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MOISTURE AND GROUNDWATER REGIME IN A SANDY SOIL UNDER IRRIGATION

by

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ABSTRACT

Moisture regime and groundwater regime were studied in a sandy soil at Portage la Prairie. The topography of the experimental field was undulating. The groundwater level at the low spots was at a depth of 1.3 m to 1.6 m below the surface and generally contributed beneficially towards the moisture content of the root zone. The groundwater level below 2.0 m had a negligible effect on the moisture regime. Irrigation was essential at the high spots which constituted nearly 80 percent of the area. Random drainage was essential only at the low spots with fine soil texture. Natural drainage of the land was effective in draining away the recharge by precipitation and irrigation. The average slope of the groundwater surface was 0.135 percent and the saturated hydraulic conductivity varied between 11.28 cm/h and 25.80 cm/h.

In an attempt to describe the observed moisture and groundwater regime quantitatively, a simple method was developed to obtain saturated hydraulic conductivity, bubbling pressure and pore-size distribution index. The Green and Ampt model (1911) was used to calculate saturated hydraulic conductivity and average capillary suction from infiltration data. The model of Gardner et al. (1970) and the concept of average capillary pressure at the wetting front put forward by Idike et al. (1977) were used to calculate pore-size distribution index and bubbling pressure. The calculated bubbling pressure was near that of unconsolidated sand, and pore-size distribution index varied from that of unconsolidated sand to that of sandy loam soil as obtained by Laliberte (1966).

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LIST OF SYMBOLS

Symbol	Definition	Dimension
A	Infiltration rate at the end of flooding in Gardner et al. model	LT^{-1}
a	Constant in Kostiakov function	none
b	Constant in Kostiakov function	none
C_w	Effective hydraulic conductivity	LT^{-1}
C_s	Saturated hydraulic conductivity	LT^{-1}
D	Constant in the method of averages	L^2
E	Constant in the method of averages	L
F	Cumulative infiltration at anytime	L
F_s	Infiltrated depth up to saturation	L
f_p	Infiltration rate in Green and Ampt equation	LT^{-1}
H	Matric potential	L
h	Head of water above the soil surface	L
I	Rainfall intensity	LT^{-1}
IMD	Initial moisture deficit	none
kr	Relative permeability	none
ks	Permeability at saturation	L^2
kw	Effective permeability	L^2
L	Depth of the moisture profile above the wetting front	L
L_s	Equivalent depth of the moisture profile at surface saturation	L
P_c	Capillary pressure - the difference in pressure across the interface between the wetting fluid and the non-wetting fluid	FL^{-2}

LIST OF SYMBOLS - Continued

Symbol	Definition	Dimension
P_b	Bubbling pressure - approximately the minimum capillary pressure on the drainage cycle at which the non-wetting fluid is continuous	FL^{-2}
P_{cav}	Average capillary pressure at the wetting front - the area under the curve drawn between capillary pressure and relative permeability	FL^{-1}
q	Flux - flow per unit area per unit time	LT^{-1}
S	Saturation	none
Si	Initial saturation	none
S_{ei}	Effective saturation at initial moisture content	none
S_{ef}	Effective saturation at final moisture content	none
S_r	Residual saturation	none
t	Time	T
Y	Cumulative infiltration	L
Z	Depth	L
α	Constant in Kostiakov function	none
ε	Constant in Gardner et al. model	none
θ_s	Volumetric moisture content	none
θ_i	Volumetric moisture content at saturation	none
θ	Volumetric moisture content at initial moisture content	none
λ	Pore-size distribution index, $-d(\log S)/d(\log P_c)$	none
ρ	Density of water	$FL^{-4}T^{-2}$
g	Acceleration due to gravity	LT^{-2}

CHAPTER I

INTRODUCTION

Development of the world's agricultural production potential is a challenge that must be met by mankind to keep pace with the increasing world population and its need for an adequate supply of food and fibre. The emphasis must be laid on the efficient use of the resources, the most important being land and water.

To achieve maximum yield, the optimum soil moisture content is one of the dominant factors. The sources of moisture are precipitation, irrigation and groundwater, if the groundwater is near the surface. Moisture is lost from the soil by deep percolation and evapotranspiration. Their combined effects govern the moisture regime of the soil. The moisture regime should provide optimum moisture throughout the growing period of a crop.

