1981

Simulation of soybean response to drainage facilities and optimization of system design

Jau Paulo Goulart

Iowa State University

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SIMULATION OF SOYBEAN RESPONSE TO DRAINAGE FACILITIES AND OPTIMIZATION OF SYSTEM DESIGN

Iowa State University                      Ph.D.  1981

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Simulation of soybean response to drainage facilities
and optimization of system design

by

Jau Paulo Goulart

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INTRODUCTION

Statement and Nature of the Problem

Rio Grande do Sul is Brazil's southernmost state (Figure 1). It is located between the 27th and 33rd degrees latitude South, and between the 50th and 60th degrees longitude West. This state has approximately 3,450,000 hectares of land suitable for flood-irrigated rice. According to the Brazilian Soil Classification System, most of the soils covering this area are classified as Planosol, Hydromorphic Brunizen and Gley. These soils are poorly drained because of the presence of an impervious layer near the surface,\(^1\) low saturated hydraulic conductivity of the upper layer, associated with a flat\(^2\) topography (Goulart, 1975). In addition to the poor drainage conditions, the current drainage installations in general are not adequate even to grow rice.

Of the total area, only 15 percent has been cultivated annually with rice. The remaining area had been left in natural pastures to raise livestock (Goulart, 1975). However, since the beginning of the last decade, South Brazil has experienced an increase in soybean acreage. With the increase of the planted area and also due to the attractive market prices, soybeans are now grown in those areas earlier farmed primarily with rice and natural pastures. This expansion of

\(^1\)The depth of the impervious layer usually varies from 40 to 80 cm.

\(^2\)Slope ranging from 0 to 0.5 percent.
Figure 1. Geographic location of Rio Grande do Sul state in Brazil
acreage created the need for studies determining the feasibility of drainage systems. It is purpose of the present study to design the most suitable drainage system to grow soybeans in those soils.

**Definition of Drainage Design**

**Evaluation Criteria**

The major concern of most engineers in designing drainage systems is to provide a root environment that is suitable for maximum crop production and sustains yields over a long period of time. It should be observed, however, that an increase in yield is associated with a corresponding increase in initial investment and maintenance costs. Furthermore, successive increments in crop yield requires additional costs, because of the law of diminishing returns. It appears, therefore, that economic criteria have to be included in the design process of drainage system for agricultural lands. Thus, the optimal design will be the one which maximizes the economic returns from the farm enterprise.

To design agricultural drainage systems based on economic evaluation of alternatives, the system performance and the crop yield response to each system alternative must be known.
Objectives

The primary objective of this study is to determine the degree of drainage which maximizes the net return from growing soybeans in soils with an impervious layer close to the surface. The specific objectives involved in this study are:

1. To find and test an equation for predicting water table heights associated with subsurface drainage facilities in soils with an impervious layer close to the surface.

2. To establish a soybean yield reduction pattern as a function of various depths and durations of the water table. Data will be used from available experimental results reported in the literature.

3. To develop a methodology for simulating crop yield reduction due to water table fluctuation under subsurface drainage facilities.

4. To perform an economic analysis to obtain the relationship between levels of drainage investments versus benefits from different degrees of drainage.

5. To determine the degree of drainage which maximizes the economic returns from the crop produced.
LITERATURE REVIEW

A considerable amount of research on subsurface drainage design has been done during the last 25 years. The goal of this chapter, rather than to give an exhaustive review of the subject in general, is to emphasize only previous research most closely related to this investigation. For convenience, this chapter is divided into four parts.

Crop Drainage Requirements and Criteria for Designing Subsurface Drainage Systems

The principal objectives of drainage of agricultural lands are to increase the yield of a crop, to improve its quality and to improve the conditions of the soil so that other crops of a higher value can be grown (Wesseling and van Wijk, 1957). The achievement of such goals is obtained mainly by improvement in: (1) soil aeration conditions and timeliness of farming operations in humid regions, and (2) salinity control in arid regions. The influences of the soil aeration conditions on plants and soil properties have been reviewed by Wesseling and van Wijk (1957), Russell (1959), and Wesseling (1974). Fireman (1957) and Bernstein (1974) reviewed the effects of salinity on plant growth and yields. The implications of the lack of timeliness in performing farming operations were reviewed by Reeve and Fausey (1974).

The water table behavior during the growing season of a crop is the major factor that influences the aeration and trafficability conditions of a soil or its degree of salinity. Because of this, crop
drainage requirements are usually described in terms of water table height. The reason for this is that the water-table depth is more easily determined than other soil properties such as aeration or thermal conductivity (Wesseling, 1974). Therefore, it is assumed that the water-table depth is the most desirable criterion upon which to base drainage design. Thus, numerous laboratory and field experiments have been conducted at various locations to relate crop yield responses with static or time dependent water-table depths. These relationships are used to define the crop requirement in designing drainage systems.

In humid regions, drainage systems are designed based on three criteria: steady-state conditions, falling water table, and fluctuating water table. The static and falling water table criteria are special cases of the fluctuating water table. The fluctuating water table conditions represent the actual situation that occurs in the field. To design subsurface drainage systems based on the water table fluctuation criterion, the crop yield responses to temporary high water table conditions must be known. This subject is reviewed in the following section.

Depths and Durations of High Water Table and their Effect on Crop Production

The tolerance of crops to temporary high water table conditions depends on many factors such as species of plants, stage of growth, weather conditions, fertility level, antecedent water table position,
etc. (Bouwer, 1965, 1974). Since soybeans were the reference crop used in this study, the literature reviewed in this section refers only to the effects of temporary high water table conditions on the yield of soybeans.

