiration obtained from weighing the lysimeters are given in Table VIII.

The potential evapotranspiration after Penman was computed from the climatological data obtained from a screen 200 m from the site of the lysimeters and plots. Solar radiation, wind velocity, average temperature, and relative humidity were measured daily throughout the growing season from a height of 2 m above the land surface.

The data of the potential evapotranspiration are also given in Table VIII. The calibration of the neutron-moisture meter was carried out as follows:

(1) Four access tubes were inserted in four separate plots around the lysimeters, and the plots were equally pre-irrigated.

(2) Samples were taken from one plot by calibrated soil tubes in replicates when the moisture reached the field capacity. Samples were taken from each 20-cm profile layer. The readings of the neutron meter were recorded. The samples were dried to constant weights, the moistures determined by weight and volume, and the bulk densities were calculated.
<table>
<thead>
<tr>
<th>Treatments and plots</th>
<th>Replicate</th>
<th>Stalk (kg/plot)</th>
<th>No. of plants/plot</th>
<th>Weight of dry grain (kg)</th>
<th>Moisture in fresh grain (%)</th>
<th>Yield (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lysimeter 1</td>
<td></td>
<td>2.60</td>
<td>23</td>
<td>1.72</td>
<td>19.8</td>
<td>4.30</td>
</tr>
<tr>
<td>1 plot</td>
<td>1</td>
<td>2.66</td>
<td>19</td>
<td>1.62</td>
<td>22.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.43</td>
<td>17</td>
<td>1.40</td>
<td>18.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2.76</td>
<td>20</td>
<td>1.75</td>
<td>19.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2.68</td>
<td>22</td>
<td>1.80</td>
<td>20.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>2.45</td>
<td>22</td>
<td>1.31</td>
<td>17.9</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>2.66</td>
<td>20.0</td>
<td>1.56</td>
<td>19.7</td>
<td>3.89</td>
</tr>
<tr>
<td>Lysimeter 2</td>
<td></td>
<td>2.56</td>
<td>22</td>
<td>1.45</td>
<td>17.4</td>
<td>3.88</td>
</tr>
<tr>
<td>2 plots</td>
<td>1</td>
<td>1.84</td>
<td>19</td>
<td>1.00</td>
<td>17.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.54</td>
<td>19</td>
<td>1.50</td>
<td>18.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2.40</td>
<td>17</td>
<td>1.32</td>
<td>18.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2.75</td>
<td>19</td>
<td>1.57</td>
<td>19.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>2.65</td>
<td>19</td>
<td>1.50</td>
<td>17.4</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>2.54</td>
<td>18.6</td>
<td>1.54</td>
<td>18.1</td>
<td>3.25</td>
</tr>
<tr>
<td>Field</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.25</td>
</tr>
</tbody>
</table>
(3) As described above, periodic samples were taken from the plots for four weeks.

By this method the curves showing the relations between soil moisture and neutron-moisture-meter readings could be taken for the different profile layers (see Fig. 1).

Tables IX and X contain the periodic moisture readings by the neutron-moisture meter in the two lysimeters and the two irrigation treatments. The data are given as averages of profiles.

The evapotranspiration from the lysimeters and plots was also calculated from the data of moisture contents determined by the neutron-moisture meter. The obtained results are stated in Table XI.

### TABLE VII. ELONGATION OF MAIZE PLANTS UNDER THE TWO TREATMENTS

<table>
<thead>
<tr>
<th>Date 1966</th>
<th>Treatment 1</th>
<th>Treatment 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lysimeter (cm)</td>
<td>Plot (cm)</td>
</tr>
<tr>
<td>31-7</td>
<td>11.0</td>
<td>10.5</td>
</tr>
<tr>
<td>8-4</td>
<td>20.0</td>
<td>19.0</td>
</tr>
<tr>
<td>8-8</td>
<td>29.5</td>
<td>28.0</td>
</tr>
<tr>
<td>14-8</td>
<td>49.5</td>
<td>47.0</td>
</tr>
<tr>
<td>20-8</td>
<td>75.0</td>
<td>72.5</td>
</tr>
<tr>
<td>22-8</td>
<td>86.0</td>
<td>84.0</td>
</tr>
<tr>
<td>26-8</td>
<td>110.0</td>
<td>105.0</td>
</tr>
<tr>
<td>29-8</td>
<td>128.5</td>
<td>122.5</td>
</tr>
<tr>
<td>31-8</td>
<td>144.0</td>
<td>136.0</td>
</tr>
<tr>
<td>5-9</td>
<td>177.0</td>
<td>170.0</td>
</tr>
<tr>
<td>8-9</td>
<td>200.0</td>
<td>191.5</td>
</tr>
<tr>
<td>10-9</td>
<td>217.0</td>
<td>208.5</td>
</tr>
<tr>
<td>13-9</td>
<td>240.0</td>
<td>228.0</td>
</tr>
<tr>
<td>15-9</td>
<td>248.0</td>
<td>236.0</td>
</tr>
<tr>
<td>20-9</td>
<td>257.0</td>
<td>248.0</td>
</tr>
<tr>
<td>22-9</td>
<td>259.0</td>
<td>249.0</td>
</tr>
<tr>
<td>24-9</td>
<td>265.0</td>
<td>249.5</td>
</tr>
<tr>
<td>30-9</td>
<td>260.5</td>
<td>250.0</td>
</tr>
</tbody>
</table>
### TABLE VIII. EVAPOTRANSPIRATION FROM LYSIMETERS AND THAT CALCULATED FROM PENMAN (5-day average in mm)

<table>
<thead>
<tr>
<th></th>
<th>1966 From</th>
<th>1966 to</th>
<th>P. E. T. (^{\circ}) Penman</th>
<th>Lysimeter 1</th>
<th>Lysimeter 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>July</td>
<td>24 July</td>
<td>28</td>
<td>6.63</td>
<td>4.00</td>
<td>4.20</td>
</tr>
<tr>
<td>July</td>
<td>29 August</td>
<td>2</td>
<td>6.99</td>
<td>3.92</td>
<td>3.68</td>
</tr>
<tr>
<td>August</td>
<td>3</td>
<td>7</td>
<td>6.63</td>
<td>4.76</td>
<td>4.50</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>12</td>
<td>6.64</td>
<td>5.12</td>
<td>4.32</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>17</td>
<td>6.11</td>
<td>4.76</td>
<td>4.16</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>22</td>
<td>6.18</td>
<td>5.10</td>
<td>4.90</td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>27</td>
<td>6.34</td>
<td>5.64</td>
<td>5.76</td>
</tr>
<tr>
<td>August</td>
<td>28 September</td>
<td>1</td>
<td>6.21</td>
<td>5.68</td>
<td>5.44</td>
</tr>
<tr>
<td>September</td>
<td>2</td>
<td>6</td>
<td>6.05</td>
<td>5.44</td>
<td>5.28</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>11</td>
<td>6.02</td>
<td>7.08</td>
<td>6.24</td>
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<td>12</td>
<td>16</td>
<td>5.42</td>
<td>7.92</td>
<td>7.98</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>21</td>
<td>5.42</td>
<td>8.04</td>
<td>7.44</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>26</td>
<td>6.09</td>
<td>8.60</td>
<td>8.00</td>
</tr>
<tr>
<td>September</td>
<td>27</td>
<td>October</td>
<td>1</td>
<td>4.77</td>
<td>7.92</td>
</tr>
<tr>
<td>October</td>
<td>2</td>
<td>6</td>
<td>5.73</td>
<td>9.24</td>
<td>9.02</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>11</td>
<td>4.72</td>
<td>8.24</td>
<td>7.74</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>16</td>
<td>4.48</td>
<td>7.44</td>
<td>6.80</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>21</td>
<td>4.34</td>
<td>5.60</td>
<td>5.40</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>26</td>
<td>4.03</td>
<td>5.32</td>
<td>5.44</td>
</tr>
<tr>
<td></td>
<td>27</td>
<td>31</td>
<td>4.00</td>
<td>5.06</td>
<td>4.48</td>
</tr>
<tr>
<td>November</td>
<td>1</td>
<td>5</td>
<td>4.13</td>
<td>3.36</td>
<td>2.34</td>
</tr>
</tbody>
</table>

Total E. T. (mm) 583.9 642.2 601.2

\(^{\circ}\) P. E. T. = Potential evapotranspiration

### DISCUSSION

#### 1. Evapotranspiration

A summary of the results showed that the total evapotranspiration for maize throughout the growing season amounted to 641.2 mm in treatment 1 in which the plants were not subjected to considerable moisture stresses, while it amounted to 601.2 mm in treatment 2 in which the plants
were subjected to considerable stresses. These results were obtained from directly weighing the lysimeters.

At the same time it was found that, for the same period, the potential evapotranspiration calculated after Penman amounted to 583.9 mm (see Table VIII).

At first glance the agreement is quite satisfactory between the direct determination through weighing the lysimeters, and the indirect one by Penman. However, the actual evapotranspiration (E.T.) starts much lower than the potential one for about five weeks at the beginning of the growing season, then they become almost equal during the last week of August and the first one of September, after which the actual E.T. surpasses the potential one throughout, from about 8 September until about 28 October. The peak of the actual E.T. is reached in both treatments between 15 September and 8 October. During the last week of the season the actual E.T. is slightly lower than the potential one.

The E.T. data of both treatments and those of the potential one, calculated for each 5-d interval to minimize the daily fluctuations, are presented in Fig.2.

The deviations of the actual E.T. from the potential one are partly due to the fact that, during the first five weeks the plants do not contribute
**TABLE IX. IRRIGATION TREATMENT 1**
Average moisture contents by vol.% in lysimeter and plot from surface to 140 cm deep

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-irrigation</td>
<td>21.9</td>
<td>25.1</td>
<td>10-9</td>
<td>28.1</td>
<td>29.3</td>
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<tr>
<td>Field capacity</td>
<td>29.8</td>
<td>31.1</td>
<td>13-9</td>
<td>27.3</td>
<td>27.8</td>
</tr>
<tr>
<td>Irrigation: 24-7</td>
<td></td>
<td></td>
<td>16-9</td>
<td>25.6</td>
<td>27.3</td>
</tr>
<tr>
<td>26-7</td>
<td>29.5</td>
<td>30.1</td>
<td>17-9</td>
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</tr>
<tr>
<td>29-7</td>
<td>27.9</td>
<td>29.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>31-7</td>
<td>26.2</td>
<td>29.4</td>
<td>20-9</td>
<td>23.3</td>
<td>29.6</td>
</tr>
<tr>
<td>1-8</td>
<td>26.1</td>
<td>27.5</td>
<td>22-9</td>
<td>26.0</td>
<td>26.7</td>
</tr>
<tr>
<td>Irrig. 2-8</td>
<td></td>
<td></td>
<td>25-9</td>
<td>27.7</td>
<td>27.0</td>
</tr>
<tr>
<td>4-8</td>
<td>28.1</td>
<td>29.9</td>
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<td>25.6</td>
</tr>
<tr>
<td>8-8</td>
<td>27.1</td>
<td>28.3</td>
<td>Irrig. 2-10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10-8</td>
<td>27.1</td>
<td>27.6</td>
<td>3-10</td>
<td>29.5</td>
<td>29.5</td>
</tr>
<tr>
<td>Irrig. 10-8</td>
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<td>5-10</td>
<td>28.0</td>
<td>28.9</td>
</tr>
<tr>
<td>11-8</td>
<td>29.3</td>
<td>30.0</td>
<td>8-10</td>
<td>26.8</td>
<td>27.8</td>
</tr>
<tr>
<td>14-8</td>
<td>27.7</td>
<td>28.9</td>
<td>11-10</td>
<td>24.9</td>
<td>26.5</td>
</tr>
<tr>
<td>17-8</td>
<td>26.6</td>
<td>27.9</td>
<td>Irrig. 12-10</td>
<td>25.0</td>
<td>25.9</td>
</tr>
<tr>
<td>20-8</td>
<td>25.2</td>
<td>26.5</td>
<td>12-10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Irrig. 21-8</td>
<td></td>
<td></td>
<td>14-10</td>
<td>29.1</td>
<td>29.8</td>
</tr>
<tr>
<td>24-8</td>
<td>29.2</td>
<td>30.0</td>
<td>17-10</td>
<td>28.0</td>
<td>28.5</td>
</tr>
<tr>
<td>26-8</td>
<td>28.6</td>
<td>28.9</td>
<td>21-10</td>
<td>24.7</td>
<td>27.6</td>
</tr>
<tr>
<td>29-8</td>
<td>27.4</td>
<td>28.5</td>
<td>22-10</td>
<td>24.1</td>
<td>26.4</td>
</tr>
<tr>
<td>31-8</td>
<td>26.6</td>
<td>28.4</td>
<td>25-10</td>
<td>23.1</td>
<td>26.0</td>
</tr>
<tr>
<td>3-9</td>
<td>25.6</td>
<td>28.0</td>
<td>29-10</td>
<td>21.4</td>
<td>24.4</td>
</tr>
<tr>
<td>5-9</td>
<td>24.2</td>
<td>--</td>
<td>3-11</td>
<td>20.4</td>
<td>23.2</td>
</tr>
<tr>
<td>Irrig. 6-9</td>
<td></td>
<td></td>
<td>3-11</td>
<td>20.3</td>
<td>22.8</td>
</tr>
<tr>
<td>8-9</td>
<td>29.5</td>
<td>29.7</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

much to the moisture losses, and the main losses are from the soil surface.

When the moisture of the top surface of a soil free from plants is reduced by evaporation and the upward capillary movement slows down and finally almost stops under the increasing water-film tension, the moisture of the underlying layers is mostly lost through diffusion and
### TABLE X. IRRIGATION TREATMENT 2

Average moisture contents by vol. % in lysimeter 2 and plot from surface to 140 cm deep, determined by neutron-moisture meter

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-irrigation</td>
<td>22.1</td>
<td>24.6</td>
<td>23-9</td>
<td>28.0</td>
<td>28.8</td>
</tr>
<tr>
<td>Field capacity</td>
<td>29.6</td>
<td>31.1</td>
<td>15-9</td>
<td>27.2</td>
<td>28.3</td>
</tr>
<tr>
<td>Irrigation: pre-6</td>
<td></td>
<td></td>
<td>17-9</td>
<td>24.4</td>
<td>27.6</td>
</tr>
<tr>
<td>26-7</td>
<td>26.9</td>
<td>29.7</td>
<td>26-9</td>
<td>23.1</td>
<td>27.7</td>
</tr>
<tr>
<td>29-7</td>
<td>26.9</td>
<td>25.5</td>
<td>22-9</td>
<td>21.1</td>
<td>26.9</td>
</tr>
<tr>
<td>31-7</td>
<td>25.6</td>
<td>29.0</td>
<td>25-9</td>
<td>20.9</td>
<td>26.3</td>
</tr>
<tr>
<td>1-8</td>
<td>23.2</td>
<td>--</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4-8</td>
<td>24.1</td>
<td>27.3</td>
<td>29-9</td>
<td>27.2</td>
<td>29.2</td>
</tr>
<tr>
<td>8-8</td>
<td>22.6</td>
<td>26.2</td>
<td>1-10</td>
<td>25.9</td>
<td>28.9</td>
</tr>
<tr>
<td>Irrig. 8-8</td>
<td></td>
<td>3-10</td>
<td></td>
<td>23.8</td>
<td>27.2</td>
</tr>
<tr>
<td>10-8</td>
<td>23.2</td>
<td>29.8</td>
<td>5-10</td>
<td>23.9</td>
<td>27.5</td>
</tr>
<tr>
<td>14-8</td>
<td>26.9</td>
<td>27.3</td>
<td>8-10</td>
<td>21.9</td>
<td>26.0</td>
</tr>
<tr>
<td>16-8</td>
<td>26.2</td>
<td>27.4</td>
<td>11-10</td>
<td>20.9</td>
<td>24.8</td>
</tr>
<tr>
<td>20-8</td>
<td>25.2</td>
<td>25.9</td>
<td>Irrig. 12-10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Irrig. 21-8</td>
<td></td>
<td>14-10</td>
<td>29.1</td>
<td>29.9</td>
<td></td>
</tr>
<tr>
<td>24-8</td>
<td>23.1</td>
<td>29.7</td>
<td>17-10</td>
<td>27.9</td>
<td>28.6</td>
</tr>
<tr>
<td>26-8</td>
<td>26.3</td>
<td>28.8</td>
<td>21-10</td>
<td>24.5</td>
<td>27.5</td>
</tr>
<tr>
<td>29-8</td>
<td>27.3</td>
<td>26.7</td>
<td>22-10</td>
<td>21.2</td>
<td>27.5</td>
</tr>
<tr>
<td>31-8</td>
<td>26.2</td>
<td>28.3</td>
<td>25-10</td>
<td>21.1</td>
<td>26.2</td>
</tr>
<tr>
<td>3-9</td>
<td>25.0</td>
<td>27.3</td>
<td>29-10</td>
<td>20.6</td>
<td>28.3</td>
</tr>
<tr>
<td>5-9</td>
<td>23.9</td>
<td>27.1</td>
<td>3-11</td>
<td>20.1</td>
<td>23.7</td>
</tr>
<tr>
<td>8-9</td>
<td>23.8</td>
<td>25.7</td>
<td>5-11</td>
<td>19.5</td>
<td>23.1</td>
</tr>
<tr>
<td>Irrig. 8-9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10-9</td>
<td>20.1</td>
<td>29.9</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Bulk air movement in the soil. Both factors are slower than the conditions assumed in Penman's equation. In fact the dry top layer becomes increasingly resistant to evaporation as the depletion of moisture increases.