In achieving improved efficiency of land use, one can not always depend upon precipitation as the only source of moisture throughout the growing period. Deficient moisture at any growing stage can be injurious to the crop and can severly limit the yield. Irrigation, therefore, may be required throughout the growing period or for a part of it. In either case, investment in an irrigation system has to be made and it must be determined whether the investment will succeed or be lost. The land may be ruined if natural drainage is not adequate to drain away the excess irrigation water which leaves the root zone. The problem is aggravated by the presence of an excess of salt in the soil as leaching of these salts will require additional irrigation water and good drainage. If the groundwater rises near to the surface a soil with good production potential can be reclaimed by providing artificial drainage. Artificial drainage is expensive and may not be justified if the capital investment is too high to be recovered in a reasonably short period. Also, the depth to which the groundwater table can be lowered is limited by impervious strata below the surface. If the groundwater can not be lowered with artificial drainage, sufficiently to allow the deep-rooting crops to grow, such artificial drainage will not succeed because with limited root growth deep-rooting crops are not economical.

In the Portage la Prairie area irrigation is often practiced on land with a shallow groundwater table. An impervious stratum is present 3 m to 5 m below the surface. Therefore, there is a high possibility of loss of investment on an irrigation system. Harmful long-term effects on the suitability of land for agriculture can also be expected. To answer some of the questions connected with permanent irrigation agriculture on the soil, classified as Almasippi series by the Manitoba Soil Survey, the present study has been conducted.

The observation of moisture content at a number of locations in two fields at depths from 15 cm to 110 cm provided information on the present state of the moisture regime as influenced by precipitation, irrigation, groundwater, deep percolation and evapotranspiration. An analysis of the irrigation and drainage requirements was undertaken based on a study of the soil moisture regime. In one of the two experimental fields, it was found that a high groundwater table at a depth of about 1.5 m was generally contributing beneficially towards the moisture content of the root zone and no irrigation was required. At places where the groundwater table was more than 2.0 m deep, irrigation was required and, in the absence of irrigation, the crop permanently wilted.

To determine the extent of natural drainage and the feasibility of artificial drainage, a study of the groundwater regime and the determination of saturated hydraulic conductivity were required. The groundwater regime was monitored in three observation wells. The slope of the groundwater table was 0.135 percent on the average which was considered quite high. The saturated hydraulic conductivity was determined by applying the model of Mein and Larson (1971) to the infiltration characteristics of the soil and was found to vary between 11.28 cm/h to 25.80 cm/h. The relatively steep slope of the groundwater table and the high saturated hydraulic conductivity showed that natural drainage was effective. This observation was substantiated by the groundwater regime which showed that almost the whole of the recharge by precipitation and irrigation was drained naturally.

The texture of the soil in the field varied from place to place. This resulted in large variations in infiltration characteristics. The representative infiltration characteristics for three sections of the field were determined. A design infiltration equation was selected using data from the sections of the field based upon the criterion of zero runoff in the section of the field having a relatively low rate of infiltration.

To determine the moisture regime quantitatively, it is necessary to know the unsaturated hydraulic conductivity-moisture content relationship, bubbling pressure, pore-size distribution index and residual saturation. Precise determination of these parameters requires long experiments in the laboratory. The conditions similar to the laboratory are not met and, hence, approximations are involved. On the other hand, in this study in an attempt to explain the observed moisture regime quantitatively, a simple method for determining the parameters of porous media in a field was developed. An assumption was made that the residual saturation is negligibly small, which is very nearly true for sandy soils. The redistribution model developed by Gardner et al. (1970) and the concept of average capillary suction at the wetting front put forward by Idike et al. (1977) have been used to determine the porous media parameters.

The topography of the field was undulating. Surface runoff on such a field could erode the upper productive layer of the soil and accumulate water at the low spots, thereby increasing the drainage requirement. Potential surface runoff was calculated from the Green and Ampt (1911) equation as modified by Mein and Larson (1971).

On the basis of these considerations the objectives of this study were defined as follows:

1. To determine a design infiltration equation for the soil.
2. To determine saturated hydraulic conductivity, the unsat-

urated hydraulic conductivity-moisture content relationship, pore-size distribution index and bubbling pressure.

3. To determine time to the beginning of runoff for various combinations of initial moisture content and precipitation intensity.
4. To study moisture content profiles from depths of 15 cm to 110 cm.
5. To determine the groundwater regime of the soil.
6. To determine draingage and irrigation requirements.

CHAPTER II

REVIEW OF LITERATURE

2.1 Infiltration

2.1.1 Infiltration Rate

Infiltration rate was first called infiltration capacity by Horton (1940) and defined as the maximum rate at which a given soil in a given condition can absorb rain as it falls. The term "infiltration capacity" has been an object of some controversy (Richards, 1952). The term infiltration rate has been accepted as more suitable.