A greenhouse study was conducted to determine the effect of flooding on wheat, barley, soybeans, grain sorghum and three forage legumes in Kansas by Mittra and Stickler (1961). The plants were grown in glazed pots. All pots were simultaneously flooded when soybeans were in the first trifoliate stage, corn in the 5-leaf stage, and grain sorghum in the 4-leaf stage. The durations of flooding were 0 (check), 7, 14 and 21 days. The yield of dry matter was used as reference. The authors found that soybeans tolerated the waterlogged condition better than either corn or grain sorghum. Significant differences in dry matter yield were not found between treated and untreated soybean pots. All comparisons showed a linear relationship between yield and duration of waterlogging. The yield trend was downward with increased duration of waterlogging.

Work was carried out in lysimeters at Raleigh, N.C., to determine crop yields at different depths of a constant water table (Williamson and Kriz, 1970). It was shown that the soybeans had a maximum yield in a fine sandy loam soil when the water table was maintained at a constant depth of 61 cm. The results are shown in Table 1. The decrease in yield for the depth of 76 cm was due to water deficiency, since there was no surface watering.

DeBoer and Ritter (1970) reported that in the depression areas of
Table 1. Soybean yield as affected by the static water table during the plant life cycle

<table>
<thead>
<tr>
<th>Static water table depth (cm)</th>
<th>Soybean yield (percent of maximum yield)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>14</td>
</tr>
<tr>
<td>30</td>
<td>63</td>
</tr>
<tr>
<td>45</td>
<td>78</td>
</tr>
<tr>
<td>61</td>
<td>100</td>
</tr>
<tr>
<td>76</td>
<td>86</td>
</tr>
</tbody>
</table>

North-Central Iowa soybeans flooded 15 to 20 days after emergence during 1966 and 1967 were killed after 3 days of inundation. In 1968, soybeans flooded 30 to 35 days after emergence were killed after 3-1/2 to 5 days of inundation.

The effect on soybean yield of waterlogging conditions in a shallow soil (Planosol) in South Brazil was reported by Goulart et al. (1976) and Lago et al. (1978). The soil profile was kept saturated (a fluctuation of the water table within the first 10 cm of soil depth was admitted) for 0 (check), 5, 10, 15 and 20 days duration. The waterlogging treatments were applied: (a) when about 80% of the crop emergence had occurred, (b) 20 days after the emergence, (c) during the flowering stage, and (d) during the grain formation stage. Two soybean varieties were tested. It was concluded that soybeans were most susceptible to waterlogging conditions during the flowering stage. The
reduction in soybean yield due to the different combinations of treatments studied is shown in Table 2 and is represented in graphical form in Figure 2.

Table 2. Soybean yield\(^a\) as a function of depth and duration of water table at different periods of growing season

<table>
<thead>
<tr>
<th>Continuous stay of the water table (days)</th>
<th>Percent of maximum yield</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Emergence period</td>
<td>20 days after emergence</td>
<td>Flowering period</td>
<td>Grain formation period</td>
</tr>
<tr>
<td>0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>5</td>
<td>92.8</td>
<td>98.5</td>
<td>94.8</td>
<td>90.8</td>
</tr>
<tr>
<td>10</td>
<td>91.9</td>
<td>94.7</td>
<td>88.6</td>
<td>88.9</td>
</tr>
<tr>
<td>15</td>
<td>91.2</td>
<td>92.3</td>
<td>68.5</td>
<td>87.4</td>
</tr>
<tr>
<td>20</td>
<td>87.3</td>
<td>84.3</td>
<td>54.3</td>
<td>85.9</td>
</tr>
</tbody>
</table>

\(^a\)Two soybean varieties, three-year average.

Barni (1978) studied the effects of 15- and 30-days of flooding on soybean yield during the periods: (1) emergence-flowering, (2) flowering, and (3) grain formation. It was concluded that soybeans were most susceptible to waterlogging conditions during the flowering period. A similar investigation was carried out by Barni and Costa (1978) at the same location (South Brazil). They concluded that the waterlogging treatments reduced crop yields during the stages of flowering, formation of beans, and grain formation. Also, they found that waterlogging conditions with durations less than 15 days did not
Figure 2. Soybean yield reduction as a function of waterlogging duration at different periods of growing season.
significantly reduce the crop yield when applied during the plant vegetative growth, at the beginning of the blooming stage, or at the end of the grain formation period. The 30-day flooding treatment during the flowering period reduced the soybean yield by more than 65 percent.

Stanley (1978) studied the root and shoot response of soybeans to different water table conditions in a rhyzotrom. One study showed that with permanent static water table depths of 150-, 105-, and 75-cm no differences in shoot growth were observed. Once downward growth had penetrated to within 15 cm of the water table levels, massive growth of new roots occurred in soil areas 15 to 30 cm above the free water level. Water use comparisons among the different water table depth treatments were made and no differences among treatments were found. Another study indicated that a temporary 7-day water table, at 45 and 90 cm below the soil surface, imposed at different growth stages of soybeans, caused different root responses.

This latter study carried out by Stanley indicates that soybeans seem to change with time in ability to tolerate temporary water table conditions. Soybean roots during the pre-flowering growth stage apparently were able to continue growth downward shortly after removal of the water table. No apparent functional or physical damage occurred to the roots below the water table levels at this stage indicating a greater tolerance by the roots to the high soil moisture (low oxygen conditions).

During the post-flowering growth stage, Stanley observed that the root system had the ability to adjust but not to completely over-
come effects of the water tables. Downward root growth ceased soon after the water tables were imposed and massive root growth occurred above the depth to which the water had been. Soybean root growth response to water tables during the post-pod set growth stage indicated no ability of the plant to overcome the situation, at least in terms of continued growth. Apparently, at this stage all root growth stopped below the level of the water table, and no new growth occurred above that level. No detrimental effects caused by the temporary water tables were observed on top growth and stage of development.