This can be seen from the data in Table XII, which shows the moisture contents during an August irrigation cycle, in the top 20-cm layers of the lysimeters and plots under both treatments, as well as the average losses of moisture per day from these top layers.
<table>
<thead>
<tr>
<th>Treatment 1</th>
<th>Treatment 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dates (1890)</td>
<td>Dates (1890)</td>
</tr>
<tr>
<td>Root zone (cm)</td>
<td>Root zone (cm)</td>
</tr>
<tr>
<td>E.T.</td>
<td>E.T.</td>
</tr>
<tr>
<td>98-7 to 3-8</td>
<td>40</td>
</tr>
<tr>
<td>2-8 to 10-8</td>
<td>60</td>
</tr>
<tr>
<td>21-8 to 31-8</td>
<td>90</td>
</tr>
<tr>
<td>5-9 to 10-9</td>
<td>120</td>
</tr>
<tr>
<td>11-11 to 12-10</td>
<td>140</td>
</tr>
<tr>
<td>12-10 to 3-11</td>
<td>160</td>
</tr>
<tr>
<td>Total</td>
<td>595.6</td>
</tr>
<tr>
<td>E.T.</td>
<td>464.2</td>
</tr>
</tbody>
</table>

Zain El Abedine et al.
TABLE XII. MOISTURE CONTENTS DURING AUGUST IRRIGATION CYCLE IN TOP 20-cm LAYERS OF LYSIMETERS AND PLOTS IN BOTH TREATMENTS

<table>
<thead>
<tr>
<th>Dates (1966)</th>
<th>Treatment 1</th>
<th>Treatment 2</th>
<th>Loss/d (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lys.</td>
<td>Plot</td>
<td>Lys.</td>
</tr>
<tr>
<td>Irrigation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21-8</td>
<td>30.5</td>
<td>34.5</td>
<td>30.5</td>
</tr>
<tr>
<td>24-8</td>
<td>29.1</td>
<td>29.9</td>
<td>29.0</td>
</tr>
<tr>
<td>26-8</td>
<td>28.6</td>
<td>27.7</td>
<td>28.6</td>
</tr>
<tr>
<td>29-8</td>
<td>25.2</td>
<td>27.1</td>
<td>25.2</td>
</tr>
</tbody>
</table>

This was also found by Zein el Abedine et al. [1, 2] in earlier studies on cyclic moisture changes in the same site. In addition, at the peak-phase of the crop growth, the actual E. T. must be greater than the potential one because of the wide surfaces of the plant leaves exposed to the hot and dry atmosphere.

The last week's deviation was undoubtedly because the plants stopped or at least greatly reduced their biological activities, and the soil moisture itself, at least the top layers, approached the hygroscopic limits.

In our opinion, the absorption coefficient 'α' should be correct in calculating the net radiation Rn from the solar radiation Rg in the equation used:

\[ R_n = a R_g - c T_a^4 (0.47 - 0.065 e_a) \]
where

\[ a = \begin{cases} 0.70 & \text{for dry soil, } 0.85 & \text{for wet soil, and } 0.75 & \text{for vegetation,} \\
\sigma T_a^4 & \text{black-body radiation at air temperature in cal cm}^{-2} \text{ min}^{-1} \\
e_a & \text{vapour pressure in the air in mb.}
\end{cases} \]

It seems that, owing to the very quick drying of the top surface layer under the sub-tropic arid conditions of Egypt, the coefficient "a" should be reduced for soil and augmented for vegetation according to its stage of growth and cover.

But these corrections will not be needed if the E.T. studies are only concerned with the whole growth period of the maize crop. It should also

**TABLE XIII. ACTUAL, POTENTIAL, AND CALCULATED E.T. IN THE TWO IRRIGATION TREATMENTS (mm)**

<table>
<thead>
<tr>
<th>Irrigation cycles from (1966) to</th>
<th>Actual</th>
<th>Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lysimeter</td>
<td>Plot</td>
</tr>
<tr>
<td>24- 7 2- 8</td>
<td>29.6</td>
<td>34.4</td>
</tr>
<tr>
<td>2- 8 10- 8</td>
<td>36.6</td>
<td>40.8</td>
</tr>
<tr>
<td>10- 8 21- 8</td>
<td>55.6</td>
<td>57.6</td>
</tr>
<tr>
<td>21- 8 5- 9</td>
<td>84.9</td>
<td>76.6</td>
</tr>
<tr>
<td>5- 9 18- 9</td>
<td>98.6</td>
<td>89.2</td>
</tr>
<tr>
<td>18- 9 2-10</td>
<td>114.8</td>
<td>72.8</td>
</tr>
<tr>
<td>2-10 12-10</td>
<td>86.4</td>
<td>82.6</td>
</tr>
<tr>
<td>12-10 5-11</td>
<td>125.6</td>
<td>147.3</td>
</tr>
<tr>
<td><strong>Total of treatment 1</strong></td>
<td><strong>641.2</strong></td>
<td><strong>592.3</strong></td>
</tr>
<tr>
<td>24- 7 8- 8</td>
<td>65.0</td>
<td>55.6</td>
</tr>
<tr>
<td>8- 8 21- 8</td>
<td>57.2</td>
<td>50.6</td>
</tr>
<tr>
<td>21- 8 8- 9</td>
<td>100.0</td>
<td>75.2</td>
</tr>
<tr>
<td>8- 9 26- 9</td>
<td>135.3</td>
<td>119.6</td>
</tr>
<tr>
<td>26- 9 12-10</td>
<td>123.1</td>
<td>115.2</td>
</tr>
<tr>
<td>12-10 5-11</td>
<td>113.6</td>
<td>141.4</td>
</tr>
<tr>
<td><strong>Total of treatment 2</strong></td>
<td><strong>601.2</strong></td>
<td><strong>558.6</strong></td>
</tr>
</tbody>
</table>
TABLE XIV. AVERAGE MOISTURE CONTENTS (M) AT END OF THREE IRRIGATION CYCLES AND AT FIELD CAPACITY (F.C.) DURING SEPTEMBER AND OCTOBER IN LYSIMETERS AND PLOTS IN THE TWO TREATMENTS (vol. %)

<table>
<thead>
<tr>
<th>Depth of layer (cm)</th>
<th>Treatment 1</th>
<th>Treatment 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lysimeter</td>
<td>Plot</td>
</tr>
<tr>
<td></td>
<td>F.C.</td>
<td>M.</td>
</tr>
<tr>
<td>0-20</td>
<td>30.5</td>
<td>19.6</td>
</tr>
<tr>
<td>20-40</td>
<td>34.0</td>
<td>25.1</td>
</tr>
<tr>
<td>40-60</td>
<td>34.0</td>
<td>25.2</td>
</tr>
<tr>
<td>60-80</td>
<td>28.2</td>
<td>24.0</td>
</tr>
<tr>
<td>80-100</td>
<td>27.2</td>
<td>25.2</td>
</tr>
<tr>
<td>100-120</td>
<td>27.6</td>
<td>26.6</td>
</tr>
<tr>
<td>120-140</td>
<td>26.4</td>
<td>26.4</td>
</tr>
</tbody>
</table>

Be noted that, with each irrigation application, the E.T. generally increases, and decreases towards the end of the irrigation cycles.

Another point is clear – with high peaks of potential E.T. there are peaks in the actual E.T. in both treatments. The E.T. data calculated from the readings of the neutron-moisture meter are considerably lower than the actual and the potential E.T. (see Table XI).

For treatment 1 the total E.T. is 592.5 mm, and 558.6 mm for treatment 2 in the lysimeters.

In comparison with actual E.T., Table XIII gives water losses in each irrigation cycle of the two treatments. The table also contains the E.T. data obtained from the corresponding plots 1 and 2, and the potential E.T. calculated from Penman.

The data in Table XIII provide some noteworthy points:

(a) The calculated E.T. values are between 0.922 and 0.923 of the actual values obtained by weighing the lysimeters. Thus a factor of 0.92 may be used for correcting the values of the moisture determined by the neutron moisture meter.

(b) In the plots, the fringe of the water table disturbs the calculation, and the obtained E.T. values are appreciably lower than the actual ones, even if the factor 0.92 is used to correct the figures obtained from the neutron moisture meter. After correction the E.T. would be 571 mm and 491 mm for treatments 1 and 2 respectively.

(c) To study this situation, the average moisture contents at the end of three irrigation cycles in September and October, when the water table rose to its maximum, were calculated from the data of the two irrigation treatments to be compared with averages of the same cycles in the lysimeters. These averages and the moisture contents at the field capacities are presented in Table XIV and illustrated in Fig. 3.
TABLE XV. APPROXIMATE pF VALUES IN LYSIMETERS AND PLOTS AT THE END OF AN IRRIGATION CYCLE IN SEPTEMBER

<table>
<thead>
<tr>
<th>Depth of layer (cm)</th>
<th>Treatment 1 cycle end 17/9/66</th>
<th>Treatment 2 cycle end 11/9/66</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lysimeter</td>
<td>Plot</td>
</tr>
<tr>
<td>0-20</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>20-40</td>
<td>2.9</td>
<td>2.5</td>
</tr>
<tr>
<td>40-60</td>
<td>2.6</td>
<td>2.4</td>
</tr>
<tr>
<td>60-80</td>
<td>2.6</td>
<td>2.5</td>
</tr>
<tr>
<td>80-100</td>
<td>2.4</td>
<td>2.3</td>
</tr>
<tr>
<td>100-120</td>
<td>2.3</td>
<td>2.3</td>
</tr>
<tr>
<td>120-140</td>
<td>2.3</td>
<td>2.3</td>
</tr>
</tbody>
</table>

These curves show that the moisture depletion from the lysimeters is greater than that from the plots.

(d) For further study of this point, and by using the characteristic moisture tension curves drawn from Table IV and the bulk densities in
Table V, the approximate pF values in the profile layers were estimated at the end of an irrigation cycle in September. The figures are stated in Table XV and graphically presented in Fig. 4.

The irrigation curves of treatment 1 show that, at layers below 100 cm, the tension is the lowest and is about the same in lysimeter and plot, but from 100 cm upwards the tension in the plots increases but maintains an appreciably lower pF than in the lysimeter. This distribution of tension most probably means a rise of capillary water from the tension zone below 100 cm owing to the tension flux.

On the other hand, the curves of irrigation treatment 2 show greater tension in the lysimeter than in the plot throughout the profile depth. In the plot, the tension was still as low as pF 2.3 below 80 cm, and it increased markedly on approaching the surface. This also means a greater possibility of a capillary rise of the water from the lower tension zone towards the upper layers. Thus, in both irrigation treatments there are possibilities of capillary supply from the almost saturated zone of the water-table fringe.

On one hand, this supply, cannot be directly measured, and on the other it screens the actual moisture depletion measured by the neutron-moisture meter. But indirectly, if the total E.T. measured from the plots is corrected by the factor 0.92, then the amounts presumably supplied by the water table in irrigation treatment 1 would be:

\[641 - 571 = 70 \text{ mm},\]
and in irrigation treatment-2:

\[ 601 - 491 = 110 \text{ mm}, \]

i.e. 9% of the E.T. may be supplied by the water table in irrigation treatment 1, and about 18% is supplied in treatment 2, which was exposed to considerable stresses during the season.

The moisture changes in the lysimeters' profiles are graphically presented in Fig. 5, for the two irrigation treatments as measured by the neutron-moisture meter. With the exception of the first irrigation cycle, in which the moisture depletion was rather greater than that intended in the experiment, the moisture depletion quantitatively increased owing to the increasing depth of root zone. The limit intended for the depletion was 5.6% below field capacity, i.e. 24% moisture content in the profile average in irrigation treatment 1, and 9.8% below field capacity, i.e. down to 20% in the profile average in treatment 2.

![Fig. 5. Soil-moisture changes in the lysimeters under the two treatments.](image)

In Fig. 6 the E.T. values obtained from the direct weighing of the lysimeters under the two irrigation treatments are plotted against the corresponding calculated values obtained by the neutron-moisture meter from plots and lysimeters.

2. Growth of maize

It should be stated that the data for sowing maize in the experiment was some four weeks later than normal in the area. This delay was unavoidable because of the final preparation of the lysimeters. The delay affected the yield of both the experiment and the surrounding field, because of the sensitivity of the variety used up to the sowing date. Anyway the experiment had to be continued, as the comparison would be made within the results obtained under the same climatological conditions.
The soil-moisture conditions after the pre-irrigation was the same in both the plots and lysimeters. Thus, there was no difference in the germination time.

The results of the plants' elongation are graphically presented in Fig. 7. The curves show marked differences between the two treatments as the final length of the plants in lysimeter 1 and the plots of treatment 1 were 260.5 cm and 250.0 cm respectively. In treatment 2 the lysimeter plants had an average final length of 226.5 cm, and the plot plants an average of 209.0 cm.

It is quite clear that the moisture stresses to which the plants of treatment 2 were subjected caused the restricted growth in both the lysimeter and the plot.

The differences between the lysimeter plants and the plot plants are undoubtedly due to the soil packing in the lysimeters, which was looser than in the natural soil. The loose packing allowed for better aeration in the root zone and better air/water balance, which favours maize growth.

The curves of treatment 2 show a marked slowing down of growth towards the end of the irrigation cycles. Three of these cases are clear: one at the end of the first cycle, where the slowing down resulted in a difference of few centimetres less than treatment 1; another instance at the end of the second cycle, which resulted in a difference of between 39 and 31 cm less than treatment 1; and, finally, at the end of the third cycle, causing a reduction in length of between 90 and 44 cm less than treatment 1. This temporary effect due to the increasing moisture stresses were not observed in treatment 1.
3. Yield of crop and water-use efficiency

The highest yield of 4.30 t/ha was obtained from the lysimeter of treatment 1, where the plots' average yield was 3.89 t/ha, i.e. the lysimeter yield was 10.5% more than the plots of the same treatment.
In treatment 2, the lysimeter yield was 3.63 t/ha, and the average plot yield 3.45 t/ha, i.e. the lysimeter produced 5.2% more than the plots.

Treatment 1 yield of lysimeter is 18.4% more than the lysimeter of treatment 2. Also, the plot yield of the former treatment is 12.8% more than that of the latter.

From Table VI it is clear that the weight of stalk decreases to the same extent as the grain yield. It is also observed that the moisture in grain is slightly higher in treatment 1 than in treatment 2, the former containing 19.8 - 19.7% moisture, while the latter contains 17.4 - 18.1%.

The crop yield, the weight of stalk, and the final length of the plants are positively correlated, as seen from Fig. 8.

To judge the water-use efficiencies in this experiment the amounts of water in kilograms used to produce 1 kg of grain from each treatment are calculated below:

\[
\begin{align*}
\text{Irrigation treatment 1} & \quad \begin{cases}
\text{lysimeter} & 1490 \\
\text{plot} & 1525 \\
\end{cases} \\
\text{average} & 1508 \\
\text{Irrigation treatment 2} & \quad \begin{cases}
\text{lysimeter} & 1660 \\
\text{plot} & 1525 \\
\end{cases} \\
\text{average} & 1593
\end{align*}
\]

It is clear from these preliminary data that the water-use efficiency is reduced by about 6.3% through subjecting the maize crop to the applied soil-moisture stresses in its root zone.

CONCLUSIONS

In conclusion the following observations should be added:

(1) The P.E.T. after Penman, for the whole growing season, is in good agreement with the actual E.T., and a certain correction for this total could be made from accumulated data.

(2) The absorption coefficient in calculating the radiation should be corrected for the absorption of soil and vegetation, at least for such semi-arid climatological conditions as found in Egypt.

(3) The indirect determination through using the data of the neutron-moisture meter can be used after certain corrections. The difficulty with the neutron meter, in our opinion, is the proper calibration of the apparatus for each layer of moisture determination. If done accurately, this would make the use of the neutron meter possible.

(4) The soil-moisture stresses in the root zone of maize crop reduced its growth and yield, and at the same time reduced the water-use efficiency.

ACKNOWLEDGEMENTS

The investigators wish to express their gratitude to the International Atomic Energy Agency, for the decision to fund this project. (Agency research contract No 310/RB).
They are also indebted to the Governing Body of the Centre for its continuous encouragement and interest. The facilities offered by the Centre made it possible to carry out this work successfully. Finally, the investigators wish to thank the staff of the Centre who helped during the progress of this work.

REFERENCES


TUBER FORMATION IN POTATOES AS AFFECTED BY SOIL MOISTURE

L. E. DANFORS AND N. GUSTAFSSON
INSTITUTE OF TECHNOLOGY,
STOCKHOLM, AND
INSTITUTE FOR PLANT RESEARCH AND COLD STORAGE,
NYNASHAMN,
SWEDEN

Abstract

TUBER FORMATION IN POTATOES AS AFFECTED BY SOIL MOISTURE. In potatoes, tuber formation is generally confined to the top 10 cm of the soil, while root development is concentrated in layers below this depth. An experiment was designed primarily to study how the soil-moisture climate of the "tuber zone" would affect potato growth.

A common "root zone" was chosen by setting the seed tubers on the surface of a loam soil. On top of this a 20 cm soil layer was placed to act as a tuber zone. Soil texture and moisture were the factors used to establish four different physical environments of the applied top layer. Soil moisture was regulated throughout the growing season by means of the neutron method. Potato growth was studied by means of successively harvesting the treatment plots. Various growth development stages could be differentiated where the moisture climate had significant effects not only on the rate, but also on the nature of the growth and the state of health of the potato plants.

1. INTRODUCTION

The effect of soil moisture on potato growth has received some attention in Sweden. Reports from the Agricultural College [1] indi-

![Diagram of potato environment]

FIG. 1. The potato environment.

cate that irrigation increases both haulm and tuber growth as well as the size of the tubers, but that it tends to decrease the dry weight and starch content of the tubers. Optimum moisture conditions seem to
prevail when the soil is maintained at or near field capacity (pF 2-2.5). Generally the studies were based on cyclic drying and wetting programmes, where the "amplitude" (soil-moisture extremes) and "wave-lengths" (irrigation intervals) were varied.

In this investigation the approach was somewhat different. We stratified the potato environment into three zones — the haulm zone, the tuber zone and the root zone (see Fig. 1). Our attention was focused on the "tuber zone", the 0-10-cm top-soil layer in which the tubers are formed and intermediate between the "haulm zone" composed of the atmosphere surrounding the aerial parts of the plant and the "root zone" that supports the root system. A systematic study of this intermediate zone seemed warranted, since it is the layer where agricultural manipulations are most pronounced and where they undoubtedly have the greatest potentialities for the future. Our idea was to select different soil media as tuber zones and thereby obtain a wide range in moisture characteristics, based on varying degrees of absorption of precipitation rather than varying irrigation intensities.

2. MATERIALS AND METHODS

The experiments were carried out in 1964 and 1965 at Nynashamn, 70 km south of Stockholm. Bintje, a common table variety, was used.

### TABLE I. CHARACTERISTICS OF SOIL MATERIALS USED AS "TUBER ZONE" LAYERS (0-10 cm).

Average values based on several determinations made in 1964-65.

<table>
<thead>
<tr>
<th>Plot</th>
<th>Soil texture (wt. %)</th>
<th>Moisture capacity (vol. %)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type</td>
<td>Clay</td>
</tr>
<tr>
<td>A</td>
<td>Course gravel (0-20 mm)</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>Fine sandy loam</td>
<td>19</td>
</tr>
<tr>
<td>C</td>
<td>Clay</td>
<td>62</td>
</tr>
<tr>
<td>D</td>
<td>Clay</td>
<td>62</td>
</tr>
</tbody>
</table>

a Pore space filled with water (≈ pore volume).
b Equivalent to field capacity (determined on suction plate).
c Wilting point (wheat-sunflower method).
d Identical with the soil underlying all plots.
e Identical with clay in plot C but, because of irrigation, it attained a different structure and moisture capacity.
FIG. 2. Physical properties of the tuber zones in treatments A-D.

- Soil temperature range at 10 cm in July 1964-65.
- Air volume.
- Moisture volume available to plants.
- Moisture volume unavailable to plants.