Infiltration rate varies with time until a certain minimum infiltration rate, called the basic infiltration rate, is reached. Flooding of an initially dry soil results in an initially very high rate of infiltration, due to a very steep gradient of moisture content acting in a thin surface layer with high conductivity and diffusivity of saturation. This rate steadily declines as the development of the moisture profile reduces the gradient of moisture content at the surface. In fact, the flow of water is in response to the hydraulic gradient set up by the moisture gradient.

The infiltration rate (Childs, 1967) should be differentiated from the hydraulic conductivity, which is only one factor entering into the process of infiltration. It may be regarded as a consequence of hydraulic conductivity and of potential gradient at the surface, in accordance with Darcy's law or alternately as the rate of increase of the total amount of water stored in the soil profile.

2.1.2 Infiltration Equations

A rational infiltration equation may be defined as one which can be derived directly from fundamental principles, which fits all experimental data and which represents the physical conditions correctly throughout the entire range of their occurrence and hence is valid outside the range of experimental observations. The Kostiakov (1932) and Horton (1940) equations are the best known infiltration equations which have been popular because of their simplicity and capacity to fit most infiltration rate data. However, both equations contain parameters which are difficult to predict because they have no physical significance.

A more recent empirical equation given by Holtan (1961) expresses the infiltration rate not as a function of time but of unoccupied pore space in the soil. A model of this type is convenient for a watershed model, but the determination of the so-called "control depth" introduces an uncertainity. This equation takes into account the storage recovery, vegetative cover, soil characteristics, soil moisture content and ponding effect when necessary.

Philip (1957) derived an infiltration equation with predictable parameters. Unfortunately, computing these parameters is difficult (Whisler and Bouwer, 1970) and their values are more commonly obtained by fitting. A further difficulty in the use of this equation for sprinkler irrigation is the assumption of an excess of water supply at the surface.

Green and Ampt (1911) derived an equation to describe vertical downward movement of water in a soil with the assumption that water was ponded on the surface. Morel-Seytoux and Khanji (1974) derived an equation of infiltration which was essentially the same as the Green and Ampt equation but without many of its restrictions. This equation is based upon the assumption that water profiles can be represented as a step function. In the strictest sense, the step function profiles will only occur in a porous medium having primary porosity and pores similar in shape and identical in size. While this is an obvious idealization, it does, nevertheless, allow for the interconnected flow through the porous medium, so that the assumption of non-interconnected parallel capillary tubes is not required. However, for the more common porous medium that departs from such idealism by having pores of more than one size, the step function profiles will be qualitatively inaccurate for time near zero. In such instances, the water content at the soil surface is at first a finitely increasing function of time (Rubin and Steinhardt, 1963; Rubin, 1967; Childs, 1967; Braester, 1973), rather than an instantaneous jump from one position to the other. Once the surface ponding has begun, it seems reasonable to expect that the step function will be followed at least to some fair degree. In the continuous ponding studies of Youngs (1957) in which excellent step-function profiles were found for a glass-bead medium, even his more general medium (slate dust) exhibited profiles that could be reasonably approximated as step functions. This was also found for field soils (Nielsen et al., 1962; Jackson, 1963) ranging from sandy loam through loam, silt loam and silt clay.

Even if there is some qualitative inaccuracy in the assumption of a step function at times near zero, it does not necessarily follow that the profile at time near zero is, therefore, rendered inaccurate, particularly for evaluating infiltration flux and cumulative infiltration.

2.2 Surface Runoff

Utilizing the concepts of flow similar to those of Green and Ampt (1911) Mein and Larson (1971) developed an equation describing the volume of water infiltrating prior to surface saturation. They considered constant application rates. The model is important in the sense that it uses parameters having physical significance and describes the process itself. All the parameters are measurable and none is dependent on field data for evaluation by fitting. However, the model does not provide a direct way of introducing variations in vegetative cover. The model also assumes constant rainfall intenstity. Idike et al. (1977) found that prediction of infiltration by the Mein and Larson model was generally good during the latter portion and middle portion of the run. The Holtan (1961) model generally under-predicted the infiltration during initial stages of the runs and generally under-predicted the time to the beginning of runoff. The Mein and Larson model predicted fairly accurately in both instances. Chu (1977) has shown that the same relationship is equally valid for time-varying rate of rainfall.

2.3 Redistribution of Moisture

Of the various flow processes involved in the field water cycle, the post-infiltration redistribution of soil moisture, often referred to as internal drainage (Gardner et al., 1970) is one of the least understood. The process is important in the sense that it determines the amount of water retained at various times at different depths in the soil profile and can affect the water consumption of plants. This is also important because of its effect on infiltration.