Methods used for Subsurface Drainage Design

Current approaches for subsurface drainage that are primarily based on water table fluctuation are reviewed in this section.

The Glover equation (Dumm, 1954), or minor modifications thereof, has been used by the Bureau of Reclamation in design of drainage systems for irrigation projects. As reported by Dumm (1964) and Dumm and Winger (1964), the proposed theory is used to determine a seasonal water balance. Using a proposed drain spacing, the rise in water table resulting from each irrigation is determined. The rise is a function of irrigation practice planned and the drop between irrigation water applications calculated from the drain-spacing equation. Thus, for a specified drainage geometry, the water table height above the drain, midway between the drains, at the end of each time interval considered, is a function of: (1) the water table height at the
previous time interval, (2) the instantaneous water table build-up from each recharge increment (deep percolation from snowmelt, rain or irrigation divided by specific yield), and (3) the water table drawdown during the same period calculated from transient-state drainage equation. According to the Bureau of Reclamation's method, referred by Dumm (1964) as incremental-step approach, the proposed spacing is presumed adequate to maintain a water balance, providing the water table height predicted at the beginning of a season does not exceed that at the corresponding time in the previous season. A somewhat similar technique based on steady-state conditions was presented by Bouwer (1969).

Maasland (1959) studied the problem of water table fluctuations between ditch drains in response to intermittent instantaneous recharge. His basic solution was obtained by using a linearization technique on the differential equation resulting from the Dupuit-Forchheimer assumptions. The linearization technique assumes that the change in depth of the water-bearing stratum is small compared to the average depth. Thus, the water-bearing stratum is not limited to the arched flow region and the important flow region occurs below the arched region. Maasland's mathematical treatment was developed for the situation where the ditches penetrate to an impervious barrier and water stands in the ditches. The design procedure described by Dumm and Winger (1964), mentioned earlier, for drainage systems in irrigated areas in effect is a practical application of the approach advocated by Maasland (van Schilfgaarde, 1974).
Kraijenhoff (1958) studied the water table responses to an arbitrary precipitation pattern approximated by a bar histogram. He also used Dupuit-Forchheimer assumptions to derive his basic solution. According to van Schilfgaarde (1965), Kraijenhoff (1958) used a different approach from Maasland (1959), but it led to essentially the same results. An idealized two-dimensional situation, as used also by Maasland (1959), was used by Kraijenhoff (1958) in his analysis.

Van Schilfgaarde (1965) used a procedure similar to Kraijenhoff's transient flow analysis, except that van Schilfgaarde's equation was derived from a steady-state solution based on potential theory while Kraijenhoff's development was derived from a steady-state solution based on the Dupuit-Forchheimer assumptions. van Schilfgaarde (1965) began by applying the Bouwer and van Schilfgaarde's (1963) analysis

\[ R = -F C \frac{dH}{dt} \]  \hspace{1cm} (1)

to the steady-state solution of Kirkham (1958)

\[ R = \frac{KH}{FS} \]  \hspace{1cm} (2)

to arrive at

\[ \frac{dH}{dt} + \frac{H}{A} = 0 \]  \hspace{1cm} (3)

where \( \frac{dH}{dt} \) equals the rate of fall of the water table midway between the drains, \( H \) is the water table height between drains above tile center, and \( A \) is a system-defining constant. The factor \( A \), with dimensions of time, combines the geometry of the drainage system as
well as the soil properties into only one constant which defines the system. \( A \) is defined as

\[
A = \frac{f F C S}{K}
\]

(4)

where

\[
F = G(\frac{r}{S}, \frac{d}{S})
\]

(5)

It can be seen that \( A \) is a function of drain radius \( r \), spacing \( S \), depth of impervious layer \( d \) below the drain axes, as well as of the hydraulic conductivity \( K \) and pore space fraction \( f \). \( F \) is an infinite series function derived by Kirkham (1958) and tabulated by Toksoz and Kirkham (1961). \( C \) is a shape correction factor that accounts for the changes in shape of the water table with drawdown. \( R \) is the steady recharge or drainage rate.

The basic van Schilfgaarde's equation for predicting the height of the water table \( H_N \) at the end of the \( N \)th time period can be written as follows:

\[
H_N = \frac{A}{F(e^1/A - 1)} \sum_{n=1}^{N} P_n e^{-(N-n+1)/A}
\]

(6)

Young and Ligon (1972) give this same equation in a simpler and somewhat more practical form which gives the height of the water table \( H_N \) at the end of the \( N \)th time period based on the height of the water table from the previous day \( H_{N-1} \) as follows:

\[
H_N = [H_{N-1} + \frac{A}{F(e^1/A - 1)}P_N e^{-1/A}]
\]

(7)

The symbol \( P_N \) (or \( P_n \), as in Equation 6), is the rate that water is added
to the soil profile. It represents that part of the precipitation occurring in the Nth time period which moves through the soil profile and is added to the water table. The rate of excess moisture addition is constant and is assumed to take place over the entire length of the Nth time period.

To predict the value of \( P_N \), van Schilfgaarde (1965) used a soil water balance developed by Wiser and van Schilfgaarde (1964). The balance accounted for water addition by precipitation and irrigation, and water removal by evapotranspiration. Surface runoff and deep seepage losses were ignored in the balance. Any water added by rainfall after the soil had reached field capacity was termed excess water and assigned to the variable \( P_N \). Equation (6) was then used to calculate the water table movement. The results were expressed in terms of frequency diagrams showing the length of period per year that a certain water table height is exceeded in relation to drain spacing and recurrence interval. Therefore, a specific drainage system design could be selected on the basis of a prescribed risk.