1964

FIG. 3. Moisture climate.

T = mean monthly air temperature (°C);
I = irrigation applied to plots C and D;
P = total monthly precipitation (mm);
W = soil-moisture content of tuber zone (vol.%).

The seed tubers (40-50 mm, 4°C storage temperature) were planted in plots with a row and plant spacing of 60 and 35 cm respectively in the second week of June (plot total: 5 × 15 = 75 tubers). The seed tubers were placed directly on the surface of a fine sandy loam soil (autumn ploughed, spring harrowed) and then covered with a 10-cm-thick "tuber-zone"
layer. Four plots, each with a different type of tuber-zone layer, were established (Table I, Figs. 1 and 2). As seen from the data, a wide range in the air, moisture and temperature conditions of the tuber zone was achieved between plots. The aim was to study how this would affect potato growth.

Cylindrical soil samples (volume 200 cm$^3$) were taken from the tuber-zone layer at different times throughout the growing season (June-September) in both 1964 and 1965. Likewise soil-temperature measurements (thermistor probe) were made at a 10-cm depth. The mean values obtained from these measurements are presented in Table I and Fig. 2. Weekly measurements of the moisture content of the soil were made in the tuber zone using a surface neutron probe and from 20-70 cm depth using a depth neutron probe (d/M Gauge P21 resp. P19, Nuclear Chicago). The results are presented in Fig. 3 and Table II.

Weather conditions in 1964 and 1965 are difficult to describe in terms that are relevant to potato growth. Mean monthly air temperatures and monthly precipitation totals for June-September are given in Fig. 3. Evapotranspiration that occurred 1965 from the different plots is reported in Table II, but equivalent data for 1964 are less complete. It will be seen that 1964 was both drier and warmer throughout the growing season than 1965 (Fig. 3), that the moisture content of the D-plots was far higher than the C, B and A-plots in both years.

**TABLE II. EVAPOTRANSPIRATION FROM POTATO PLOTS 1965 EXPRESSED IN mm AND ESTIMATED FROM NEUTRON MOISTURE MEASUREMENTS IN THE 0-70-cm SOIL LAYER.**

<table>
<thead>
<tr>
<th>Period</th>
<th>June 16/6-30/6 14 d</th>
<th>July 30/6-30/7 30 d</th>
<th>August 30/7-24/8 25 d</th>
<th>September 25/8-14/9 15 d</th>
<th>Total 16/6-14/9 84 d</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETPg a</td>
<td>65</td>
<td>113</td>
<td>73</td>
<td>30</td>
<td>281</td>
</tr>
<tr>
<td>Plot A</td>
<td>5</td>
<td>40</td>
<td>61</td>
<td>45</td>
<td>151</td>
</tr>
<tr>
<td>&quot; B</td>
<td>23</td>
<td>79</td>
<td>41</td>
<td>35</td>
<td>161</td>
</tr>
<tr>
<td>&quot; C</td>
<td>44</td>
<td>71</td>
<td>58</td>
<td>31</td>
<td>294</td>
</tr>
<tr>
<td>&quot; D b</td>
<td>40</td>
<td>197</td>
<td>123</td>
<td>30</td>
<td>396</td>
</tr>
<tr>
<td>Irrigation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>plot C</td>
<td>20</td>
<td>20</td>
<td>-</td>
<td>-</td>
<td>40</td>
</tr>
<tr>
<td>&quot; D</td>
<td>30</td>
<td>170</td>
<td>60</td>
<td>-</td>
<td>260</td>
</tr>
</tbody>
</table>

a Mean potential evapotranspiration from a grass-covered surface calculated from Penman’s formula for Stockholm 1931-60

b Values for this treatment are unfortunately much too high owing to run-off from the plot during irrigation, which could not be measured and subtracted. The actual evapotranspiration can be assumed to be very similar to the C-treatment or, as a total, about 220 mm for the 84-d period.
(Fig. 3), and that the evapotranspiration from the D-plots was therefore also far higher than from the other plots (Table II). The explanation of these large differences is, of course, irrigation, which was 175/280 mm for the D-plots, 70/40 mm for the C-plots and no irrigation at all for the A- and B-plots for 1964/1965. The idea was to use irrigation to complement soil texture as a factor in establishing as wide a gradation as possible in the moisture climate of the tuber zone between plots. Thus, soil texture covered, so to speak, the qualitative aspects – distribution and accessibility of moisture – while irrigation helped
maintain quantitative differences. Irrigation was applied to plots C and D in weekly doses (0-30 mm) according to an assessment of the climatic situation and the aim to maintain a suitable moisture gradation from plot A to D.

![Graph showing changes in tuber frequency per plant.](image)

**FIG. 6.** Changes in tuber frequency per plant.

![Bar chart showing tuber size distribution.](image)

**FIG. 7.** Tuber-size distribution, 1964 and 1965.

- □ Less than 40 mm diam.
- ○ 40-50 mm diam.
- △ Greater than 50 mm diam.

Potato growth was measured by means of successive harvests made at intervals of 10-20 d throughout the growing season. At each harvest 5-10 plants were dug up and divided into haulm and tubers, which were weighed separately. The health state was appraised and the size distribution, starch content, and dry weight of the tubers determined — Figs 4 and 5 (growth of haulm and tubers), Fig. 6 (change in frequency of tubers), Fig. 7 (size distribution of tubers).

3. RESULTS AND DISCUSSION

Many suggestions have been made concerning the differentiation of the growth cycle of the potato into separate phases [2, 3]. Although the
phases may be well appreciated, their separation by means of well-defined time instances is lacking. In the presentation of our data we have tried to overcome this deficiency by introducing some growth-time constants of our own and on this basis attempt to analyse the soil-moisture/growth relationship systematically during the growing season.

3.1. Time of haulm emergence

We have arbitrarily defined this time as the number of days after planting that the haulm has reached a fresh weight of 25 g/plant. In our plots the haulm had then protruded a few centimetres above the soil surface. The date of this growth stage could be determined with plus or minus a day on the basis of the growth curves and our observations from the field (interpolation, whereby the curves are appropriately smoothed towards the abscissa, as shown in Fig. 5).

The time of haulm emergence was found to vary in our studies from 13-22 d and occurred during the last week of June and first week of July (see Table III). Emergence was longest in A (gravel), where the moisture content was lowest. The delay was, however, not so much a matter of moisture deficiency as of penetration resistance. This was obvious from the rather swollen and injured stalks that protruded through the gravel. In 1965 emergence became so alarmingly delayed in A-plot, that we felt obliged to remove 2-3 cm of the gravel that covered the seed tubers. This was a hasty measure that we were later to regret, since it alleviated the desired stress and made us lose similarity between 1964 and 1965 as far as the following growth development was concerned.

In the C- and D-plots (drier and wetter clay respectively) time of haulm emergence was rather similar (average 18-19 d), but about 6 d later than in the B-plots (fine sandy loam). Here again penetration resistance seemed a major factor in delaying emergence — heavy wet clay soil against the friable loam. However, temperature and oxygen could also be involved. The moist C- and D-plots were a few degrees lower in temperature at 10-cm depth and had considerably poorer aeration conditions than the B-plots, as determined from solitary measurements and observations.

From studies on Bintje 1960-62, Carlsson [3] has reported an equation to fit his haulm growth curves: \( y = -249.8 + 24.4 x - 0.086 x^2 \) \((r^2 = 0.54)\), where \( y \) is the haulm weight in grams and \( x \) is the number of days after planting. Haulm emergence according to our definition \((y = 25)\) here works out to be 12 d. This coincides with our results from the B-plots.

3.2. Time of tuber initiation

We have defined this as the number of days after haulm emergence that the tuber weight has reached 25 g/plant. It is derived from appropriate interpolation of the growth curves, Figs. 4 and 5. We have used haulm emergence here as a better reference time than date of planting. For our studies, tuber initiation has been very constant in all plots, i.e. 15-16 d. From Carlsson's work [3] it may be calculated as 29 d. His tuber growth equation is \( y = -712.8 + 21.8 x - 0.095 x^2 \), where \( y \) is the tuber weight in grams per plant and \( x \) the number of days after planting.
TABLE III. GROWTH DEVELOPMENT IN POTATOES 1964/1965 REPORTED IN STAGES AND EXPRESSED AS DAYS AFTER EMERGENCE OF HAULM

<table>
<thead>
<tr>
<th>Growth stages</th>
<th>A (gravel) (d)</th>
<th>B (loam) (d)</th>
<th>C (moist clay) (d)</th>
<th>D (wet clay) (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planting&lt;sup&gt;a&lt;/sup&gt;</td>
<td>22/22</td>
<td>-22</td>
<td>12/14</td>
<td>-13</td>
</tr>
<tr>
<td>Haulm emergence</td>
<td>0</td>
<td>0</td>
<td>17/19</td>
<td>-18</td>
</tr>
<tr>
<td>Tuber initiation</td>
<td>14/18</td>
<td>16</td>
<td>13/20</td>
<td>16</td>
</tr>
<tr>
<td>Maximum growth-rate</td>
<td></td>
<td></td>
<td>12/19</td>
<td>15</td>
</tr>
<tr>
<td>(haulm)</td>
<td>27/57</td>
<td>27</td>
<td>26/16</td>
<td>21</td>
</tr>
<tr>
<td>&quot; rate (tubers)</td>
<td>36/40</td>
<td>37</td>
<td>43/41</td>
<td>42</td>
</tr>
<tr>
<td>Haulm withering</td>
<td>49/65</td>
<td>52</td>
<td>53/56</td>
<td>55</td>
</tr>
<tr>
<td>Tuber harvest</td>
<td>97/103</td>
<td>95</td>
<td>102/96</td>
<td>99</td>
</tr>
<tr>
<td>Haulm/tuber weight = 1</td>
<td>42/38</td>
<td>40</td>
<td>48/36</td>
<td>40</td>
</tr>
<tr>
<td>Haulm/tuber growthrate = 1</td>
<td>27/19</td>
<td>23</td>
<td>28/19</td>
<td>23</td>
</tr>
</tbody>
</table>

<sup>a</sup> Planting occurred 25/6 1964-11/6 1965. The negative sign is used to indicate days before emergence. All other data implies days after emergence.

<sup>b</sup> Values imply 1964/65 and the average for both years respectively, e.g., 22/22 -22.
At \( r^2 = 0.88 \). At \( y = 25 \), \( x = 41 \) and initiation time according to our definition is 41 - 12 = 29, which is too large, owing to a poor fit of the regression equation during the early part of the growth period. There is a slight indication in our experiments that a high moisture level (C and D) shortens the time of tuber initiation, but otherwise the results indicate little sensitivity to differences in environmental conditions. It also seems difficult to draw any general conclusions regarding differences in the number of initiated tubers in the various plots (see Fig. 6).

3.3. Maximum growth rate of haulm

By plotting the growth curves in Figs. 4 and 5 it is possible to follow the growth intensity of the potato plants throughout the growing season. At the time of emergence, the growth rate of the haulm can be estimated to be about 5 g/plant per day. Then it is found to increase until a maximum is reached, after which it decreases and finally approaches zero (withering). Variability in the potato population and other experimental errors will make exact determinations difficult. In Fig. 4 the haulm and tuber substance measured at the different harvest instances (1964) were connected by straight lines. In Fig. 5, which concerns 1965, smooth curves were used. Both presentations must be regarded as approximations of the actual growth conditions. The dates of maximum growth rate of the haulm have been estimated within ± 2 d and expressed in number of days after emergence (see Table III). In 1964 maximum growth rates occurred more or less simultaneously about 26-28 d after emergence, while in 1965 they occurred from 11 to 27 d after emergence. High moisture levels (C and D) seemed to accelerate haulm development, while the penetration-impeded gravel treatment (A) prolonged it. In 1964 the growth rates were 15, 16, 23 and 29 g/plant per day, and in 1965 11, 10, 8 and 8 g/plant per day for the A-, B-, C- and D-plots respectively. The reversal in the order of magnitude between the 1964 and 1965 plots depends on climatic differences, in that the moisture conditions were favourably projected towards optimum in 1964 and detrimentally brought beyond optimum conditions in 1965. Thus, much less plant substance was developed in 1965 than in 1964, owing to the wetter and colder climate that year. Because of the mistaken removal of some of the gravel from the A-plots in 1965, growth was alleviated after emergence of the haulm.

3.4. Maximum growth rate of tubers

The growth rate of the tubers at the time of initiation was estimated from derivation of the growth curves to be 6-8 g/plant and day. This rate reached a maximum 31-45 d after haulm emergence and varied between 15-27 g/plant per day (see Table III). The growth rate was lowest and reached maximum earliest in the A-plot of 1964 (growth impeded by penetration resistance) and in the D-plot of 1965 (growth impeded by excess moisture, i.e. oxygen deficiency).

3.5. Time of withering or destruction of the haulm and harvest of the tubers

According to modern techniques, the haulm is seldom left to wither in a natural way, but destroyed as soon as there are signs of Phytophthora
infection. It is, however, important to note when the haulm becomes ineffective as a growth organ, so that account can be made of this when tuber production is to be evaluated. Likewise the harvest time should be taken into consideration. Both these times may be expressed as days after emergence of the haulm (see Table III). The time of killing the haulm occurred 49-63 d after emergence. Thus the B-plot had the benefit of its haulm 8-10 d longer than the A-plot and 5-6 d longer than the C- and D-plots, owing to early emergence.

The time of tuber harvest varied between 93-106 d after haulm emergence and occurred latest in the B-plots – 9 d later than the A-plots and 4-6 d later than the C- and D-plots, owing to early emergence in this plot.

The largest tuber yields were obtained in the B- and C-plots, where environmental conditions were seemingly more optimal. Irrigation was beneficial in the D-plot 1964, but detrimental in 1965 owing to poorer aeration, which limited growth very severely (see Figs 4 and 5). Penetration resistance in the A-plot retarded growth, but did not seem to be a hazard to the health of the tubers.

3.6. Frequency and size of tubers

The change in frequency of tubers is shown in Fig. 6. At initiation time there is a very rapid development of tubers, but as these grow larger, resorption occurs, which minimizes the number. The explanation to this is, undoubtedly, changes within the plant regarding the supply and demand of growth substance. At initiation time, the stolons find access to growth substance sufficient for thickening, and therefore proceed unrestrained to establish young tubers. As this process develops, however, the demand for growth substance increases very rapidly and soon the supply fails and competition between expectant tubers develops into a survival of the fittest. In this "battle", the weakest tubers become resorbed.

Our studies show that tuber frequency changes over the growing season from about 20 to 10 tubers per plant (see Fig. 6). The frequency was consistently highest in the B-plots and was lowest in plots where growth was retarded most (A-plot, 1964 and D-plot, 1965). Carlsson [3] reports 10 tubers at initiation and 7-8 tubers per stalk at harvest, as an average trend for studies made in 1960-62.

Figure 7 illustrates the size distribution of the tubers at harvest. The A-plot had the highest percentage of large tubers (above 50 mm diam.), while the B-plot had the lowest. The mean tuber weight was 68/66, 52/56, 80/58 and 104/58 g/tuber for the A-, B-, C- and D-plots respectively in 1964/1965.

3.7. Interrelationship between haulm and tubers

The development of the haulm and tubers is an integrated growth process that results from the accumulated effects of the environment during the life of the potato. The haulm answers for the photosynthetic surface and the actual sites for the formation of the tubers. Its growth is promoted by high radiation, high temperature and ample water and nutrient supply. Vigorous stem and leaf growth leads to an appreciable
delay in tuber formation but, as tubers develop, competitive effects appear between these and the leaves. If the tubers are initiated when only a small leaf area has developed, haulm production ceases earlier and existing leaves senesce more quickly, giving smaller final yields than when tubers are initiated on plants with much larger haulms [2].

One possible way of integrating haulm and tuber development is to study changes in their weight ratio during the growing season. The haulm weight will initially be infinitely greater than the tuber weight, but as time passes, their quotient will approach and, towards the end of the season, will fall below 1. The time at which the quotient is 1 (haulm weight = tuber weight) is reported in Table III. It is remarkably constant = 40 d after emergence.

Another relationship that may be more pertinent in analysing growth, is the relationship between the growth rates of the haulm and tubers. When the haulm tuber growth-rate quotient is 1, the haulm and tubers equally share the available growth substance. At first the haulm has disposal over all the assimilate that is formed, but after tuberization, an ever-increasing proportion is absorbed by the tubers. The rate quotient reaches 1 about three to four weeks after emergence and about two weeks before the haulm and tubers have reached equal weights (see Table III). It appears from 1964 that soil moisture delays tuber growth and benefits input of growth substance into the haulm. Excess moisture (oxygen deficiency) has an opposite effect according to the data from 1965 (C and D).

4. SUMMARY

The purpose of this investigation was to study how potatoes (Bintje) react to differences especially in the moisture conditions of the 0-10-cm soil layer (tuber zone). Soil texture and irrigation were the environmental modifiers used. The role played by moisture was judged on the basis of growth data, but was complicated by the effects of moisture on other environmental factors, such as temperature, aeration and penetration resistance.

The studies show that haulm emergence is sensitive to several environmental factors of the tuber zone – the major limitation to emergence was penetration resistance in the A treatment, excess moisture (poor aeration) and probably lower temperature in the C and D treatments. Moisture was found to favour haulm growth and delay tuberization (see Table III): haulm/tuber growth ratios. As far as the quantitative aspects are concerned, moisture favoured haulm development during warm evaporative weather (1964), but was detrimental under contrasting conditions (1965, when poor aeration limited growth). As pointed out by Penman [4] some kind of adjusted value of potential transpiration is probably a more pertinent parameter to define moisture effects than is the content of soil moisture. Our data responds fairly well to the theory that high rates of transpiration benefits haulm development, which later promotes the initiation of a large number of tubers and finally results in large tubers and a large total yield. However, the dry weight and starch content of the tubers is reduced 1-2% by moisture.
REFERENCES


DISCUSSION

W. H. GARDNER: How did you correct for potato-tuber water content in the surface measurement of soil-water content using neutron scattering methods?

L. E. DANFORS: This difficulty was overcome by making the measurements at a safe distance from the plants.
ETUDE DES MODALITES D’UTILISATION DE L’EAU DU SOL PAR DES CULTURES SECHES ET IRRIGUEES A L’AIDE D’UN HUMIDIMETRE A NEUTRONS

C.E. MAERTENS ET M. COURAU
INRA, STATION D’AGRONOMIE ET D’OCENOLOGIE DE TOULOUSE, FRANCE

Abstract — Résumé

NEUTRON-MOISTURE-METER INVESTIGATION OF WAYS IN WHICH DRY AND IRRIGATED CROPS UTILIZE SOIL MOISTURE. The preparation of numerous water balances with the aid of a neutron-moisture meter has made it possible to determine the accuracy of this type of instrument and the best way of using it in agronomical work.