The presumed water content at which internal drainage becomes negligible within a few days or ceases entirely, termed the 'field capacity', had long been accepted as an actual physical property, characteristic of and constant for each soil. Though the field capacity concept was originally derived from crude measurements of water content in the field, some workers have sought to explain this concept in terms of a static equilibrium value or a discontinuity in the capillary water (Kohnke, 1968).

In recent years with the development of theory and more precise experimental techniques in the study of unsaturated flow processes, the field capacity concept as originally defined has been recognized as arbitrary and is considered by some that it may have done more harm than good (Richards and Moore, 1952). The experimental work of Youngs (1958 a, 1958 b) with synthetic porous materials, and the numerical analysis of Rubin (1967), and Staple (1969) showed that redistribution in the absence of a water table is a continuous process and one that is influenced by the hysteretic properties of the soil.

Several infiltration models and a few redistribution models have been proposed and used. These models are either based on the Richards unsaturated flow equation or empirical relationships between infiltration rate and time. Models based on the Richards equation are more desirable because they use measured, physical parameters rather than empirical "constants" and, in general, are more accurate. They are, however, difficult to use. Since the Richards equation does not have a general analytical solution, it must be solved numerically. Such solutions are complex, use a lot of computer time and require more detailed input data.

Gardner et al. (1970) developed a redistribution model by simplifying the Richards equation by applying certain assumptions based on actual observations. The model is relatively simple. James (1976) used this model to describe the moisture profiles and showed a good agreement of calculated and observed values.

2.4 Drainage

2.4.1 Drainage Requirements of Crop

The purposes of the drainage engineer are best served if the data are available for every stage of every crop telling how much flooding the crop could stand under all circumstances. Hoveland and Webster (1965), for example, have found that among several clovers, ball and white clover were the most resistant to flooding damage, and that these two clovers could be flooded three days out of every ten for a three-month period without suffering reduction in yield. Experimental verification made by Williamson (1964) showed that in the absence of salt problems, most annual crops can grow and produce well even if only the top 30 cm of soil are well drained.

When water stands in the low areas of a field for a period of time after a rain and the plants in the area die, two things are obvious. The drainage is inadequate and the crop suffocates due to the deficiency of oxygen at the plant roots. To properly evaluate the adequacy of drainage in such situations requires that the aeration status of the soil during the stress period be measured (Erickson et al., 1964).

2.4.2 Design Criteria of Drainage

The properties of soils required for the design of a drainage system are: hydraulic conductivity, drainable porosity, texture and structure. Hydraulic conductivity has been used most extensively in the design equations of the drainage system. The other three quantities are indirect measures of the ability of soils to transmit water. They are not directly usable in design equations, but in some cases may be correlated with hydraulic conductivity.

In the last two decades considerable interest has developed in evaluating the hydraulic conductivity of soils. Bouwer (1961, 1962, 1964) has developed a double-tube method for the in-place measurement of the saturated hydraulic conductivity of soils in the absence of a water table. The soil is saturated through the tubes placed in the soil at depth of measurement and the flow from one tube to the other is rated to obtain the conductivity. Collis-George (1964) devised a two-well method for measuring hydraulic conductivity in discrete soil layers. Dendy and Asmusson (1963) used small well points to determine the hydraulic conductivity. Snell and Van Schilfgaarde (1964) developed a four-well method for measuring the conductivity of soil in place, and Fang Ching (1965) and Thomas (1965) tested the method in the field. In the Snell four-well method, one of the wells supplies water, one recieves water and two act as piezometers. Smiles and Young (1965) developed and tested in a sand tank a multiple-well method in which alternate wells received a supply of water. They compared, using the same sand tank, several field methods for measuring hydraulic conductivity.

2.5 Properties of Porous Media

A good deal of work has been done to describe unsaturated flow in terms of parameters which have physical significance. These parameters are pore-size distribution index, bubbling pressure, tortuosity, effective porosity, hydraulic radius, and residual saturation. All of them except tortuosity can be determined in the laboratory (Laliberte, 1966; Corey, 1977). The tortuosity is determined indirectly. Burdine (1952) employed the concept of hydraulic radius to develop a relationship of relative permeability with residual saturation, saturation and capillary pressure. This relationship was verified by Corey (1954). Brooks and Corey (1966) suggested an empirical relationship of effective saturation with capillary pressure and a constant, characteristic of the soil, called the pore-size distribution index. Laliberte (1966) made a study of this constant for a number of soils. The Brooks and Corey equation is valid for capillary pressure greater than bubbling