Vaigneur and Johnson (1966) applied van Schilfgaarde's method to the soil and climatic conditions of central Iowa. They first tested Equation (6) with a glassbead-glycerol drainage model. A daily water balance based on procedures of Shaw (1963) was used to evaluate the time and amount of excess moisture. Surface runoff was included in their balance and deep seepage was assumed negligible. From tabulations of the calculated water-table heights during the critical drainage period (April-June), recurrence interval for specific water tables and durations
were developed for use in drainage design.

The probabilistic basis procedure to establish subsurface drainage system design was also used by Young and Ligon (1972). The van Schilfgaarde's transient drainage equation was used to calculate water-table heights for given soil characteristics and drainage facilities. They modified the water balance model of Ligon et al. (1965) to include surface runoff and used it to determine the daily amount of excess moisture added to the soil profile.

Wiser et al. (1974) have linked van Schilfgaarde's fluctuating water table equation with a crop response model, developed from Tovey's (1964) water table experimental data, to optimize the design of a drainage system. They used the water balance of Wiser and van Schilfgaarde (1964) to determine excess soil moisture. The daily water-table heights were scanned to determine the single longest period for each year during which the water table was at the surface. These lengths of time were then compared to a graph showing the relationship between damage and duration of the damaging period for alfalfa for each year of the simulation period (50 years). From these comparisons, frequency distributions were developed giving the probability of different levels of damage for various drainage geometries studied.

The maximum yield of alfalfa, corresponding to a static water table at each depth of drain used in the analysis, was based on results obtained by Tovey (1964). By simply subtracting the computed yield reductions from the maximum yield, annual values of yield were determined. These values (50 for each drainage geometry studied) were
averaged to give the average annual value of the yield. The annual net return was obtained by subtracting the assumed annual cost of drainage from the annual benefit (taken equal to the annual yield). The annual net returns were plotted against drain spacings for the three different depths of drain. From such plots, the drainage system giving the maximum net return (optimum) could be selected.

A simulation model was developed by Wendte et al. (1977) to predict the effect of subsurface drainage on the number of available working days and, thus, on timeliness of farming operations. The moisture budgeting technique of Elliott (Wendte et al., 1977) was used to compute the amount of excess water added to the water table, and the daily water-table heights were calculated using the van Schilfgaarde drainage equation as given by Young and Ligon (1972).

Bhattacharya et al. (1977) proposed a water balance model for subsurface drainage design. In their approach, the system installation cost and the market value of harvested crop were compared for drainage systems designed with different drainage rates. Each drainage rate corresponded to a certain spacing. The water balance model was used with a certain drainage rate and spacing to give a particular distribution of water table depths. A drainage system was considered to be inadequate if the water table remained closer than 40 cm from soil surface for more than two successive days. It was assumed that the drainage rate follows Hooghoudt's steady-state drainage equation when the water table was beyond the allowable water table depth from the soil surface. Therefore, it was assumed that steady-state conditions are
valid during each time interval. Basically, the same water balance approach of Bhattacharya et al. (1977) was used by Chieng et al. (1978) to estimate minimum drainage rates that could be acceptable for the locations studied.

Skaggs (1975a) proposed a water management model for predicting the fluctuation of the water table. The model also gave the changes in water content above the water table caused by rainfall, evapotranspiration, given degrees of surface and subsurface drainage, and such management techniques as water table control or subirrigation practices. By simulating the performance of alternative systems over several years of record of climatological data, optimum water management systems could be designed on a probabilistic basis. The drainage design criterion based on the probabilistic distribution of water table heights was initially proposed by van Schilfgaarde (1965).

The computer simulation model was based on a water balance in the soil profile. To simplify the required inputs to the model and to make them consistent with available data, approximate methods were used to evaluate the rates of infiltration, drainage and evapotranspiration (potential and actual), and the subsequent water content distribution in the profile. To evaluate the subsurface drainage or subirrigation rates, the model used the Hooghondt's steady state equation with the modification introduced by Bouwer and van Schilfgaarde (1963).

The concept of the limiting water table depth within which the evaporation rate at the soil surface is the same as the potential rate, first reported by Gardner (1958), was used by Skaggs (1975a) in his model. He assumed that the potential evapotranspiration rate is
supplied from the water table until the distance between the root zone and the water table becomes greater than the limiting. This subject is reviewed in more detail later.

Ravelo et al. (1978) expanded the work of Skaggs (1975a, 1976) by incorporating a drainage crop response model based on the stress-day index approach for drainage (Hiler, 1969). Thus, a drainage design methodology was developed through frequency analysis of simulation results from the modified water management model. Design graphs for specified drain depths and surface drainage conditions were presented. From them one could determine the necessary drain spacing to avoid a crop damage greater than a certain percentage in a given recurrence interval.

**Influence of Evaporation or Evapotranspiration on Water-table Recession**

Gardner and Fireman (1958) conducted a laboratory study of evaporation from soil columns in the presence of a water table. They found that for a water table position within the range given by soil surface to a depth of 60 to 90 cm, evaporation was limited largely by the external conditions in most soils. As the water table was lowered below 60 or 90 cm, the evaporation rate became limited by the soil properties and decreased markedly with depth. Laliberte and Rapp (1965) studied the influence of evaporation on water table recession in a glacial till soil following irrigation. They found that water table drawdown rate following irrigation was significantly influenced by evaporation. With tile
drainage, evaporation was no longer influenced by the water table when it reached a depth of 1.5 to 2.0 feet. With no artificial drainage, the limiting depth of influence was 2.5 to 3.0 feet. Aldabagh and Beer (1975) found that if the water table was kept below a depth of 1.5 to 2.0 feet, the soil surface would be dry enough to permit spring plowing.