The author used these data in a critical study of the concept of water reserves utilisable by plants, and demonstrate the effects of root development on the way in which the water is used. It is shown that the effectively available water reserves vary considerably throughout the plants’ growth. Irrigation modifies the environmental conditions; the more intensive the irrigation, the less the groundwater reserves contribute to the plants’ supply.

A study of several types of soil has shown that the physical properties of the soil influence yields, even in the case of irrigated crops. In fact, serious growth anomalies have been observed after the irrigation of degraded soils.

A knowledge of the physical properties and potentialities of root growth is therefore essential for rational irrigation.

INTRODUCTION

TABLEAU I. COMPARAISON DES HUMIDITÉS VOLUMIQUES OBTENUES PAR PRÉLEVEMENTS ET PAR UN HUMIDIMÈTRE A NEUTRONS POUR DES SOLS DE GRANULOMÉTRIES VARIÉES

<table>
<thead>
<tr>
<th>N° du sol</th>
<th>Granulométrie en % de terre fine</th>
<th>Humidité volumique + eau de constitution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;2 µm</td>
<td>2 - 20 µm</td>
</tr>
<tr>
<td>1</td>
<td>4,5</td>
<td>4,9</td>
</tr>
<tr>
<td>2</td>
<td>8,6</td>
<td>9,9</td>
</tr>
<tr>
<td>3</td>
<td>16,7</td>
<td>11,7</td>
</tr>
<tr>
<td>4</td>
<td>12,9</td>
<td>12,9</td>
</tr>
<tr>
<td>5</td>
<td>24,4</td>
<td>12,0</td>
</tr>
<tr>
<td>6</td>
<td>31,0</td>
<td>17,8</td>
</tr>
<tr>
<td>7</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Nous avons tenté de déterminer quelle était l'influence de certains facteurs dépendant du végétal et du sol sur les modalités d'alimentation hydrique des plantes, et d'estimer l'importance des modifications apportées à ces modalités par l'irrigation. L'humidimètre à neutrons s'est avéré particulièrement bien adapté à ce genre d'études.

PRÉCISION ET MODALITÉS D'UTILISATION DE L'HUMIDIMÈTRE A NEUTRONS EN AGRONOMIE

Dans nos études de la dynamique de l'eau dans les sols, des bilans hydriques et de l'irrigation, nous utilisons un humidimètre à neutrons mis au point par le Commissariat à l'énergie atomique français (CEA), à source de 5 mCi de radium-béryllium placée contre la paroi du détecteur en sa partie médiane [1].

Nous avons vérifié sa précision en comparant les humidités (humidité volumique + humidité volumique de constitution) obtenues par des prélevements de sol aux données recueillies par l'humidimètre [2]. On peut constater au tableau 1 que sa précision est largement suffisante pour des études agromonomiques.

L'étude de nombreux bilans hydriques, établis sur plusieurs années, nous a permis de constater que les différences entre les données climatiques (pluviométrie et évapotranspiration) et les variations d'humidité du sol mesurées par cette méthode ne dépassaient pas 15 mm de hauteur d'eau pour l'ensemble de la campagne.

Ce type d'appareil est particulièrement bien adapté à l'estimation des réserves en eau du sol. En effet, il permet d'obtenir aisément la capacité de rétention du sol en place (capacité au champ). Cette capacité se détermine par des mesures répétées en période de faible évapotranspiration; cependant, cette donnée n'est pas toujours obtenue à une
mêmes dates sur l'ensemble d'un profil. Ainsi, après réhumectation complete du sol, nous avons obtenu des humidités stables à des périodes variables selon la profondeur:
- de 0 à 30 cm, de fin février à mi-mars,
- de 40 à 70 cm, de début mars à mi-mars,
- de 80 à 110 cm, de fin février à fin mars,
- de 120 à 170 cm, de mi-mars à fin mars.
Cependant, on peut estimer de manière précise, au cours de la croissance des végétaux, la proportion des réserves utilisables consommées aux différentes profondeurs.

MODALITES DE LA PARTICIPATION DES RESERVES D'EAU DU SOL A L'ALIMENTATION DES PLANTES

L'eau du sol ne peut participer à l'alimentation des plantes qu'à la condition que le milieu soit exploité par les racines. Les modalités d'utilisation de l'eau vont donc dépendre du type et du mode d'encrasinement des végétaux.

C'est ainsi qu'une luzerne âgée de deux ans, installée dans un sol ayant 250 mm de réserve utilisable sur 150 cm de profondeur, a consommé l'eau du sol de la manière suivante: la dessiccation intéressait 90 cm dès le début de juin et atteignait 150 cm à la fin d'août. Cependant, la proportion des réserves utilisées n'était pas la même aux différentes profondeurs, elle semble dépendre de la répartition des racines au sein du profil (tableau II).

Lors des premières observations (3 juin 1966), l'encrasinement avait atteint au minimum 90 cm avec un chevelu nettement plus abondant de 0 à 30 cm, horizon dans lequel la consommation de l'eau s'est faite préférentiellement. Le dessèchement s'est ensuite effectué de plus en plus profondément. Le sol oppose en effet une certaine résistance à la circulation de l'eau [3, 4], résistance qui est fonction des distances à parcourir et sera donc d'autant moins importante que l'encrasinement sera plus abondant. Puech [5] a démontré que la mobilité de l'eau pouvait être très différente d'un sol à l'autre: elle est plus importante dans le sable que dans l'argile. Il semble alors que l'abondance de l'encrasinement puisse revêtir des importances différentes selon le type de sol.

L'encrasinement des cultures annuelles progresse différemment de celui des cultures pérennes; les modalités d'utilisation de l'eau y sont donc très différentes.

Pour un maïs non irrigué, par exemple, la participation des réserves en eau du sol est directement liée à la croissance des racines, comme le montre l'évolution des profils hydriques que nous avons observés. Au début de juillet, la dessiccation n'intervenait que sur les 30 premiers centimètres du profil; aussi, les réserves utilisables susceptibles de participer à l'alimentation n'étaient-elles que de 60 mm. À la mi-juillet, la dessiccation atteignait 60 cm de profondeur, les réserves possibles étant alors de 120 mm; au début d'août, elles étaient de 204 mm sur 120 cm de sol (fig. 1) [6]. Dans ce type de sol, la quasi-totalité des réserves en eau a été utilisée sur l'ensemble de la période végétative du maïs, les différents horizons s'étant relayés dans l'alimentation des
TABLEAU II. UTILISATION DE LA RESERVE UTILE SOUS LUZERNE DE DEUX ANS

<table>
<thead>
<tr>
<th>Profondeur (cm)</th>
<th>% de la reserve utile utilisee au</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 juin 1966</td>
</tr>
<tr>
<td>0 - 30</td>
<td>80,7</td>
</tr>
<tr>
<td>30 - 60</td>
<td>51,7</td>
</tr>
<tr>
<td>60 - 90</td>
<td>32,2</td>
</tr>
<tr>
<td>90 - 120</td>
<td>0</td>
</tr>
<tr>
<td>120 - 150</td>
<td>0</td>
</tr>
</tbody>
</table>

FIG. 1. Evolution d'un profil hydrique sous une culture de maïs non irrigué.

plantes au cours de la progression du système radiculaire, et cela à partir de faibles quantités de racines dans les zones les plus profondes (fig. 2).

Le volume de sol exploité par les racines varie encore avec l'écartement des lignes de plantation. Nous avons pu observer pour une période de deux mois des différences de 48 mm dans la fourniture de l'eau par le sol de la ligne et de l'interligne d'une culture de maïs plantée en lignes espacées de 90 cm. Ce phénomène peut provoquer en culture sèche une certaine économie de l'eau en régularisant sa consommation. Nous avons observé que des plantes semées en lignes restaient plus
Grammes de matière sèche de racines par dm$^3$ de sol

FIG. 2. Colonisation du sol par les racines.

longtemps vertes que des plantes semées en carré à une même densité de population.

Dans le cas de plantes annuelles, la connaissance des réserves théoriques en eau utilisable n'est donc pas suffisante pour déterminer les systèmes et les doses optimales d'arrosage. De plus, l'irrigation modifiant l'enracinement [7, 8], les réserves réellement utilisables pour les cultures arrosées sont nettement diminuées. En effet, nous
avons pu constater que la consommation dans les parcelles irriguées intensivement (260 mm) du même essai s’était faite principalement de 0 à 30 cm, et jamais au-delà de 80 cm de profondeur. Les réserves susceptibles de participer à l’alimentation des plantes étaient donc pour ce traitement de 120 mm, contre 200 mm pour le traitement sec. De plus, la proportion des réserves réellement utilisée était très faible dans le traitement irrigué : 50 mm seulement contre 180 mm dans le traitement sec [5]. Cette participation du sol représentant 15% de la consommation totale a atteint 40% pour une irrigation moins intensive (160 mm).

L’importance du volume des réserves utilisables en culture irriguée n’est cependant pas négligeable, son rôle principal étant de servir de «volant», qui détermine les doses partielles et les rythmes des arrosages. En fonction de l’importance de ces réserves et selon les modalités de croissance des racines, les arrosages pourraient être de plus en plus conséquents et espacés au cours du temps.

Ainsi, la notion de réserve facilement utilisable semble dépendre plus de la colonisation radiculaire, c’est-à-dire du volume de sol exploité, que des états de l’eau du sol.

INFLUENCE DU TYPE DE SOL SUR LES RENDEMENTS DE MAIS ET INTERACTION AVEC L’IRRIGATION

Les propriétés physiques des sols, par leur influence sur l’enracinement, ont une incidence importante sur la production des cultures.

Un essai comparatif d’irrigation du maïs a été réalisé sur trois types de sols différents [9]:

Sol n°1 - sablo-limoneux, bien structuré, profond de 150 cm, avec 200 mm de réserve d’eau utilisable totale.
Sol n°2 - limoneux, mal structuré, profond de 70 cm avec 120 mm de réserve d’eau utilisable totale.
Sol n°3 - limoneux, très mal structuré, profond de 50 cm avec 80 mm de réserve d’eau utilisable totale.

Les rendements en culture sèche ont été principalement influencés par l’importance des réserves utilisables. Ils étaient en grain sec de 62 qx/ha pour le sol n°1, 40 qx/ha pour le sol n°2 et 11 qx/ha pour le sol n°3, cela pour des consommations respectives de 360 mm, 260 mm, et 180 mm. La participation des réserves du sol était de 200 mm, 120 mm, et 80 mm. Les rendements ne sont pas directement proportionnels à la quantité d’eau utilisée; en effet, l’efficience de l’eau consommée diffère d’un sol à l’autre: 17,5 kg de maïs par mm d’eau consommée pour le sol n°1, 15,7 pour le sol n°2, 6,0 pour le sol n°3 [9].

Les différences de consommation de l’eau ne suffisent pas à elles seules à expliquer les écarts de rendements; il semble que l’on puisse mettre en cause les propriétés physiques. En effet, l’influence de la fertilisation ne peut pas être incriminée, non plus que les différences climatiques locales.

L’influence du type de sol semble confirmée par les rendements obtenus en culture irriguée, où l’alimentation hydrique était cependant assurée. Les rendements ont été respectivement pour les sols n°1, 2 et 3, de 82, 71 et 35 quintaux de grain sec par hectare [9]. Les pro-
priétés physiques des sols ont en effet une influence marquée sur le bon développement et le bon fonctionnement du système radiculaire [10].

À l’extrême, l’irrigation en sol de structure très instable et de faible perméabilité peut provoquer des accidents radiculaires dont la répercussion est importante sur la production. Dans un tel sol nous avons pu observer la formation d’un gley dans les 30 premiers centimètres à la suite d’une pluie de 20 mm consécutive à un arrosage [11]. Les racines de maïs situées dans cette zone étaient nécrasées. Des observations à partir de coupes microscopiques faites dans ces racines ont montré que seul le parenchyme cortical était atteint, ce qui a permis l’émission de radicelles saines à partir du cylindre central. Ce nouveau système radiculaire a assuré la survie des maïs; cependant cet accident s’est répercrit sur les rendements qui sont tombés de 60 à 15 qx de grain sec à l’hectare.

CONCLUSIONS

L’humidimètre à neutrons est particulièrement bien adapté aux études concernant les modalités d’utilisation de l’eau par les cultures sèches et irriguées. Son emploi nous a permis d’étudier de manière détaillée, dans divers types de sols, les modalités de l’alimentation en eau des cultures.

La compréhension de l’alimentation hydrique des plantes, qui est à la base de l’irrigation, ne peut plus se satisfaire d’une connaissance globale des réserves hydriques disponibles dans le sol.

En effet, au fur et à mesure de la croissance des végétaux annuels, l’enracinement progresse vers la profondeur, ce qui oblige à considérer les réserves utilisées sous un aspect dynamique. Par ailleurs, l’obtention de rendements élevés par irrigation intensive conduit à faire en grande partie abstraction des réserves du sol. Leur rôle de «volant» n’est cependant pas négligeable, et conditionne en fait la conduite de l’irrigation.

Enfin, les résultats que l’on peut espérer de l’irrigation restent limités par le potentiel de production propre à chaque sol, et notamment par son état physique. C’est ainsi que, dans des sols de structure très instable, l’irrigation est délicate à conduire, et la moindre erreur susceptible d’entraîner des accidents graves.

En conséquence, en raison de leur action sur l’enracinement des végétaux et certaines caractéristiques hydriques, la connaissance des propriétés physiques du sol est indispensable à la conduite rationnelle de l’irrigation.

REFERENCES

DISCUSSION

J. MARCESSE: Mr. Zein El Abedine's paper stresses the inflow of water from a fairly deep-lying water table. Did you find such a water table in your experimental field and, if so, at what level? I am asking this because the moisture content is still very high at deep levels and in these circumstances the stability of neutron gauge readings does not rule out water movements.

C. E. MAERTENS: No. We naturally checked to ensure that there was no water layer sufficiently close to contribute to the plants' supply.

M. DE BOODT: You stressed the importance of the soil's physical properties in securing beneficial irrigation. May I ask what measurements you made, and how did you assess the results?

C. E. MAERTENS: We measured physical properties such as apparent density, porosity and structural stability (Heinen method). We also carried out gravimetric measurements of the root system. The results will be published.

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1 ZEIN EL ABDINE, A., ABDALLA, M.M., ARDEL-'AL, Sh.I., "Evapotranspiration studies on maize in Giza, United Arab Republic", these Proceedings.
USE OF RADIOISOTOPES WHEN DEALING WITH PROBLEMS ASSOCIATED WITH IRRIGATION CHANNELS LOCATED ON LOESS*

B. CELAN AND V. PERLEA
INSTITUTUL DE ÎNBUŞĂTĂŢII FUNCIARE ŞI PEDOLOGIE,
BUCUREŞTI, ROMÂNIA

Abstract

USE OF RADIOISOTOPES WHEN DEALING WITH PROBLEMS ASSOCIATED WITH IRRIGATION CHANNELS LOCATED ON LOESS. The authors describe the application of radiometry during a study of the behaviour of irrigation systems when located on loess. Radiometric methods were used specifically to trace the moisture flow and to determine the soil settlement of the loess layers at varying depths. The tests were undertaken at an experimental station in a region that has a 24-m-deep loess layer, which shows a marked tendency to settle. The soil stratification is almost identical throughout the area; an 0.8-m-deep organic soil layer underlain by an approximately 20-m-deep yellow, porous, crumbling, relatively dry loess that is rather homogeneous physically.

The station is situated in an overflow basin that is continually supplied by one of the channels of an irrigation system.

The portable radiometric equipment used consisted of a detection head sensitive to gamma radiations, a rate meter with a transistor, and the operating mechanism. Any displacement of the detection head caused during drilling was detected at the surface by a mechanical monitoring device. From laboratory and field determinations it can be concluded that this equipment enables soil settlements to be traced perpendicularly within a 1-cm precision.

To determine the moisture flow by a neutron method, a portable apparatus was developed by the radiometry staff at the Institute for Land Reclamation and Soil Science.

The main result of the experiments was that an adequately precise and convenient method for determining soil settlement at deep layers was established. This was achieved by detecting previously implanted radiation sources (147Sm) whose shifts were detected by the radiometric equipment. These sources were placed perpendicularly at different levels. It was found that such determinations could be carried out satisfactorily even below groundwater level.

The progress of the moisture flow was determined by neutron measurements and by electrometric drilling in two profiles perpendicular to the channel axis. The neutron moisture measurements were accurate almost to soil-moisture saturation, while the conventional electrometric method was unsuitable above a soil-moisture content of 20%.

The neutron moisture method of measurement proved useful in designing irrigation systems on loess soils of the type described here.

DISCUSSION

D. RANÇON: As you made moisture measurements to depths of 20 m, could you tell me the maximum increases in moisture which you observed between 10 and 20 m?

B. CELAN: The moisture at that depth varied between 12% and about 30%.

* Since a final text of this paper has not become available only an Abstract is printed here.
SECTION V

DESALTED WATER FOR AGRICULTURE
WATER DESALTING COST – PRESENT AND FUTURE

D. B. BRICE,
INTERNATIONAL ATOMIC ENERGY AGENCY,
VIENNA, AUSTRIA

Abstract

WATER DESALTING COST – PRESENT AND FUTURE. The rapidly increasing demands for fresh water have led to intensified efforts to develop the desalination of saline water. At present some of the more promising processes for desalination of sea water are multi-stage flash distillation and long-tube vertical evaporation. These processes are described in the paper. For desalination of brackish water the electrolysis process is normally selected.

A modern multi-stage flash-distillation plant requires a thermal energy input of 50,000 or more kcal/m³. Thus, the large-scale desalination of saline water will require an enormous amount of energy. Also, a substantial reduction in the cost of desalted water could be realized if an inexpensive source of energy were available. It is in this respect that nuclear energy offers considerable potential for the future of desalination.

Developments in nuclear reactor technology are described. By the end of 1960 the nuclear reactors in operation had a total capacity of 9000 MW(e). It is anticipated that this capacity will increase to 20,000 MW(e) by 1970 and 100,000 MW(e) by 1975. Improvements in reactor technology and decrease in nuclear fuel costs are expected to bring the cost of steam to about 70 US cents per million kcal by the mid 1970's, to 40-60 US cents per million kcal with advanced converters in the late 1970's and to 24-40 US cents per million kcal with advanced converters in the late 1970's and to 24-40 US cents per million kcal with breeder reactor by the early 1980's.

The maximum evaporator brine temperature in a multi-stage flash-distillation plant is at present limited by economic means of scale control to about 120°C, whereas the generating costs of electric power plants are lowest when the steam is produced at higher temperatures. This leads to economic advantages in combining the production of water and power. The ratio of water-to-power output for dual-purpose nuclear plants is limited at present to about 0.3-0.8 million US gal/MW(e), depending on the type of reactor.