Schwab et al. (1957) studied the effect of tile spacing on crop yield and water table level in a Planosol soil. By comparing tile outflow volume and rate of water table drop, they concluded that following the first day after rainfall, evapotranspiration and other losses appeared to influence the rate of drop more than the tile. Beer et al. (1965), studied the yield response of corn in a Planosol soil to subsurface drainage. They found that during the growing season evaporation and transpiration were probably more effective in lowering the water table than was tile. The influence of evapotranspiration on water table drawdown, in many cases, is equal to or greater than that due to drainage. This is particularly true during the growing season when plant roots can take up water from various depths in the profile (Skaggs, 1975b). Underdrain flow response in a fragipan soil in central New York was reported by Walter et al. (1977). They found that seasonal evapotranspiration had a direct effect on average monthly tile flow.

The effect of tile spacing on corn yield and water table behavior in a Gley soil was studied by Goulart (1975). The drain tubes were laid on the impervious layer 70 cm from the soil surface. The
spacings used were 8, 12, and 16 m. It was concluded that the water removal from the upper layers of the soil appeared to be more related to the losses of evapotranspiration than to the effect of tile drainage. This is shown in Figures 3 through 5, where two drawdown curves at the midpoint between tile lines are compared. The data referent to one curve were recorded when corn was being harvested. The other curve refers to the period when corn was at 30 percent of its growing season. This curve was shifted to the right to match the other curve at point P, for a common water table referral height. The estimated potential evapotranspiration rates during these two periods were 3.06 and 0.98 mm/day, respectively (Goulart, 1975).

Gardner (1958) showed that for steady-state conditions the evaporation rate at the soil surface is the same as the potential rate so long as the water table is above some limiting depth. This depth is dependent on the unsaturated hydraulic conductivity of the soil and on the evaporation rate. The rate of evaporation decreases as the depth of the limiting depth increases. For water table depths greater than the limiting depth, water will still move upward, but at a rate less than the potential evapotranspiration. By solving numerically the governing equation for unsaturated upward water movement, Wells and Skaggs (1976) established the relationship between maximum rate of upward water movement and water table depth below root zone for a Wagram loamy sandy soil.

Based on informations found in the literature, Wendte et al. (1977) selected the 46-cm depth as the limiting depth used in their model. Thus, they assumed that the soil could not start drying out
Figure 3. Recorded water table drawdown curves for 8 m spacing tile drained soil with tiles laid on the impervious layer
Figure 4. Recorded water table drawdown curves for 12 m spacing tile drained soil with tiles laid on the impervious layer.
Figure 5. Recorded water table drawdown curves for 16 m spacing tile drained soil with tiles laid on the impervious layer.

- 30% corn growing season
- Corn harvesting

\[ S = 16 \text{ m} \]
\[ K = 14.4 \text{ cm/day} \]
\[ f = 2.53\% \]
until the water table was below that depth. When the water table depth was less than 46 cm, evaporation was assumed to take place only from the water table and not from available soil moisture. Because of the difficulty of determining relationship between maximum rate of upward water movement and water table depth, Skaggs (1978) developed a more approximate method. His method estimates a single critical or limiting depth parameter, which could be used as an option in Skaggs' model. When this option is used, it is assumed that the potential evapotranspiration rate will be supplied from the water table until the distance between the root zone and the water table becomes greater than the limiting depth. After the distance between the root zone and the water table reaches the limiting depth, it is assumed that water will be extracted from the root zone at a rate still equal to the potential evapotranspiration rate. This condition will persist until the root zone water content reaches the wilting point. When the depth of the dry zone is equal to the rooting depth, evapotranspiration is assumed equal to zero.
To design a subsurface drainage system using fluctuating water tables as a design criterion, certain requirements have to be fulfilled. Thus, the water table hydrograph for a given drainage system and its effect upon the crop yield must be predicted. The input data required to use this approach consist of climatological factors and soil, crop and drainage parameters. The following design steps are described in this chapter: (1) Development of a methodology to predict water table fluctuation and the corresponding crop yield response under subsurface drainage facilities, (2) the basis of the economic analysis, and (3) the role of the required input data.

Simulation of Water Table Fluctuation

Applicability of the existing transient flow equations to field conditions

As pointed out in the review of literature, Kraijenhoff (1958), Maasland (1959) and van Schilfgaarde (1965) developed equations for computing the elevation of the water table at the midpoint between drains. However, their equations cannot be used when the water level in the drainage ditch or the grade line of the tile coincide with the level of the impermeable layer. In this case, the flow region and the arched region are the same. The solutions of Kraijenhoff (1958), Maasland (1959) and van Schilfgaarde (1965) to this situation is not applicable due to the assumptions used in deriving their equations.
Maasland (1959) and Kraijenhoff (1958) obtained their solutions by using a linearization technique on the differential equation resulting from the Dupuit-Forchheimer assumptions. On the other hand, van Schilfgaarde (1965) began the derivation of his equation by applying the analysis of Bouwer and van Schilfgaarde (1963) to the Kirkham's steady-state solution (1958). To derive his steady-state drainage equation, Kirkham (1958) assumed that an impermeable barrier preventing deep seepage lies below the drain centers at some depth, say D. Furthermore, by neglecting the loss of the hydraulic head in the arched region above the drains, his model consisted of a rectangular flow region. This region is bounded by the impervious layer, the vertical planes of symmetry through the drain axis and through the midplane between drains, and a horizontal plane through the lowest point on the water table. Therefore, Kirkham's steady-state solution cannot be used in situations where the rectangular flow region does not exist.