Projected desalted water costs from large dual-purpose plants have been estimated as low as US$0.05/m³. Further into the future, with improved technology and from very large plants, the cost envisaged is in the neighbourhood of US$0.02/m³.

INTRODUCTION

In recent years there has been a growing concern about the adequacy of fresh water supplies to meet anticipated requirements, which are expanding as a result of increasing populations, rising living standards, progressive industrialization, and more intensive irrigation. The limited fresh-water supplies are unevenly distributed in relation to demands, and in certain populated areas serious water shortages are beginning to appear. If arid and semi-arid regions, which constitute about two-thirds of the total land surface of the world, are to be developed, additional ways of supplying water must be found. The desalting of sea or brackish water offers a promising means for helping to meet a part of fresh-water needs of the future.

DESALINATION PROCESSES

For desalination of sea water a boiling and evaporation technique is generally employed. For brackish water containing dissolved solids of
up to several thousand parts of salt per million parts of water a semi-permeable membrane is used to separate the water from the saline solution. Modifications of these processes are also being developed as well as other techniques such as freezing. One very promising process which utilizes a membrane is the reverse osmosis process. In the future it may be useful for both sea-water and brackish-water desalination.

**Sea water**

Most of the major commercial sea-water desalination plants under construction employ the multi-stage flash-distillation process. In this process, as shown in Fig. 1, the major equipment is composed of vessels in which salt water is allowed to boil. The vapour that results from the boiling is essentially salt free. The vapour travels to the top section of the vessel and is condensed on the tubes positioned in the upper portion of the vessel and through which salt water is pumped. Since the salt water in the tubes is at a lower temperature than the vapour it condenses on the outside surface of the tubes. The drops that form on the tubes drip off and fall into a fresh-water collecting trough (see Fig. 1).

Sea water is added to the process and desalted water and concentrated brine, which is referred to as blowdown, are removed. The blowdown carries away the salts introduced into the system by the sea water.

Starting with the sea water, it is pumped from the ocean through the tubes located in the heat-rejection section. This is the section which is at the lowest temperature. Since it is no longer economic to recover the major portion of the heat available in this low-temperature vapour, the heat of condensation is removed by that portion of sea water referred to as cooling water. It is discharged back to the ocean. The remainder of the sea water used for condensing the vapour becomes added (make-up) to the process. After chemical treatment for the control of scale and de-areation to remove dissolved gases, the make-up sea water is mixed with the concentrated brine. This mixture, called the recycle stream, is pumped through the tubes located in vessels of the heat-recovery section. As previously mentioned, vapour condenses on the outside surface of the tubes. When the vapour condenses it releases heat that is transferred to the recycle flowing inside the tubes. This transfer of heat to the recycle stream increases its temperature. This re-use of heat makes the utilization of heat by the process more efficient. Finally the recycle reaches the heat exchanger. In the heat exchanger the final heating of the recycle is accomplished by the primary steam which can be produced by a nuclear or fossil-fuel source. The heated recycle is then introduced into the shell side of the vessel. At this point evaporation takes place causing some water to become vapour and to simultaneously cool the recycle. The recycle and the condensate, which is located in the fresh-water collecting trough, cascades from stage to stage. Each succeeding stage is at a lower pressure than the one before. Therefore, in each stage additional evaporation is possible. Finally the recycle and fresh water reach the lowest temperature stage. At this point both are pumped from the vessel.

Another promising process is the long tube vertical evaporator process (LTV), so called because of the vertical arrangement of the tubes. This process is shown in Fig. 2. After being warmed in heater exchangers (not shown in Fig. 2) the sea water is introduced into the first evaporator.
FIG. 2. Long-tube vertical distillation process.

FIG. 3. Electrodialysis process.
vessel. Primary steam is used to heat the sea water further causing a part of it to evaporate. A mixture of vapour and brine flows out of the lower end of the tubes. The brine falls to the bottom of the evaporator and is pumped to the next evaporator, which is at a lower pressure. Also most of the vapour is sent to the next evaporator to heat the brine. The steam that condenses in the first evaporator is returned to the boiler. The vapour that condenses in the second and all other evaporators after cooling becomes the product water.

The more often the evaporation and condensation take place, the more efficient is the use of heat; hence, in order to conserve heat, several evaporators are used in series. Finally in the last evaporator the brine is discharged to the sea. The cooled desalted water is also pumped from the system.

Brackish water

Electrodialysis is the process generally employed for desalination. It is the most advanced membrane process. An electrodialysis conversion assembly contains two different types of ion selective membranes. One of the membrane types allows passage of the anions and the other allows passage of the cations. By alternate arrangement of such membranes as shown in Fig. 3 it is possible to produce compartments that are depleted in salt and compartments that are enriched with salt as compared with the salt concentration in the brackish water feed.

An electric current imposed across the cell causes the ions to move toward the electrode of opposite charge. As shown in Fig. 3, by the alternate arrangement of the cation and anion permeable membranes, alternate compartments are depleted in salt, thereby producing less salty water than the feed. The process may be repeated with the depleted salt stream serving as feed to another cell until the desired concentration is reached. Normally the electrodialysis process is designed to produce a product that contains a few hundred parts of salt per million parts of water.

ENERGY REQUIREMENTS

The energy required to separate water from a salt solution is appreciable. Even the minimum work for the separation of fresh water from sea water at 25°C is about 0.71 kWh/m³ [1]. This amount of work is independent of the process of separation. In actual processes, however, considerable energy must be expended to overcome fluid friction, pressure losses, finite temperature differences in heat exchangers, heat losses and fluid mixing when there is a temperature or concentration difference. When all the losses are taken into account, the energy required in a modern multi-stage flash-evaporator plant is normally 50,000 or more kcal/m³.

For brackish water the minimum energy requirement is primarily a function of salt concentration and to some extent the composition of the salts present. The minimum energy required for desalting sodium
chloride solutions at 25°C is as follows [1]:

<table>
<thead>
<tr>
<th>Salinity (ppm)</th>
<th>Energy (kWh/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 000</td>
<td>0.037</td>
</tr>
<tr>
<td>6 000</td>
<td>0.129</td>
</tr>
<tr>
<td>3 000</td>
<td>0.065</td>
</tr>
<tr>
<td>1 200</td>
<td>0.026</td>
</tr>
</tbody>
</table>

Many brackish groundwaters and agricultural drainage water contains no more than a few thousand parts of salts per million parts of water (ppm). As can be seen from the tabulation the minimum energy required for desalting such brackish waters is a small fraction of that required for desalting sea water.

DEVELOPMENTS IN NUCLEAR REACTORS

By the end of 1966, nuclear power plants in operation had a total capacity of nearly 9000 MW(e). These plants have performed well and have provided a firm basis for the development and the costing of further similar plants. The developments in existing systems, particularly increases in size and more compact designs, have led to very great reductions in the capital cost per kilowatt installed. The capital costs for some recent contracts have been equivalent to about $20/kW(th) for the nuclear-steam generating system, which could supply a desalting plant and this figure may go down to $15/kW(th) with further improvements. Figure 4 shows the trends in the capital costs of nuclear plants of various types with increasing size and associated improvements in design. The capital costs have not been normalized and refer to the conditions and assumptions used in the countries of origin; therefore, no comparison between reactor types should be made.

![Graph showing capital costs for various types of nuclear power plants and conventional steam-electric generating units.](image)

**Note:** These costs refer to the conditions and assumptions used in the countries of origin and do not, therefore, afford a basis for comparison between reactor types.
The reduction in unit capital cost has been a big factor in bringing the over-all generating costs for nuclear power plants below those for conventional plants, at least in large sizes. This achievement has resulted in a dramatic increase in the ordering of nuclear stations such that, by the end of 1970, the total installed nuclear capacity will be about 35 000 MW(e) and by 1975 the figure will approach 100 000 MW(e).

As a consequence, there will be a large increase in the throughput of nuclear fuel, which is expected to give significant reductions in the fuel costs. Besides the cost of uranium and its enrichment, the principal cost components of nuclear fuel cycle for enriched reactors are fabrication and reprocessing. The fuel fabrication costs applicable in 1980 are expected to be 30 to 40% below those for the early 1970s. With regard to reprocessing, at present an industrial reprocessing plant with a nominal throughput of one ton of uranium per day leads to reprocessing charges of $50/kg. When the size is increased to 5 t of uranium per day throughput, the reprocessing charge can drop to one-half, and for a plant of 10 t of uranium per day throughput it may be less than one-third.

It is estimated that the above-mentioned improvements in the capital cost per kilowatt thermal and in the fuel fabrication and reprocessing costs could lead to steam costs of about 70¢/million kcal (about 18¢/million Btu by the mid 1970s.

Although the existing water and gas-cooled reactors can compete successfully with conventional steam boilers and will continue to improve their economics, they still have certain limitations, including rather poor fuel utilization. If the projected nuclear capacity were to consist entirely of light-water and enriched gas-cooled reactors, then the currently assured low-cost uranium reserves of 500 000 to 600 000 t would clear one, which is to say a large jump, expected to be over 500 million kW. The use of such reactors for any large-scale desalting applications would increase the pressure on low-cost uranium reserves. It is obvious that there is real need for developing advanced types of reactors offering better fuel utilization and even lower costs of steam for production of electricity and water.

In this connection, two general approaches are being followed: development of advanced converter reactors and breeder reactors.

The advanced converters include heavy-water-moderated, high-temperature gas-cooled and liquid-fuel systems. These systems all have good fuel utilization characteristics and either use or could use thorium as a fertile material. Estimates show that advanced converters of the high-temperature gas-cooled and heavy-water organic-cooled types, developed in the late 1970s could, in units of 3000 to 4000 MW(th), achieve steam costs of 48-60 ¢/million kcal [2].

The successful development of breeder reactors would free mankind for a very long time from concern about fuel resources for the production of power and process steam. The thermal breeder reactors could evolve from advanced thorium converters, mentioned above. The fast breeders could be based upon the fast reactor prototypes currently under construction. These include the 1000-MW thermal BN-350 in the USSR to which it is planned to couple a 120 000-m³/d desalting plant and the 600-MW thermal Dounreay prototype in the United Kingdom. The projections made in the United Kingdom, the USSR, and the United States
of America indicate that commercial breeder reactors could be in
operation by the late 1970s or early 1980s. A 4000-MW(th) breeder
reactor in operation by the early 1980s costing $25/kW(th), may yield
steam costs of 24-40¢/million kcal (6-10¢/million Btu). Further
developments may reduce the steam costs to 8-12¢/million kcal for
very large breeders in the 1990s [3].

Factors in the adoption of nuclear power

The initial decision on whether a nuclear plant may be economically
justified will depend on considerations such as the availability and cost
of hydroelectric power and the availability and cost of fossil fuels. Also,
because of the strong dependence of nuclear plant capital cost on size,
it will depend on the maximum unit size that can be accommodated in
the system — generally in the range of 10-20% of the total network capacity.
For developing countries and for small developed countries, the maxi-
mum unit size is unlikely to exceed 400 MW(e); where it is less than
100 MW(e), the unit capital cost is likely to make a nuclear plant uneconomic
except in very special circumstances.

Estimation of the capital cost will require a comparison of the cost
and productivity of labour for the actual location with that for the countries
which have developed nuclear power plants. Most important, perhaps,
are the economic ground rules, viz. interest rate, load factor and
amortization period.

Fixed-charge rates vary from about 6% to about 15% depending on
the country and on whether a utility is state-owned or private. The lower
the fixed-charge rate the more favourable will be the case for a nuclear
plant because of its relatively high capital cost.

The appropriate load factor depends not only on the availability
factor which the plant could achieve but also on the system to which it
will belong. Many existing reactors have been shown to be capable of
an annual availability factor of over 75% and current designs of proven
reactor types are expected to achieve at least 80-85% availability. The
higher the load factor the better is the case for a nuclear plant because
of the latter's relatively high capital cost. In competition with fossil-
fuelled plants, the low fuel cost of a nuclear plant justifies its use as a
base-load station throughout most if not all its life, but where a system
is at present dominated by hydro-power the problem of assigning a
realistic load factor is more difficult.

While no power reactor has been in operation for more than about
11 yr, careful measurements and analysis and, in some cases, accelerated
tests, have been made of the factors that could limit plant life. Based
on this work current designs of proven reactor types are expected to
have a life of 30 yr or more. For economic comparisons, an amorti-
ization period shorter than the expected plant life may, of course, be chosen.

Several important considerations arise in respect of the fuel cycle
for the various reactor types, particularly the likely cost trends in basic
components and their effect on the total cost. Before discussing these
components, two general points may be mentioned. Firstly, the very
small quantity of fuel required by a nuclear plant as compared with a
conventional plant tends to minimize the required provision of transport
to the plant site and thus to reduce the effect of the uneven distribution
of fuel resources in the world. Secondly, considerable progress has
<table>
<thead>
<tr>
<th>Items</th>
<th>Percentage of total fuel-cycle cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium concentrate supply</td>
<td>25 - 35</td>
</tr>
<tr>
<td>Conversion to UF₄</td>
<td>~ 5</td>
</tr>
<tr>
<td>Enrichment</td>
<td>25 - 35</td>
</tr>
<tr>
<td>Fuel-element fabrication</td>
<td>15 - 25</td>
</tr>
<tr>
<td>Reprocessing</td>
<td>5 - 15</td>
</tr>
</tbody>
</table>

Note: The ranges shown allow for uranium concentrate prices of $6-10/lb and for enrichments of 1.5-3.0%. No credit is made for plutonium in the irradiated fuel.


been made in dealing with the special problems associated with the transport of reactor fuel elements and, particularly, irradiated fuel.

The percentage contribution of the components of the fuel-cycle cost is shown in Table I for an enriched reactor. The ranges allow for a variation in uranium ore price of $6-10/lb U₃O₈ and in fuel enrichment of 1.5-3.0%; no credit has been given for plutonium in the irradiated fuel.

The cost of uranium in the near future (10-20 yr) is the subject of considerable discussion in which conflicting views appear. It depends, of course, primarily on the requirements for uranium and the resources of low-cost ore. The present reasonably assured low-cost ($5-10/lb U₃O₈) reserves of over 600,000 t U₃O₈ were established as the result of intensive prospecting in the 1950s. It is expected that further prospecting now beginning will reveal further reserves, at least as great, in this price range. The consensus of opinion is that the price of U₃O₈ will stabilize at about $8/lb in the 1970s. The effect on the generating cost (mills/kWh) of an increase in ore price of $1/lb U₃O₈ is shown in Table II for the proven reactor types.

The current cost of converting U₃O₈ to UF₄, for feeding to the enrichment plant, is about $2.5/kg U₃O₈. With increasing scale of operations as nuclear capacity grows, this cost is expected to fall gradually to, perhaps, $1/kg in 1980.

Gaseous diffusion plants for uranium enrichment are in operation in France, the USSR, United Kingdom and United States of America, although the only firm prices available are those published by the USAEC. These are based on a separative work price of $30/kg uranium. It is not expected that this price will increase and it may even fall in the next decade or two to $20/kg uranium. The effect on generating cost of a $1/kg decrease in the price of separative work would be a reduction in the range of 0.01 to 0.02 mills/kWh for the current enriched reactors.

The present costs of fuel-element fabrication vary widely depending on the complexity of the element and on the scale of manufacture. Thus,
TABLE II. INCREASE IN GENERATING COST (mills/kWh) FOR AN INCREASE IN URANIUM ORE PRICE OF $1/lb U₃O₈

<table>
<thead>
<tr>
<th>Reactor type</th>
<th>Increase in generating cost (mills/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnox (gas-cooled)</td>
<td>0.12</td>
</tr>
<tr>
<td>AGR (advanced gas-cooled)</td>
<td>0.07</td>
</tr>
<tr>
<td>BWR (boiling water)</td>
<td>0.09</td>
</tr>
<tr>
<td>PWR (pressurized-water)</td>
<td>0.09</td>
</tr>
<tr>
<td>HWR (heavy water)</td>
<td>0.04</td>
</tr>
</tbody>
</table>


for magnox reactors the fabrication cost is about $30/kg uranium, for heavy-water reactors and AGR about $55/kg uranium, and for light-water reactors about $95/kg uranium. Process improvements and increasing throughput are expected to give large reductions of 25-40% by 1980 for the reactors using clustered fuel elements; for magnox reactors with their simpler fuel elements the reduction will be less. A 20% reduction in fabrication costs would decrease the generating cost by about 0.1-0.15 mills/kWh.

A rather similar situation exists with respect to reprocessing. For the Windscale plant in the United Kingdom with a throughput of about 5 t uranium/d the cost is about $17/kg uranium for magnox fuel and about $30/kg uranium for AGR fuel. In the latter case, a reduction of 10% in reprocessing cost would reduce the generating cost by about 0.02 mills/kWh.

Heavy-water production plants are in operation in Canada, Norway and the United States of America and present prices are around $45/kg. The heavy-water inventory for heavy-water reactors accounts for about 10 to 15% of the total capital cost. The cost of heavy water is expected to fall to about $30/kg in the coming years. This would reduce the generating cost by about 0.1 mills/kWh.

DUAL-PURPOSE PLANTS

All the processes for desalting water use energy, whether thermal, electrical or mechanical. Thermal energy is utilized in the previously described multi-stage, flash-distillation process, which is one of the most practicable for large-scale dual-purpose application in the near future. Only this process is discussed for the dual-purpose plant application. The maximum evaporator brine temperature for this process is at present limited by economic means of scale control to about 120°C (about 250°F). On the other hand, the generating costs of electric power plants are lowest when the steam is produced at higher temperatures. Because of these two facts, there are economic advantages in combining the production of water with the production of power.
Such a dual-purpose plant rather than a power-only one gives two advantages to nuclear as compared with fossil-fuelled plants,
(a) The unit cost of reactors falls more rapidly with increasing size than does that of fossil-fuelled plants,
(b) For economic production of desalted water such installations should operate at very high load factor, which favours a power plant with low fuel costs.

The normal method of coupling the power and desalting plants is by means of a back-pressure turbine in which the steam is expanded from the initial pressure and temperature of the reactor to the conditions acceptable to the brine heater of the desalination plant.

With standard back-pressure turbines there is a range in this ratio of water to power over which the incremental water cost is nearly constant, the upper value of this range depending on the steam conditions. For example, for high-temperature reactors producing superheated steam, this value is around 0.3 million US gal/d/MW(e)(about 50 litres/kWh). For reactors producing saturated steam it is about 0.8 million US gal/d/MW(e) (about 125 litres/kWh).