A glassbead-glycerol drainage model was used by Vaigneur (1965) to generate daily water table heights for certain subsurface drainage geometry and soil characteristics. The model results were compared with those obtained from the analytical procedures given by Kraijenhoff (1958) and by van Schilfgaarde (1965). The van Schilfgaarde equation gave results closer in agreement with the model results than the Kraijenhoff's approach, and it was selected by Vaigneur (1965) to be used in his investigation. However, he did not find good agreement with the model results, except for tile spacing of 40 feet (12 m), when assuming an impervious layer at 0.5 foot (0.076 m) below the bottom.
of the drain.

Since this investigation deals with subsurface drainage of soils with an impervious layer close to the surface and requires the tile lines to be laid on that layer, neither of the methods just discussed could be used. Thus, a way to predict the water table fluctuation at the midpoint between tile lines had to be found.

The first approach thought was to derive an empirical steady-state equation for the condition where the drain lines are laid on the impermeable layer. If such an equation had the terms corresponding to the steady rainfall (R) and to the height of the water table halfway between tile lines (H) raised to the first power, it could replace the Kirkham equation used by van Schilfgaarde (1965) without any change in his analysis. The only modification would be in the value of the term A (see Equation 4). With this modification, the van Schilfgaarde equation could then be applied to predict water table fluctuation in the type of soils under consideration in this study. To empirically derive the steady-state equation, a glassbead-glycerol drainage model was used.

Drainage model

The glassbead-glycerol drainage model used in this research had two purposes. The first was to obtain a prediction equation for steady-state drainage when the tiles are laid on an impermeable layer. The second was to generate daily water table heights for certain tile spacings and soil characteristics to compare with those results obtained
Dimensional analysis and similitude

Ligon et al. (1963) investigated the application of similitude to the modeling of unsteady-state soil drainage problems, particularly the problem of the falling water table between open ditch drains. It was found that three simplifying assumptions were valid, namely: (1) that the effect of a capillary fringe in the model could be eliminated, (2) that all the effects of fluid characteristics, acceleration of gravity, and characteristics of the porous medium could be taken into account by the hydraulic conductivity \( K \) and the drainable porosity \( f \) of the porous medium, and (3) that flow occurred in two-dimensional planes perpendicular to the drains.

For the case of steady-state drainage conditions, the second assumption made by Ligon et al. (1963) was modified. Thus, it was assumed that all the effects of fluid characteristics, acceleration of gravity, and characteristics of the porous medium could be taken into account only by the hydraulic conductivity \( K \) of the system.

Based on these assumptions, the variables considered pertinent for a viscous-fluid model used to investigate steady-state drainage with tiles laid on an impermeable layer were identified. These variables, along with their dimensions (length, \( L \), and time, \( T \)), and the symbols used to represent them are as follows:

- \( H \), height of the water table midway between tiles above an impermeable layer (L)
- \( S \), drain spacing (L)
d, drain depth or impermeable layer depth (L)
r, radius of tile (L)
K, hydraulic conductivity of the porous medium-fluid system (LT$^{-1}$)
R, excess moisture infiltrated per day (LT$^{-1}$)

The position of the water table could be written as a function of the remaining variables in the form

$$H = F(r, d, S, K, R)$$

However, it was observed that when the tiles are laid on an impervious layer, its depth (d) could not be considered as a variable, since it did not produce any change in the hydraulic head (H) if all the remaining variables were kept constant. On the other hand, Grover and Kirkham (1964) observed that if they had used drain tubes half or twice as large as the size used in their model, the rates of fall of the water table would not have differed more than about 18.3 percent from those values reported. Furthermore, the results of Kirkham's (1949) analysis of the flow of ponded water into drain tubes in soil overlying an impervious layer, show that the diameter of the tile apparently has little effect on the flow rate. For example, at a depth of 2 feet (61 cm), the flow rate increases only 13.3 percent when the drain size increases from 4 inches (10.2 cm) to 12 inches (30.5 cm). This value is based on the assumption that the drains are running full with no back pressure.

In view of the small effect of the drain size on the rate of flow under model or field conditions, the size of the drain in the model
was no longer considered as pertinent variable. Thus, the hydraulic head \( H \), could be given as

\[
H = F(S, K, R)
\] (9)

There are now four variables involving two basic dimensions which could be expressed in two dimensionless pi terms according to the Buckingham Pi Theorem (Guitjens, 1974). The two pi terms were used to give the following expression

\[
\frac{S}{H} = F\left(\frac{K}{R}\right)
\] (10)

Corresponding pi terms of the model and the prototype must have the same magnitude to satisfy similitude; hence, using the subscripts \( m \) and \( p \) for model and prototype, respectively,

\[
(S/H)_m = (S/H)_p \] (11)

\[
(K/R)_m = (K/R)_p \] (12)

The operation of the model under transient flow conditions requires that two more pertinent variables be included in the dimensional analysis, namely the drainable porosity \( f \) of the porous medium and the time \( t \). In this case, the second assumption of Ligon et al. (1963), as previously described, could be accepted in full. Hence, the hydraulic head \( H \) became a function of five variables as follows

\[
H = F(S, K, R, f, t)
\] (13)
There are six variables involving two basic dimensions. Thus, according
to the Buckingham Pi Theorem (Murphy, 1950), four dimensionless and
independent pi terms can be written, one of them being formed by the
already dimensionless variable f. One possible set is as follows, with
the term involving the water table height written as a function of the
remaining terms:

\[ \frac{H}{S} = F\left(\frac{K}{R}, \frac{Kt}{S}, f\right) \] (14)

According to Ligon's (1961) findings, the last pi term, f, could be
combined with the second pi term on the right of Equation (14) in the
form \( \frac{Kt}{Sf} \). Hence, Equation (14) became

\[ \frac{H}{S} = F\left(\frac{K}{R}, \frac{Kt}{Sf}\right) \] (15)

In accordance with the laws of similitude, all of the pi-terms
in Equation (15) must each be set equal in model and prototype as follows

\[
\frac{S}{H}_m = \frac{S}{H}_p \quad (16) \\
\frac{Kt}{Sf}_m = \frac{Kt}{Sf}_p \quad (17) \\
\frac{K}{R}_m = \frac{K}{R}_p \quad (18)
\]

where m and p stand for model and prototype, respectively.