For agriculture the power requirements may be relatively small so that essentially the energy source would be utilized for water production. The power requirements would be for in-plant use and for the pumping of desalted water. In such a situation it would be desirable to have a relatively high water-to-power ratio without economic penalty. In addition to the possibility of designing a single-purpose reactor for desalination, discussed below, there are several ways of increasing this ratio, for example:
(i) Steam may be by-passed around a back-pressure turbine. With present reactors and nuclear fuel costs this is expensive (the incremental cost of heat is doubled at least). When fuel cost is very low, this can be the preferred technique.
(ii) The commercial reactor may be redesigned to produce heat at a lower temperature, and, it is hoped, at a lower cost per unit of heat output.
(iii) Increasing the acceptable maximum brine temperature in the evaporator.
(iv) The mechanical energy available from the high-temperature steam could be used in an additional desalination process such as vapour compression that requires mechanical energy.
(v) In a suitable terrain it may be possible to provide some peaking power by a pumped storage arrangement for power production.
(vi) It may be possible to develop a market for low-priced power supplied on an interruptable basis for special industrial applications.

Under most circumstances special reactor designs are not necessary as it seems likely that the present type of power reactors can be applied in dual-purpose plants for municipal and industrial use and for very special agricultural applications involving high-value fruits and vegetables. Application to general agricultural purposes, if achieved, would require very large units and very low fuel costs; and would need to be accompanied by improvements in distillation and agricultural technology. This necessity for low cost and the length of time that will elapse until such units are possible indicates that developments should most likely be concentrated in the advanced converter and breeder reactor fields.
TABLE III. COST OF DESALTED WATER FROM A DUAL-PURPOSE NUCLEAR PLANT\textsuperscript{a}
(18 800 m\textsuperscript{3} /d, 150 MW(e), 90% load factor)

<table>
<thead>
<tr>
<th>Items</th>
<th>7%</th>
<th>10%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed charge</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steam energy cost (US $/million Btu)</td>
<td>19.5</td>
<td>21.3</td>
</tr>
<tr>
<td>Fuel costs (US mills/kWh)</td>
<td>2.30</td>
<td>2.30</td>
</tr>
<tr>
<td>Electric power cost (US mills/kWh)</td>
<td>5.71</td>
<td>6.87</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Annual production cost of desalted water (US$ x 10\textsuperscript{3})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct costs</td>
</tr>
<tr>
<td>Steam energy</td>
</tr>
<tr>
<td>Electric power</td>
</tr>
<tr>
<td>Chemicals</td>
</tr>
<tr>
<td>Operation and maintenance labour</td>
</tr>
<tr>
<td>Stores and maintenance material</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Indirect costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed charges</td>
</tr>
<tr>
<td>Tube replacement</td>
</tr>
<tr>
<td>Total annual cost</td>
</tr>
<tr>
<td>Water cost USD/m\textsuperscript{3}</td>
</tr>
</tbody>
</table>

\textsuperscript{a} See Reference (4).
An example of a study for a dual-purpose nuclear plant involving agricultural uses for the water has been made for the Borg El-Arab Project, United Arab Republic [4]. Consideration is being given to constructing a dual-purpose nuclear reactor producing 150 MW(e) (net) and 20,000 m³/d of desalted water. The study includes the establishment of a 4000-ha experimental agriculture project [5].

The team [4] involved in the study concluded from a preliminary economic analysis that the use of high-cost desalted water (see Table III) to supplement the limited conventional sources is economically feasible at current prices for the special circumstances of olive production. Additional information, as would be obtained if the pilot project were constructed, is necessary in order to determine possible crops and cropping patterns to permit water production throughout the year. Also from the pilot project the economic quantity of desalted water, taking into account yield, salt tolerance and application methods, would be determined.

A project of particular interest to the Agency is the joint IAEA/Mexico/United States study on the technical and economic practicability of constructing dual-purpose plants to supply water and electricity, and possibly single-purpose water-only plants later, to the border states in both countries near the head of the Gulf of California. The study is detailed and far-reaching and includes surveys of hydrological and soil conditions, seismological and geological surveys of possible plant sites, arrangements for the best use of reactors and water plants, problems of transporting and distributing the water produced, and of using the power produced. It is considered that much of the water produced would be used for agricultural purposes. Therefore, the capacity of the desalination plant must be large to produce desalted water at sufficiently low cost. A one-thousand-million-US-gal/d¹ conceptual study has been conducted to provide preliminary plant design and economic data with a view to extrapolating it to larger sizes. Either single plants consisting in general of a multi-stream water plant coupled to one or more reactors, with or without power production, or complexes of such plants including common facilities, may be envisaged.

Consideration has been given to the consumption within the region of large amounts of base-load power produced in large dual-purpose plants. The electric power that could be supplied by single plants has been assumed to range from 600 MW(e) (corresponding to dual-purpose plants having the largest available single-unit reactor) up to 2000 MW(e) (corresponding to those producing one thousand million gal/d desalted water). The power requirements in the area have been investigated, and it appears that from 1970 to 1975 units of 750 to 1000 MW(e) must be installed annually, with the constraint that the grid system does not allow for individual stations of more than 2000 to 3000 MW(e). It has been decided, therefore, to study the possible use of single-purpose water-only or low power-to-water ratio desalination plants for the long-term programme. But for supplying the needs of the region in the near future, the power produced in dual-purpose plants at present available would pose no marketing problems. The size of the nuclear reactors considered is in the region of the largest available unit size envisioned by 1975. However, other sizes and concepts can be considered for

¹ At a 90% load factor, the annual output would be sufficient to provide one metre of water to 125,000 ha.
1980 and 1985 needs. Studies on the reactor concepts, which are reasonably expected to be available in the 1975-1980 interval, such as light-water reactors, graphite pressure-tube reactors and heavy-water-moderated, organic-cooled reactors, have been revised and evaluated.

**Single-purpose reactors for desalting**

Reactors producing high-temperature heat may be attractive when power is the principal commodity desired and heat for desalting is a by-product. However, in situations where a large quantity of low-cost heat for desalination is required and the need for power is relatively low, the high-temperature characteristic of the high-efficiency power-only system may have less economic importance.

A study was made by the Oak Ridge National Laboratory, USA, [6] to investigate design features and economics of a low-temperature, sodium-cooled, fast-breeder reactor for single-purpose desalting applications. The premise that low-temperature, sodium-cooled fast reactors should be particularly well suited as heat sources for desalting applications was based on the following considerations:

1. Low fuel-cycle costs typical of high-temperature fast-breeder reactors might be improved even further by using a metal blanket,
2. Lower cost equipment could be used if coolant and steam temperatures were lower than those used for high-efficiency power-only systems, and thus unit heat costs would be reduced in applications requiring large quantities of heat for brine evaporation with little or no electrical power generation, and
3. Problems involved in proving sodium component reliability in the 1000 to 1200°F range would be by-passed, and thereby the number of problems to be solved before large sodium fast reactors could be built would be reduced.

The results of the ORNL study confirm the favourable potential of this concept as a desalination-plant heat source. Surveys of sodium equipment costs indicated that, in comparison with high-temperature plants, substantial reductions in capital cost should be realized by designing the system for low-temperature operation. The use of a metal blanket instead of an oxide blanket appears to offer an improvement in breeding gain, with comparable if not lower processing and fabrication costs and thus a net improvement in fuel-cycle costs. Refuelling frequency is not increased because of low metal burn-up. A sodium temperature of 800°F maximum, suitable for using the metal blanket, permits production of saturated steam from 260 to 495°F without imposing severe operating conditions for the heat transfer equipment.

In view of the economic and operational advantages projected by this study, it appears that sodium-cooled fast reactors designed for low-temperature operation would at least be well suited for desalting applications requiring limited by-product power and very large quantities of desalted water.

**COST OF DESALTED WATER**

Ten years ago, the cost of desalted water was at least US $1.00/m³. For some of the larger plants (4000-6000 m³/d), built within the last
TABLE IV. DESALTED WATER COST
(Nuclear dual-purpose case studies)

<table>
<thead>
<tr>
<th>Plant capacity</th>
<th>Desalted-water cost</th>
<th>Fixed charge</th>
<th>Proposed location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mgd(^f) Nominal (KW(e) net) (US$/m(^3))</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>150</td>
<td>16.9</td>
<td>7.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20.3</td>
<td>19.0</td>
</tr>
<tr>
<td>30</td>
<td>150</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>50</td>
<td>300</td>
<td>12.5</td>
<td>7.81</td>
</tr>
<tr>
<td>100</td>
<td>200</td>
<td>7.6</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>17.7</td>
<td>10.0</td>
</tr>
<tr>
<td>150</td>
<td>1,600</td>
<td>8.9</td>
<td>5.4</td>
</tr>
</tbody>
</table>

\(^a\) Proposed Borg El-Abab Project in the United Arab Republic. October 1966.

\(^b\) Under construction at Shevchenko, Caspian Sea, USSR.


\(^e\) Engineering and Economic Feasibility Study for a Combination Nuclear Power and Desalting Plant USAEC No. TID-28330 (December 1965).

\(^f\) Mgd = million gallons a day.
few years, the cost is about US$ 0.25/m$^3$. The cost of desalted water from very large desalination plants with capacities of around 400,000 m$^3$/d, operated in conjunction with power generation has been estimated as low as US$0.06/m$^3$. Larger plants such as the size being considered in the IAEA-Mexico-US study with improved technology may eventually produce desalted water at costs below US$0.03/m$^3$.

Cost of desalted water from nuclear dual-purpose plants based on several case studies for specific locations are listed in Table IV. The addition to the capacity that affects the cost, the ground rules of the studies were not the same, hence a direct comparison should not be made between the studies.

Hunter [7] presented cost data at the Water for Peace Conference for a range of desalted sea-water-plant capacities from one to one thousand million US gal/d. The costs are projected from the time a plant with a given capacity could be placed on-stream. The curves in Fig. 5 show anticipated cost reduction with time.

For the two smaller capacities of one and ten million US gal/d, the energy costs were based on those assumed as most probable using fossil fuel. For the 100- and 1000-million US gal/d capacities nuclear energy costs were assumed. For the latter part of the 1000-million-gal/d curve, breeder reactors were assumed to provide the energy at the lowest cost.

Comparable studies do not exist for electrodialysis plants utilizing nuclear energy. However Gilliland reported [7] in 1965 that the cumulative production in the past 10 yr from desalting by electrodialysis exceeded one thousand million US gallons. Gilliland concluded that experience with these plants has shown that, for desalting brackish water, reliable plants with capacities up to about 100 million US gallons per day can be built. Based on electrical energy costs in the range of 4 to 8 US mills/kWh, he projected costs over a wide range of plant capacities as shown in Fig. 6.

For dual-purpose plants cost allocation between water and power is important. Several methods are reviewed in a technical report of the International Atomic Energy Agency [9]. One method used in a number
of studies is the power credit method. An example of this method is
the Israeli study [10] listed in Table IV. This engineering feasibility
study was done in detail and it may be of interest to list some of the
principle ground rules on which the study was based:
1. The range of net saleable electric power is 175-200 MW.
2. The range of the desalting plant capacity is 100-150 million m³/yr.
3. The dual-purpose plant will be ready for full commerical operation
by 1972.
4. Israel will own the nuclear fuel, with appropriate payment for US
toll enrichment, reprocessing and credit for plutonium.
5. The credit for saleable power is 5.3 mills/kWh which represents
Israel Electric Corporation's estimate of the cost of producing power
in the most economical single-purpose plant in the range of the study.
6. The cost of fossil fuel is $12.85/t(metric), C.I.F. unloaded,
(39 000 000 Btu/t (metric), lower heating value).
7. The annual cost for the reference plant will be determined for 5%, 7%
and 10% fixed-charge rates. These fixed-charge rates include
interest, 30-year sinking fund depreciation, normal insurance, and
costs in lieu of local taxes. They do not include interim replacement,
nuclear rider on property insurance, or nuclear liability insurance,
all of which are included in operating costs.
8. Neither capital nor annual costs include general Israeli taxes or
customs duties.
9. Estimates for the reactor, turbogenerator and major equipment
for the desalting plant are to be obtained from US manufacturers.
10. Local Israeli materials and equipment will be used where it is practical
to do so.

The importance of fixed charges can readily be seen from Table IV.
For optimized water cost, doubling the fixed charges from 5 to 10% more
than doubled the cost of desalted water, from 7.6 to 17.7¢/m³.
SUMMARY

It has been estimated by Hammond [11] that if nuclear desalters were utilized to produce irrigation water for one tenth of the world’s need for new food supplies in the next 30 years, nuclear desalters would rival or exceed the growth rate for electrical power reactors. Unfortunately not all the elements of the solution to the application of desalted water to irrigation are yet available. Indeed it is not clear that they can be found.

In the past food output has been increased primarily by placing more land under cultivation, but this will no longer be possible. A major portion of the fertile well-watered lands are under cultivation and less favourable or marginal lands are available. There is no hope of finding enough new land to double the world food output.

There are important differences in the type of farming that may be possible when irrigation with desalted water is practised. Some of the more important considerations in addition to adequate storage to balance out fluctuations in demand with plant output, are:
1. The land must have nearly a year-round growing season.
2. Crop-utilization efficiency of water must be high to minimize the use of desalted water for a given amount of crop produced.
3. Sprinkler irrigation would be preferred.
4. Fertilizer application must be optimized.
5. Less drainage would be required.
6. The application of an adequate crop pattern or rotation would be necessary.

CONCLUSIONS

The technology now available or under current development seems adequate for making nuclear desalination economically feasible for municipal and industrial use. The technology must, however, be proved in the first plants. For large-scale irrigation with desalted water there are still important gaps in the technology. It will be necessary to develop an approach to a plant primarily producing desalted water. Also we will need either to improve evaporation or another desalination process. Reduction in the cost of energy through improved reactors will also be required. These improvements in technology must be finally translated into reality through the construction and operation of experimental and prototype plants of sufficient size so that full-scale plants with sufficient capacity for large-scale irrigation can be constructed.

The projected cost of 20-25$/100 US gal² of 100 to 200 million gal/d can probably be reduced to 15-20$/1000 US gal by some improvement and by increasing the size to 1000 million GPD for plants to operate in the late 1970s. Advanced reactors and improved desalination technology should permit 1000 million GPD plants to produce desalted water for about 10-15$/1000 US gal³ in the late 1980s.

² 20$/100 US gal is equivalent to 5.3$/m³.
³ 10$/1000 US gal is equivalent to 2.6$/m³.
REFERENCES

FACTORS AFFECTING THE ABILITY OF AGRICULTURE TO PAY IRRIGATION-WATER COSTS

M. A. HAGOOD
LAND AND WATER DEVELOPMENT DIVISION,
FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS,
ROME, ITALY

Abstract

FACTORS AFFECTING THE ABILITY OF AGRICULTURE TO PAY IRRIGATION-WATER COSTS. There are no universally acceptable standard criteria for determining how much agriculture can pay for irrigation water. Justification of cost will depend upon the country's need to develop its soil and water resources for food, for international trade, and for its cumulative effect on other industries in comparison with other possible uses and their over-all contributions to the economy.

Social and political conditions often have as much or more influence on development cost decisions than do strictly economic analyses. Many studies indicate that US $6.10/1000 US gal is an upper limit of acceptable costs for developing irrigation water at present economic levels. Under private development and on projects where water users must pay total water costs, methods are available for making feasibility budgets based on present prices. Because of inflation, world food shortage, recessions, future population and other unknown factors, it is hazardous to predict how much farmers or agriculture can pay for irrigation water. Better utilization of water available now offers opportunities for "developing" sources at costs much less than those for sources such as sea-water conversion.

Water not at present fully utilized is becoming limited and will be frequently expensive to develop and deliver. From this situation competition will arise for the future use of water, and for water that has traditionally been used for agriculture. Concerning this problem the question is posed regarding how much can agriculture pay for water for irrigation?

SOIL AND WATER ARE BASIC RESOURCES

Since soil and water are still the basic resources available for man's existence and the economies of most major countries are based on the use of these resources, local planners as well as individuals and industrial users need to know the value of agriculture to the economy. Newly developing countries must anticipate the cumulative effects of basic water development on the general economy, and more industrialized countries should decide if and at what point industrial uses of water will infringe on the basic agricultural wealth, and thus start a chain-reaction reduction effect.

SOCIAL CONDITIONS MAY MAKE MONETARY DECISIONS LESS IMPORTANT

In less developed areas, there may be an urgent need for economic growth to keep pace with expanding population and demands for improved
living standards. The need for a specific section of development, for example increased food production, may be so critical and clear that no alternative possibilities of economic development will satisfy natural needs. In these cases social, public and other intangible benefits, which cannot be evaluated financially, may be the determining factors in project justification.

FACTORS AFFECTING AGRICULTURE'S ABILITY TO PAY

Even in the most highly industrialized countries, agriculture still plays a very important part in the over-all economy, and even if only a small percentage of the population is actively engaged in farming, the largest labour force is usually involved in the manufacturing, processing and distribution of food and fibre. A recent study [1] of one irrigation project in the United States of America shows that, for each 10,000 acres of land irrigated, there were 69 farm operators and 56 farm labourers, or 125 persons who made $792,000/yr for their labour, management and capital. Secondary industries associated with receiving and processing the agricultural commodities from the farms employed 1290 workers, with a return on labour, management and capital of $9,769,000. Related industries, those providing services and supplies to all people involved in the project, employed 6346 people, with a return of $32,517,200 for their management, capital and labour.

MOST WATER DEVELOPMENTS ARE MULTI-PURPOSE

An irrigation scheme is seldom constructed strictly on its own merits, unless it is a private groundwater pumping scheme. Most irrigation projects also involve multiple water-use programmes, such as hydro-electric power, navigation, flood control, and more recently, recreation.

It is difficult to measure in monetary terms the benefits of a multi-purpose project since some of the benefits tend to be so widely diffused that they cannot be measured by present techniques. Irrigable acres developed and kilowatt hours of electricity produced can be determined, but to what extent other citizens, business and industry benefit is very difficult to ascertain. As a result, no one has devised a satisfactory system of computing the equitable share that should be paid by agriculture, other enterprises and the government, which is applicable to all countries and situations.

In newly developing countries, a government may decide that water costs are comparatively unimportant since an irrigation project will have a cumulative effect, which could be more important than the material benefits to the direct water users.

In more developed countries where agricultural water may be consumed by industrial and domestic users, many economists have set a studied, but still arbitrary, cost of about $US 0.10/1000 gal. or $US 0.0264/m³ as being the upper limit for irrigation under present economic conditions.
HOW MUCH CAN FARMERS PAY FOR WATER?

When water is to be costed or when a decision is to be made concerning the economic feasibility of a project, based only on the farmer’s ability to pay, there are established procedures and systems that can be applied.

A farmer can pay for water all that income which remains after he has paid for other crop production costs, food, clothing and shelter. But this could only be expected from a very undeveloped society or from a very uneducated farmer. In a developed society a man expects, in addition to his basic needs, to be allowed a reasonable return on his own efforts, management abilities, and a comparable return on capital investments, which he has obtained from labour and management outputs. The farmer should be entitled to a standard of living comparable to his abilities and commensurate with the rest of the society of his

### TABLE 1. NET RETURNS FROM SUPPLEMENTARY IRRIGATION[2]

<table>
<thead>
<tr>
<th>Increased returns</th>
<th>525 acres per acre of grain</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 bushels/acre increases = 60 bushels × 525 acres = 31,500 bushels × $1.25 =</td>
<td>$39,375 $75.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Increased costs</th>
<th>525 acres</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Irrigation (fixed and variable)</td>
<td>$15,073</td>
<td>$28.71</td>
</tr>
<tr>
<td>2. Fertilizer–96 lb of additional N (34 used before irrigation) making a total of 130 lb N/ac on 525 acres at $1 f + tax</td>
<td>5,250 $15.00</td>
<td></td>
</tr>
<tr>
<td>3. Extra cultural practices and costs associated with dealing with more stubble, etc. $2.00/ac</td>
<td>1,050 $2.00</td>
<td></td>
</tr>
<tr>
<td>4. Additional harvesting costs on additional yield $2.15/ac</td>
<td>1,129 $2.15</td>
<td></td>
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<tr>
<td>5. Interest on additional operating capital $25,000 + 2 × 6.5% =</td>
<td>725 $1.36</td>
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</table>

**Total increased costs**

| $23,217 | $44.22 |

**Net increased return to owner-operator’s labour and management**

| $16,158 | $30.78 |
country. Unless this opportunity is allowed, the agriculture of a country will always remain unsophisticated and below its potentials.

Most systems of feasibility determination rely on cost of production-yield analysis similar to a partial budget based on the economics of drilling a well and the sprinkler irrigation of large-scale wheat operations in Eastern Washington, USA, shown in Table 1 [2].

**FACTORS WHICH AFFECT FARMER'S ABILITY TO PAY WATER COSTS**

In feasibility studies that involve large projects, it is necessary to consider many variables such as size of a farm unit, possible cropping and livestock enterprises, the physical aspects of the land and climate, and expected long-term economic conditions.

This type of system must include a thorough analysis of expected production costs versus expected returns. These estimates can be calculated fairly accurately a few years in advance, but no one can predict sufficiently in advance to realistically establish costs and prices that would safely establish prices to be paid by farmers over a long period for water. A series of bad-weather years, unexpected disease or soil problems, and world-market trends, could be disastrous to an otherwise well-planned and managed system. On the other hand, improved crop varieties, favourable weather and prices might make it possible for a greater share of total water costs to be paid. For these reasons a realistic approach might allow flexibility based on a cost/price index, but should not be so severe that they result in reducing incentives for the maximum utilization of a farmer's labour and management skills.

**POSSIBILITY OF SOCIAL AND POLITICAL CONDITIONS PREVENTING EFFICIENCIES IN WATER-USE RETURNS**

Studies have shown increased production and increased net returns when larger production units are utilized as long as management is competent. This economic principle may conflict with other aims of developing countries, since there is usually a need to provide employment and farming opportunities to the local people. Serious consideration should be given to providing employment through other non-farming development schemes when maximum agricultural production is desired. It may be easier to train some people in semi-skilled manufacturing or processing work than in modern agricultural skills.

In developing countries, where improved agricultural production is vital to the economy, schemes that provide top management and close supervision may be justified.

Since many farmers lack the capability for top efficiency in management, they produce less and therefore cannot pay as much for water if they are to remain in business. In project planning it is necessary to make feasibility studies based on less than top efficiency, whereas usually a higher level of management is obtained on privately developed operations.
AGRICULTURAL PRACTICES CHANGE WHEN WATER PRICES BECOME HIGH

Once a pricing system has been established on a project, very few changes are ever made but, when water costs must be raised because of either delivery costs or in order to discourage excess usage, the sequence of possible adjustments available to farmers as water prices rise are, first, that they shift to drier treatments on existing crops; second, they reduce the acreage of the higher use crops and allocate the water to those with a lower requirement; third, they leave the less productive land idle; fourth, they leave parts of the better land idle — planting only more productive crops; and fifth, they cease farming altogether since costs continuously preclude a profitable operation.

Throughout these adjustments farmers will, as long as it is profitable, continue to improve water-use efficiencies on their farms by all possible means. When labour is relatively inexpensive, extra labour is used to assure efficiencies, but when labour or water costs become uneconomical, capital improvements will be made. Land levelling, canal lining, concrete pipe lines, portable sprinkler systems, solid set sprinklers and complete project pressurized systems will often be employed.

In areas where losses are recoverable through re-use of surface run-off, or by pumping groundwaters from over-irrigation leaching effects, the main savings of developing present water resources are through the prevention of evaporation and losses from unwanted vegetation.

THE LEAST EXPENSIVE WATER TO DEVELOP IS ALREADY AVAILABLE

The easiest and often the cheapest water to develop is that which is now being lost needlessly. If a 10% saving of water could be achieved on a farm normally using 1 ha-m/yr, a large investment could be justified.

Ten per cent of 1 m over 1 ha = 1000 m$^3$ = 264 000 US gal. At a price of $0.05/1000$ US gal, $13.20/ha/yr$ could be saved.

If money is available at 5% an investment of approximately $264/ha$ could be justified at only half the cost some economists suggest as reasonable for sea-water conversion.

REFERENCES


OPEN DISCUSSION ON
"DESMULTED WATER AND THE POSSIBILITY
OF ITS USE IN AGRICULTURE"

L. E. DANFORS: Several values seem to be used in Hagood's paper
to denote the price of water. Is it not possible to use a uniform criterion
for assessing these values? For example, take the value of the water in
the field in a form accessible to the plants and then discuss backwards
the costs of getting it there. Plant value minus application costs would
then represent the net return.

M.A. HAGOOD: This approach is possible in computing the value
for crop production, but will have many disadvantages arising, for
example, from management practices and other factors which may be
of greater influence than water. Much information would also be needed
on the contribution of additional water to increased yield. Regardless
of the method of approach, we have to know the value of the water delivered
to the field.

D. KIRKHAM: Theoretically, if brackish water is almost continuously
poured through a highly porous sand, it should not be toxic to the plants,
and there should still be enough air space in the sand for roots to develop,
provided the brackish water contains nutrients. In arid areas, the water
would have to run almost continuously, or evaporation would bring salt
to the surface, concentrations would become too high and the plants would
die. If such brackish water were to be used, it would have to be extremely
cheap, since large amounts would be needed. The drainage system would
also have to be excellent, to ensure removal of the brackish water passing
downwards through the root area.

Desalination is not an urgent matter in the midwestern states of the
United States of America, since there is enough water to leach salts from
the soil, except in specific small areas. The state of Iowa, for example,
has only 800 ha where salt (sodic soil) is a problem (G.M. Schafer, Proc.
Iowa Acad.Sci. 59 (1952) 288). The following is a quotation from the
American Scientist, 53 (1965) p. 101:

"Man looks longingly at the seas as an inexhaustible source of water;
and so it is, but at a high cost. Large quantities of energy are re-
quired to reduce the salt content to tolerable levels. Many methods
have been tried, and work satisfactorily, but cost hovers at a level
about ten times that of present water systems. Considerable publicity
has been given recently to the report of a Task Committee. ... This
report proposed the development of nuclear-fired plants to produce
large volumes of water by distillation of sea water, plus vast quanti-
ties of by-product electric power. The proposed reactors and dis-
tilling units are larger than existing facilities by a factor of several
hundred. Allowing for necessary research, scaling up of plants in
several steps, and financing, the estimated water and power costs
for one of the largest facilities contemplated (an 8300 thermal mega-
wat nuclear plant capable of producing 620 million gallons per day
of water megawatts and 1460 of electric energy) is something of the order of
twenty-five cents per thousand gallons, depending on the price paid
for the electric power generated. Delivery costs are not included."

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The article goes on to say that disposal of radioactive wastes, heat and salt brine pose difficult engineering problems and that some of these problems did not appear adequately covered in cost aspects of the report. The article continues:

"Accepting the costs estimates of the Task Committee as realistic, what is the competitive position of water from a large nuclear-fired plant? The householder may pay thirty-five to forty cents per thousand gallons for water delivered to his home. Except for high value crops, the agricultural user apparently cannot afford to pay more than about five cents per thousand gal. Nuclear plants may therefore be acceptable in some areas for household and industrial water, but not for the much larger quantities required by agriculture.

"Experiments with the application of atomic energy and of other types of energy to desalination will be, and certainly should be, continued. Some islands and desert areas simply have little hope of developing other supplies. However, we should not ignore potential sources of natural water which may still be developed for most areas by diligent pollution control and by imaginative engineering."

The article points out the relatively high cost to agriculture of desalination, but does not refer to costs that could be paid for a specific high-value crop.

According to a 1964 M.S. thesis of Alan P. Kleinman on file at the University of Arizona, Tucson, Ariz., entitled "The Cost of Pumping Irrigation Water in Central Arizona", cotton is one of the most valuable irrigated crops. The thesis (p. 91-92) gives $15.42/acre ft as an average high cost paid by farmers for irrigation water and $6.92/acre ft as an average low cost. These figures correspond to costs of 4.73¢ and 2.12¢ respectively/1000 gal, on the basis of the conversion: 1 acre ft = 325,000 US gal. (1 acre = 43,560 ft², 1 ft³ = 7.481 US gal)

According to Kleinman, agriculture can be sustained in Arizona with water containing about 4000 ppm of salt. Water from the Salt River Project there contains 3500 ppm and is used quite generally.

With regard to cotton, Kleinman's thesis (p. 103, Fig. 25) gives $1.63 \times 10^6$ gal/acre as the most advantageous amount of water to use for cotton. The pumping of water for 400 ft to give this amount of irrigation would cost $53.00/acre, or $39/1630 = $0.033/1000 gal.

Interesting data on the amount of salt that crops can tolerate can be found in the US Salinity Manual, Agr. Handbook No. 60, US Dept. of Agriculture, Feb. 1954. Figure 3 and Table 8 of this Handbook show that barley can tolerate 0.9 g salt/100 g water, which is the same as 9000 ppm salt.

The salinity of sea water, according to the Handbook of Chemistry and Physics, 40th Edn (1959) p. 3369, is 30 g/litre. Since barley can tolerate only 9 g/litre, two-thirds of the salt would have to be removed from sea water to raise barley. Barley is a low-value crop, but according to the above-mentioned US Salinity Handbook, p. 67, sugar beet and cotton, which are high-value crops, can stand this same salinity.

It should be remembered that fresh water can be mixed with brackish water. This is often done in Arizona and other parts of the world.

According to the article in American Scientist, one might obtain water for as little as 25¢/1000 gal by nuclear desalination if the plant can sell its electricity. Thus, the Kleinman figures for the high-value
cotton crop (4.73 - 2.12¢/1000 gal) indicate that sea-water desalination is 5-10 times too expensive for agriculture.

Some remote possibilities might be mentioned in connection with use of sea water. I understand that water fresh enough to drink can be pressed from a fish. Now, although fish and plants are not comparable, this raises the question whether crop plants could be bred, possibly by means of radiation-induced mutations, to grow in saline water and still yield non-saline fruits and crops. In the meantime, we should perhaps endeavour to make better use of plants that can already stand saline conditions.

Possible ways of using sea water directly are being explored by Dr. Hugo Boyko and Elizabeth Boyko. Dr. Hugo Boyko had an article, entitled "Salt Water Agriculture", in the March 1967 issue of Scientific American.

A personal communication sent to me on 8 March 1967 by a colleague, contains the following pertinent paragraph:

"A new dimension may soon be added to irrigation agriculture. Work sponsored by the AEC... shows present costs of desalination of sea-water as 20¢/1000 gal, with future costs anticipated as low as 10¢/1000 gal. At these cost levels, it has been estimated that food production based on desalinized water can be economic in desert regions close to an ocean with favourable temperatures. However, the high capital investment will require a careful blending of the best that agricultural technology has to offer if such a system is to remain solvent."

D.B. BRICE: Except in very unusual circumstances, it is highly unlikely that inexpensive, nutrient-containing brackish water will be available in arid areas in sufficient quantity for continuous irrigations. It would not therefore seem that this scheme would offer much promise for arid regions.

The Task Committee report quoted from the American Scientist is identified in the article as "An Assessment of Large Nuclear Powered Sea Water Distillation Plants", March 1964, 31 p., Superintendent of Documents, US Government Printing Office, Washington DC, 20402. What is not clear from the article is whether the author also examined the "Appendices to An Assessment of Large Nuclear Powered Sea Water Distillation Plants", March 1964, 478 p., Superintendent of Documents, US Government Printing Office, Washington DC, 20402, which gives considerable detail and shows that the engineering problems involved in the disposal of radioactive waste, heat and brine were adequately considered.

While scaling up is required, the report gives an orderly programme for accomplishing it. An 1800-MW(e) plant producing 150x10^5 gal (US)/d is at present planned in California. Its construction will be a big step towards testing this technology.

Figures are cited for the cost paid by farmers for irrigation water in Arizona. The figures quoted represent the price paid by the farmers, but the actual cost of water may be different from the price paid by the farmer, because, in the area mentioned, irrigation water is usually subsidized.

The cost data discussed in my paper related to the estimated total cost of desalting water. One must be careful, when comparing alternative
water supplies, to ensure that the estimates are on the same basis of
total cost of providing a given quantity of water to a specific site.

W. R. GARDNER (Chairman): I agree with Mr. Kirkham that we
should more fully explore the possibility of developing salt-tolerant plants.
However, we haven't yet made much progress in developing economic
plants which will grow in sea water. The use of brackish or highly saline
water is feasible only where there is sufficient rainfall during at least
part of the year.

Regarding Mr. Brice's comment, the quality of the water also affects
its value. Some estimate of this is possible, but a completely satisfactory
means of determining value is not yet known.

W. H. GARDNER: I have collected the following comments from
colleagues specialized in agricultural economics. In general, experience
and the results of economic analysis indicate that agriculture is still not
in a good position to repay the cost of water development or compete for
water with other potential users. Agriculture's problems in paying for
water development and delivery systems arise from the relatively large
amounts of water required per dollar of product produced or, looked at
the other way, the low value of production per cubic metre of water
utilized. An average figure for irrigation projects in the western United
States would be somewhere in the range of 2.4-4.1; value of product
produced per cubic metre of water withdrawn for irrigation. This has
to cover the cost of land, labour and capital as well as water. Thus,
there is very little margin to cover high water-delivery costs. Potentially
irrigable lands that can be supplied with water only at high cost simply
cannot be developed unless there is a subsidy, or the land is suited to
producing a high-value specialty crop, for which the return on water
withdrawn may of course greatly exceed the average figures above.

In industry, on the other hand, the value of output per cubic metre
of water would be about 10£ at the worst and for many industries $1-10/m³
water withdrawn (consumption is often only a small fraction of withdrawals).
Many studies have shown that industries are not greatly influenced in their
choice of locations by the cost of obtaining water. A doubling, tripling
or even greater increase in the cost of water can be fairly well accommo-
dated, e.g. by changing techniques or making small adjustments in product
price.

Results in the western United States during the last 10 to 15 years
present something of a paradox if one is attempting to evaluate the trend
in which the repayment ability of irrigated agriculture is moving. On the
one hand, there has been very substantial development of private irrigated
acreages supplied primarily by pumping from groundwater supplies (e.g.
along the Snake River in southern Idaho) and surface sources. This de-
velopment is private and is therefore expected to repay the total cost of
delivering the water. However, at the same time, some public agencies
find it increasingly hard to find locations for projects which are economic,
even with substantial subsidies. Some of the difference may be attributable
to scale limitations in publically financed farming enterprises. There is
growing evidence that substantial gains can be achieved on irrigated farms
by scaling up. Thus, private developments organized around larger and
more efficient farms can obtain water at lower cost.

Certainly, from a long-term point of view, agriculture is now in a
better position than in the past to pay for the delivery of irrigation water.
DISCUSSION

Two factors have been at play in this: one is the increased yield from irrigated lands and specialization in high-value crops for which there is a relatively strong demand in our economy at present; the other is improved technology for delivering water to the land, resulting in lower and lower prices.

To these statements, I should like to add additional comments of my own.

There appears to me to be a considerable degree of uncertainty regarding the economics involved in the long-range water problem facing the United States of America. This uncertainty comes from inability to predict accurately (1) if or when population will level off and become stable, so that increased rates of food production will be unnecessary; (2) the degree to which modern agricultural technology will continue to increase production efficiency on existing lands and extend production to lands now economically unproductive; and (3) the success to be achieved by industry in producing food and fibres from non-agricultural raw materials. It seems evident to me that food and fibre production is of greater fundamental importance than any other type of production and that people will pay whatever the economy demands for these items. Thus, excessive population pressures, unaccompanied by equal increases in food and fibre production, could greatly increase the value of agricultural products and the value of water to produce them. Alternatively, successes in the chemical production of food and fibres from non-agricultural raw materials, with more efficient use of water, might prevent a significant increase in the value of agricultural products. My own personal opinion is that, in the United States of America at any rate, agriculture will continue for some time yet to be much less able than industry to pay for the water it needs.

D. KIRKHAM: Mr. Gardner, did your economists state what recreational bodies will pay for water?

W. H. GARDNER: The recreational use of water was indeed one of the questions we discussed. However, I believe that it would be most difficult to assess the recreational value in terms of dollars or cents, or to do any more than say that water is of great value for recreational use and this value may well far exceed the value for any other use in certain areas, under present economic conditions. However, like other economic evaluations of water use, this would be subject to wide change as the pressures of agricultural, domestic and industrial uses change.

W. K. G. KÜHN: There is a specific relationship between irrigation and yield. In arid climates, the relationship is quite clear. Studies made by FAO have shown that economical irrigation of dry areas is possible only if fresh water can be supplied at a price of about 0.5¢/m³. Improved yield can be obtained in temperate climates, even in normal years, by the use of sprinkling systems. For example, the irrigation of vegetables can increase yields by 20–80% (average over 8 yr), depending on the species. Over a 9-yr investigation the average return resulting from the application of 1-mm irrigation water per hectare (this corresponds to 100 m³ of water) amounted to $9; in other words the return resulting from the application of irrigation water (sprinkling) was up to 9¢/m³ of water. In the Federal Republic of Germany, water costs up to 5¢/m³ are regarded as acceptable for irrigating market gardens where the water can be drawn from a communal plant. Where costs are higher, users tend to set up their own water plants.
Many sprinkling systems have been established over the past few years, but the total is less than the number of farms which could benefit from irrigation, for there is no doubt about the economy of using irrigation in vegetable gardening.