**Measurement of K and f**  
The model was operated in a room in
which the air temperature and relative humidity could be held within
ranges of about plus or minus one degree Fahrenheit and five percent,
respectively. Thus, the fluid viscosity did not change appreciably
during any particular run. Between runs, however, there were changes in viscosity because the water content of the glycerol moved toward equilibrium with the humidity of the air. A direct determination of the hydraulic conductivity $K$ was made initially in the same manner as described by Ligon (1961). At that time, the viscosity of the glycerol was measured. The hydraulic conductivity $K$ for each particular drainage run was determined by correcting the initial value in accordance with changes in viscosity of the glycerol.

In order to operate the model under unsteady-state condition, it was also necessary to determine the drainable porosity $f$ of the porous medium. Ligon et al. (1963) reported that by following a standardized procedure for packing and saturating the glassbeads (2 mm in diameter), the drainable porosity could be kept constant for all practical purposes. Therefore, the drainable porosity $f$ was only measured at the time when a direct determination of the hydraulic conductivity $K$ was made. The measurements were made in place to avoid the variation in void geometry between the spheres and between the spheres and model boundaries. Thus, the drainable porosity $f$ was determined by measuring the volume of fluid discharged and dividing it by the volume of the medium drained. The average value of two determinations was 45.7 percent.

**Capillary fringe** It was assumed in the dimensional analysis that the effect of the capillary fringe could be eliminated in the model. Grover and Kirkham (1964) showed that a suction head of 7.5 mm of
glycerol was required to pull the glycerol through silicone treated glassbeads with a diameter of 2 mm. They appropriately used the term "pseudo" capillary fringe because the glycerol did not rise 7.5 mm in the beads by capillarity. Ligon et al. (1963) observed a fringe of 0.3 inch (7.6 mm) in their model which had the characteristics of a capillary fringe when the model was operating. The beads were also 2 mm in diameter and were silicone treated. Tests designed to evaluate the effect of such a fringe were conducted. It was found that the fringe did not appreciably affect the water table drawdown curves provided the model was operated with a minimum bead depth of 2 inches (5.1 cm).

To measure the size of the capillary fringe, a system similar to the one reported by Grover and Kirkham (1961) was used. The bottom of two cylindrical containers were connected by a flexible tube so that any differential pressure between the containers could be equalized by flow through the tube. One container was filled with untreated silicone 5 mm beads. Glycerol was added to the other container and allowed to flow into the bead-filled one and to equilibrate. To obtain a reading on the magnitude of the capillary fringe, the elevation of the bead-filled container was raised so that the surface of saturation would move. When the system had reached equilibrium, a positive difference of 3 to 5 mm between the surface of saturation (bead-filled container) and the free surface of glycerol in the other container was measured. About the same difference was observed during the determination of the
hydraulic conductivity directly in the model. It was noticed during the drainage tests that the fringe did not affect the water table curves when, at the halfway between drains, the water table height was greater than 2.0 cm. It was observed further that after the tile outflow became zero, a horizontal water table height of 1.4 cm still was held regardless of the tile spacing being used.

Model description

The model constructed was similar to the tile drainage model of Vaigneur (1965) and is shown in Figure 6. It had a study section (chamber) 200 cm wide, 35 cm deep and 1.5 cm in thickness. The model chamber and the rainfall distributor were constructed of 0.64 cm transparent plexiglass. The front and back of the chamber were formed from a single sheet of this material. The inside back, edges and bottom were painted with a flat finish black paint to produce a dark background which accentuated the surface of saturation in the porous medium.

For studying the cases where tiles are laid on an impermeable layer, openings for the tile insertions were established every 50 cm on the front wall exactly on the bottom of the chamber. The three openings at the middle had a diameter of 1.91 cm and the two at the corners were made with a diameter of 1.22 cm. The diameter of those at the corners was made somewhat smaller since they would carry less fluid. An exact correction as in Warrick and Kirkham (1968) does not seem to be available. Cylindrical brass screen with 18 meshes per inch was used to simulate drain tiles. According to Grover and Kirkham (1964), model drain tubes formed of wire screen correspond to a field condition.
Figure 6. Photographs of the drainage model: (a) Front view of the model chamber and fluid distributor, (b) Back view of the model chamber and fluid applicator, (c) Model feeding and constant head reservoirs
of drain tile being surrounded by highly permeable material, such as coarse gravel or large stable soil aggregates. An outlet tube equipped with a valve was connected to each of the openings. During a drainage run the outlets were at atmosphere pressure. Glass spheres, approximately 5 mm in diameter, were used as the porous medium which was 25 cm deep.

Glycerol was used as the model fluid. It has been used by other researchers (Grover and Kirkham, 1961; Ligon et al., 1963; Asseed and Kirkham, 1966; Vaigneur and Johnson, 1966) because of its relatively high viscosity which slows the drainage process and insures laminar flow in the pores. Laminar flow is a requisite for applying Darcy's Law and thus the use of the hydraulic conductivity $K$ as a pertinent variable.