J. A. DAMAGNEZ: The cost of irrigation water has to be estimated in terms of the water's productivity, i.e. as a function of the increase in yield obtained for each additional cubic metre of water supplied. The countries with the largest needs for fresh water are in areas where potential evaporation also is highest and experience has shown that beyond a certain potential evaporation threshold, the maximum yield of dry material is inversely proportional to the potential evaporation. Thus, extremely high potential evaporation limits production just as much as shortage of water.

In arid zones, producers have hitherto tended to favour crops capable of giving a large yield in the summer (megathermic species). Would it not be wiser to switch to crops, and especially fodder crops, which are harvested in the autumn, winter and spring, since areas which could be irrigated with desalted sea-water are those with a maritime climate (mild winters) favourable for winter crops?

H. W. SCHAPPENSEEL: As the Federal Republic of Germany has a semi-humid climate, irrigation water is rarely the decisive minimum-growth factor, as it is in a semi-arid climate. Any irrigation measures and the associated costs must therefore always be considered in conjunction with additional costs for fertilizer and management operation when trying to enhance productivity by the addition of water. While costs of 2.2¢/m³ were acceptable for a potato project which we established in the semi-arid climate of Tunisia, potato growers in the Federal Republic of Germany would certainly be hesitant to risk so much on the small chances of higher yields, especially in view of the correspondingly higher investment in fertilizer which would be necessary. In view of these parallel expenditures for water and fertilizer, it is not surprising that, in climatic areas ensuring reasonable crops from natural rainfall alone, irrigation water for pasture and grassland has to be free from private wells, rivers or drainage canals, the only charges being for pumping or ditch-digging.

Only on very large farms — such as those where vegetables are grown on the Würm-loess of the middle terrace of the Rhine, or on the grey and brown steppe soils of the Pfalz or Hesse, which support three crops yearly — is it possible to use irrigation water costing 4-5¢/m³. Normally, the price should not exceed 4¢.

H. KICK: To make an exact assessment of the cost of desalted water, we need precise data on the yields of various plants under different ecological conditions. I have the impression that the amounts of water recommended to farmers in various arid or semi-arid countries are not yet based on sufficiently precise research carried out under the conditions found in the region in question, but are more often based on studies made in, for example, the United States or other countries. My observations indicate that precise experimental research on water usage in many countries with dry climates runs into serious technical difficulties, because investigators have to consider soil salinity, drainage, the water table, the physical state of the soil and the quality of the water, which are not the same everywhere. Mineral fertilization may also play an important role.
As far as the Federal Republic of Germany is concerned, my view is that water desalination appears to be of some potential importance, especially for high-value crops or crops cultivated in greenhouses.

D. J. BROWN: In the article quoted by Mr. Kirkham from the American Scientist, March 1965, the author implies that the waste liquids produced in power reactors are "highly lethal" and pose serious disposal problems. He also raised the question whether power reactors should be used as a source of thermal energy for desalination.

For those of us who have a direct or indirect interest in the disposal of radioactive wastes, it should be stated for the record that the normal waste liquids generated in a nuclear power reactor are not "highly lethal". Because of the rapid development in the treatment, handling and disposal of waste liquids from power reactors by the world community, the radionuclide concentrations in these waste liquids are usually several orders of magnitude lower than those found in most rivers and streams — and well below accepted public drinking-water limits.

It has been stated many times in this conference that the use of isotope and radiation techniques should be encouraged whenever they can be used for the benefit of mankind. If the use of thermal energy from power reactors is economically and technologically feasible for water desalination, efforts should be made to alleviate any concern the public may have regarding radioactivity in the biosphere at these very low concentrations, rather than alarm them by using terms such as "highly lethal".

The high-level radioactive wastes resulting from the reprocessing of nuclear fuels from power reactors do present a waste disposal problem to the nuclear industry to-day. Even for high-level wastes, however, a great effort is being made to find a safe method of ultimately disposing of these wastes into the ground, and it appears likely that a solution to this problem will be found in the near future.

S. ÖZBEK: While discussing new sources of water for agriculture, I think we should also reflect on whether the best possible use is being made of the water already available. Are we at present able to tell the farmer when and how frequently to irrigate various crops in different growing regions and how much water they need? In most cases, I believe we are not able to do so and we must assume that the water used in agriculture is often used uneconomically. I therefore propose that scientists seek more reliable and practical irrigation systems.

Mr. Kirkham has proposed breeding new salt-resistant species. In a similar context, we in Turkey already have experience with fruit trees resistant to drought. Pistachio, olive and fig trees and most vines are grown without irrigation.

Y. BARRADA: I believe we all agree that agriculture still has a long way to go in making better use of its land and water resources. This becomes obvious when we compare the record yield of maize (19.1 tons/ha) and of wheats (8.8 tons/ha) with the average world yields of about 1.5 and 1.3 tons/ha respectively. It is not enough to improve the efficiency of water use, fertilizer application and other cultural practices. We should also try to make better use of the vast areas of arid and semi-arid regions covering about 50% of the land area of the world, and this can be achieved only by the use of vast amounts of water. Like Damagnez, I believe that the net return from the use of a certain amount of irrigation water is a good basis for assigning a certain value to desalted water.
However, this net return should be estimated under optimum conditions by carrying out experiments on various crops at different locations. This is not an easy task, because additional water necessitates the application of more fertilizers and more attention to the control of pests and weeds. Furthermore, better varieties should be selected and drainage problems may arise. Once the production cost of desalted water approaches the value that could be assigned to irrigation water, it will be possible to ease appreciably the growing world need for food and fibres.

G. HAUSER: Several speakers have pointed out that in many countries with traditional agricultural methods, the first need is to prevent wastage of water. FAO, in supervising massive experimentation in many countries, has observed that over-irrigation is a rather common mistake. On the high plateau of Iran for instance, where four irrigations after the winter are the economic optimum, wheat is irrigated up to eight times. We must establish the best use of resources area by area. What is appropriate in Anatolia is not necessarily right for Iran, etc.

L. G. KING: We hear estimates of the world’s finite reservoirs of fossil fuels and of the time in which they will be used up, and we know that power generation with nuclear plants is increasing. It might therefore be useful if the engineers concerned with the thermal problems of reactor coolant disposal could get together with the agriculturalists for their common benefit. Could the heated water from a reactor be applied with benefit to the growing of crops? What factors are involved? Is this an alternative to the use of desalted water for irrigation?

D. B. BRICE: It is true that large quantities of cooling water are required for condensing steam in thermal power stations, and at locations where good-quality river water is sufficiently abundant to be used for condenser cooling purposes, the warmed water could possibly be beneficially employed if irrigation is also practised. However, precisely because an adequate supply of condenser cooling water is one of the most important considerations in siting power plants, a large number of power stations are sited adjacent to oceans and sea water is used for cooling. The sea water, of course, cannot be used for irrigation. This is particularly the case in the arid and semi-arid regions, which constitute such a large fraction of the land surface.
SYMPOSIUM ON THE USE OF ISOTOPE AND RADIATION TECHNIQUES IN SOIL PHYSICS AND IRRIGATION STUDIES

HELD IN ISTANBUL, 12 - 16 JUNE 1967

CHAIRMEN OF SESSIONS

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<td>NURINNISA ÖZBEK</td>
<td>University of Ankara</td>
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<td>D. KIRKHAM</td>
<td>Iowa State University, Ames</td>
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<td>3</td>
<td>J. A. DAMAGNEZ</td>
<td>Institut national de la recherche agronomique, Paris</td>
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<tr>
<td>4</td>
<td>H. W. SCHARPENSEEL</td>
<td>Institut für Bodenkunde der Universität Bonn</td>
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<tr>
<td>5</td>
<td>L. E. DANFORS</td>
<td>Institution för Kulturteknik, Stockholm</td>
</tr>
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<td>6</td>
<td>M. J. FRISSEL</td>
<td>Association Euratom-Institute for Atomic Sciences in Agriculture, Wageningen</td>
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<td>7</td>
<td>W. R. GARDNER</td>
<td>University of Wisconsin, Madison</td>
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<td>8</td>
<td>N. F. BONDARENKO</td>
<td>Agrophysical Institute, Leningrad</td>
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<td>9</td>
<td>M. A. HAGOOD</td>
<td>Food and Agriculture Organization of the United Nations, Rome</td>
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SECRETARIAT OF THE SYMPOSIUM

Scientific Secretary: Y. BARRADA
Joint FAO/IAEA Division of Atomic Energy in Food and Agriculture

Administrative Secretary: H. H. STORHAUG
Division of Scientific and Technical Information, IAEA
LIST OF PARTICIPANTS

BELGIUM
De Boedt, M. 
State Faculty of Agricultural Sciences, Coupure Links 235, Ghent

BULGARIA
Bachvarov, N. 
Institute of Physics, Bulgarian Academy of Sciences, Sofia

CZECHOSLOVAKIA
Čabart, J. 
Výzkumný ústav meliorací, Malostranské nám. 2/25, Prague 1
Pasák, V. 
Výzkumný ústav meliorací, Malostranské nám. 2/25, Prague 1
Patejdl, G. 
Výzkumný ústav meliorací, Malostranské nám. 2/25, Prague 1
Šantorá, V. 
Výzkumný ústav meliorací, Malostranské nám. 2/25, Prague 1

DENMARK
Jensen, P.A. 
The Danish Isotope Centre, Skelbækgade 2, Copenhagen V
Søren, E. 
The Danish Isotope Centre, Skelbækgade 2, Copenhagen V

FINLAND
Koivinen, E.H. 
Isotope Laboratory, Faculty of Agriculture, University of Helsinki, Viikinkatu, Helsinki 71
Sillanpää, M. 
Department of Soil Science, Agricultural Research Centre, Tirkk利用

FRANCE
Corpet, E.P. 
CEA, Centre d'études nucléaires de Grenoble, B.P. 269, 38 Grenoble
Couchat, P. 
Service de radioagromomie, Département de biologie, CEA, Centre d'études nucléaires de Cadarache, B.P.1, 13 St. Paul-lez-Durance
LIST OF PARTICIPANTS

Damagnez, J.A.
Centre de recherches agronomiques du Sud-Est,
Institut national de la recherche agronomique,
Montfavet (près Avignon), 84 Vaucluse

Maerens, G.E.
Station d'agronomie et d'onomologie, Institut national de la recherche agronomique,
67 Bd Delsis, 31 Toulouse

Marcese, J.
Service de radioagronomie, Département de biologie,
CEA, Centre d'études nucléaires de Cadarache,
B.P. 1, 13 St. Paul-lex-Durance

Rançon, D.
Service d'étude de sûreté radiologique,
CEA, Centre d'études nucléaires de Cadarache,
B.P. 1, 13 St. Paul-lex-Durance

GERMANY, FEDERAL REPUBLIC OF

Benecke, P.
Institut für Bodenkunde, Förschliche Fakultät der Universität Göttingen,
Mitscherlichstr. 3, 371 Hann-Münden

Kerpen, W.
Arbeitgruppe für Landwirtschaft, KFA Jülich, Institut für Bodenkunde,
Nussallee 13, 53 Bonn

Kick, H.
Agrifakturchemisches Institut der Universität Bonn,
Meckenheimer Allee 176, 53 Bonn, und
Arbeitgruppe für Landwirtschaft, KFA, Jülich

Kühl, W.K.G.
Institut für Strahlenbiologie der Technischen Hochschule Hannover,
3 Hannover-Herenhausen

Rüggenmann, H.
Lehrgebiet Verfahrenstechnik im Bauwesen, Technische Hochschule Karlsruhe,
Postfach 1687, 76 Karlsruhe

Schapernel, H.W.
Institut für Bodenkunde der Universität Bonn,
Nussallee 13, 53 Bonn

Zimmermann, U.
Physikalisches Institut der Universität Heidelberg,
Philosophenweg 12, Heidelberg

ITALY

De Pace, M.
Ministero dell'Agricoltura e delle foreste,
Via XX Settembre 20, Rome

Gera, F.
Divisione di protezione sanitaria e controlli,
Comitato nazionale per l'energia nucleare,
Via Lucania 29, Rome

Romano, E.
Stazione chimico-agronomia sperimentale,
Ministero dell'agricoltura e delle foreste,
Villa Celimoniana, Piazza della Navicella 4, Rome
NETHERLANDS

Colenbrander, H.J.
Service for Water Management, Rijkswaterstaat, The Hague

Frisse, M.J.
Association Euratom-Institute for Atomic Sciences in Agriculture, Keyenbergseweg 6, Wageningen

Pootstra, P.
Association Euratom-Institute for Atomic Sciences in Agriculture, Keyenbergseweg 6, Wageningen

NORWAY

Rognerud, B.
Ministry of Agriculture, Agricultural College of Norway, Vollebekk

Steenberg, K.
Isotope Laboratory, Agricultural College of Norway, Vollebekk

PORTUGAL

Castimiro, J.F.
Agronomic Research Institute of Mozambique, Caixa Postal 1731, Lourenço Marques, Mozambique

Godoelho Gouveia, D.H.
Agronomic Research Institute of Mozambique, Caixa Postal 1731, Lourenço Marques, Mozambique

ROMANIA

Celar, B.
Institutul de in bn sf ari funciare și pedologie, 294 Splaiul Independenței, Bucharest

Paflegoa, P.
Institutul de fizica atomica, C.P. 35, Bucharest

Sandru, P.
Institutul de fizica atomica, C.P. 35, Bucharest

Teodoru, O.
Institutul de in bn sf ari funciare și pedologie, 294 Splaiul Independenței, Bucharest

SENEGAL

Jacquinot, L.
Institut de recherches agronomiques tropicales et des cultures vivrières, Centre de recherches agronomiques, Bamby

SPAIN

Ortin, N.
Dirección de Química e Isótopos, Junta de Energía Nuclear, Avenida Complutense, Madrid-3
LIST OF PARTICIPANTS

SWEDEN

Danfors, L.F.
Institution för Kulturteknik, Tekniska Högskolan,
Stockholm 70

SWITZERLAND

Bezzegh, M., M.
 Eidgenössische Anstalt für Wasserversorgung,
Abwasserreinigung und Gewässerschutz an der ETH,
Physikstr. 5, 8044 Zurich

Müller, P.
AC-Schutzdienst, Abteilung für Sanität, Eidgenössisches Militär-
department,
Reiteturmstr. 13, 3000 Bern

Rod, P.
Station fédérale d’essais agricoles, Bugnon 44,
1905 Lausanne

TURKEY

Alkan, Z.
Kültürteknik Bölümü, Ziraat Fakültesi, Atatürk
Üniversitesi, Erzurum

Atakan, Y.
Research Department, State Hydraulic Works, Ankara

Ayben, N.
Institute for Nuclear Energy, Technical University of Istanbul,
Istanbul

Eray, N.
Turkish Atomic Energy Commission, Ankara

Erkan, İsmail
Research Department, State Hydraulic Works, Ankara

Erdoğru, H.
Ziraat Fakültesi, Atatürk Üniversitesi, Erzurum

Göcer, C.
Toprak Muhafaza Araştırmaları İstasyonu, Ankara

Güler, Sevil
Research Department, State Hydraulic Works, Ankara

Güzel, H.İ.
Soil and Fertilizer Research Institute, University of Ankara

Kepecioğlu, G.
Ziraat Makinaları Kursu, Ziraat Fakültesi,
Ege Üniversitesi, Bornova, İzmir

Kıvanç, İ.
Birlik Besleme Kursu, Ziraat Fakültesi,
Ege Üniversitesi, Bornova, İzmir

Öğüt, L.
Atatürk Üniversitesi, Erzurum

Onay, Yıldız
Research Department, General Directorate, State Hydraulic Works,
Ankara

Önal, Zibeyde
Soil and Water Laboratory, State Hydraulic Works, Ankara

Özalp, N.
Toprak Muhafaza Araştırmaları İstasyonu Md., Bakanlıklar, Ankara
LIST OF PARTICIPANTS

Özbek, Nurminsa
Radiophysiology and Soil Fertility Department, Faculty of Agriculture, University of Ankara

Özbek, S.
Faculty of Agriculture, University of Ankara

Öztan, B.
Soil and Fertilizers Research Institute, University of Ankara

Özünklik, A.
Soil and Water Laboratory, State Hydraulic Works, Ankara

Saatçi, F.
Toprak Kütüphanesi, Ziraat Fakültesi, Ege Üniversitesi Bornova, İzmir

Şahin, A.
Kültür Teknik ve Ziraat İngiliz Kütüphanesi, Ziraat Fakültesi, Ege Üniversitesi Bornova, İzmir

Semtlik, F.
Research Department, State Hydraulic Works, Ankara

Şemitlik, H.S.
Material Section State, Highway Department, Ankara

Tüürün, G.C.
Research Dept., State Highway Department, Ankara

Utkan, Sevim
State Highway Department, Ankara

Yeşilbüy, M.Ş.
Soil and Fertilizer Research Institute, University of Ankara

UNION OF SOVIET SOCIALIST REPUBLICS

Bondarenko, N.P.
Agrophysical Institute, Grashdanski Pr. 14, Leningrad K-21

Globus, A.M.
Agrophysical Institute, Grashdanski Pr. 14, Leningrad K-21

UNITED STATES OF AMERICA

Brown, D.J.
Isochem Inc., P.O. Box 250, Richland, Wash. 99352

Gardner, W.H.
Department of Agronomy (Soils), Washington State University, Pullman, Wash. 99163

Gardner, W.R.
Department of Soil Science, University of Wisconsin, Madison, Wis. 53706

Klog, L.G.
Bartelle Memorial Institute, Pacific Northwest Laboratory, P.O. Box 999, Richland, Wash. 99352

Kirkham, D.
Iowa State University, Ames, Iowa

McHenry, J.R.
USDA Sedimentation Laboratory, US Department of Agriculture, P.O. Box 30, Oxford, Mass. 01655

Rast, P.A.C.
US Department of Agriculture, University of Wisconsin, Madison, Wis. 53706
LIST OF PARTICIPANTS

YUGOSLAVIA

Filip, A.

Boris Kidrić Institute of Nuclear Sciences,
P.O. Box 522, Belgrade

Hajdušković, M.

Federal Nuclear Energy Commission, Institute for the Application of Nuclear Energy in Agriculture, Veterinary Medicine and Forestry, Zemun

ORGANIZATIONS

EACSO

Dagg, M.

Physics Division, East African Agriculture and Forestry Research Organization,
P.O. Box 30148, Nairobi, Kenya

FAO

Hagood, M.A.

Water Resources and Irrigation Branch, Food and Agriculture Organization of the United Nations,
Via delle Terme di Caracalla, Rome, Italy

Hauser, G.

Division of Land and Water Use, Food and Agriculture Organization of the United Nations, Via delle Terme di Caracalla, Rome, Italy

IAEA

Brice, D.B.

Division of Nuclear Power and Reactors, International Atomic Energy Agency,
11 Kramner Ring, A-1010 Vienna, Austria
AUTHOR INDEX

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