To operate the model under steady-state condition, it had to be supplied with a constant and uniformly distributed simulated rainfall. To secure a constant head, a feeding reservoir (3.8 liters in capacity) was connected by a flexible tube to a constant head reservoir. Since the glycerol had a relatively high viscosity, it was easy to control the head by operating a clamp activated by one screw on the flexible tube connecting both reservoirs. A flexible tube connected the constant head reservoir to the center of a plexiglass cylindrical manifold 180 cm long and 3.8 cm in diameter. Sixteen 0.64-cm inside-diameter flexible tubes 30 cm long were placed 12 cm on center along the manifold. A clamp activated by a screw near the outlet of the tubes provided a means for calibrating the discharge. The flow from each tube could be controlled
giving a uniform discharge into the distributor. The distributor was fabricated from two pieces of plexiglass, 5 cm deep and 200 cm long. The two pieces were separated by strips 5 cm long and 1 cm wide, and placed in a vertical position 12.5 cm on center from either end. The strips formed partitions such that the inflow from each of the sixteen flexible tubes connected to the manifold remained separated from the flow of the tubes on either side. A bottom made of plexiglass was cemented to the distributor. Holes 0.15 cm in diameter and 2.5 cm on center were drilled in the plexiglass member on the bottom of the distributor. Rigid plastic tubings 0.16-cm inside-diameter and 2 cm long were cemented on the bottom of the distributor such that each one was symmetrically located over the hole in the plexiglass. No further means were used to calibrate the orifices.

To measure the variation in distribution, five runs were made after the 16 tubes had been adjusted to the same rate of flow. A constant head was established at the reservoir and the discharge from individual tubes was collected. An analysis of variance indicated no significant difference at the 0.05 probability level. The data from the calibration test are given in Table A1 in Appendix A.

A similar evaluation was made for the volume collected from the five outlets beneath each of the compartments which made up the distributor. One cell at a time was run by pouring a 50-ml quantity of fluid into the center of the cell and measuring the volume discharged by each outlet. Four runs were carried out for each compartment. Analysis of variance performed individually for each compartment showed
that in 4 of the 16 compartments there was no significant difference at the 0.05 probability level. The most likely cause of the differences among the collected volumes was the formation of air bubbles inside the outlets (rigid plastic tubings 0.16-cm inside diameter and 2 cm long). However, since the outlets were constructed 2.6 cm on center, such discharge differences did not affect the distribution of the glycerol in the porous medium. The average values of the four runs for each outlet are given in Table A2 in Appendix A.

**Prediction equation**

Drainage runs were conducted with the model to obtain steady water table heights for a wide range of the dimensionless parameter K/R (ratio of the hydraulic conductivity to constant simulated rainfall rate). This ratio was varied between values of 18 and 1590. Five different tile spacings were used, namely 50, 100, 200, 300 and 400 cm. Since the model was only 200 cm wide, data for the 300- and 400-cm spacings were obtained by setting the model to simulate half of these spacings. This approach was supported by the study reported by Grover et al. (1960). The water table heights halfway between drain tubes were recorded when the system had reached equilibrium (Appendix B). Figures 7 through 10 show the drainage model operating when equilibrium conditions were obtained for K/R = 132. At this time, the inflow rate R entering the system was also recorded. Sometimes, when the system was operating with small rainfall rates, it was difficult to determine by visual observation of the water table behavior whether equilibrium had been reached. For this
Figure 7. Drainage model showing a steady-state condition for $K = 76.42$ m/day, $R = 0.58$ m/day ($K/R = 132$) and tile spacing = 100 cm
Figure 8. Drainage model showing a steady-state condition for $K = 76.42 \text{ m/day}$, $R = 0.58 \text{ m/day}$ and tile spacing = 200 cm
Figure 9. Drainage model showing a steady-state condition for $K = 76.42$ m/day, $R = 0.58$ m/day and tile spacings = 50 and 300 cm
Figure 10. Drainage model showing a steady-state condition for $K = 76.42 \text{ m/day}$, $R = 0.58 \text{ m/day}$ and tile spacing = 400 cm
condition, it was necessary to compare the inflow with the outflow from the system to check equilibrium.

The experimental values of the two dimensionless parameters (S/H and K/R), when plotted on logarithmic paper, indicated that a straight line could be fitted to the data (Figure 11). A linear regression analysis gave the following equation with a correlation coefficient of 0.97

\[
S/H = 2.565 (K/R)^{0.42}
\]

Solving this equation for H yields

\[
H = 0.39 S(R/K)^{0.42}
\]

which is very similar to the ellipse equation when the water level in the drains is at the same depth as the impermeable layer

\[
H = 0.5 S(R/K)^{0.5}
\]

The straight line corresponding to the relationship between S/H and K/R given by Equation (21) is also shown in Figure 11. The model and the ellipse equations give the same results when the ratio K/R is approximately equal to 22. As this ratio decreases, the model equation gives lower values of H than the ellipse equation. The opposite occurs when the ratio becomes greater than 22.

Equation (20) does not have both terms H and R raised to the first power as desired. Therefore, it could not be used to replace the Kirkham's equation in the van Schilfgaarde's analysis (1965). Hence, van Schilfgaarde's equation could not be modified and applied to the
Figure 11. Dimensionless values of S/H versus the dimensionless values of K/R obtained from the drainage model operating with tile drains laid on the impervious layer.

Model: \( S/H = 2.565 (K/R)^{0.42} \)

Ellipse: \( S/H = 2.0 (K/R)^{0.50} \)
case under consideration.

At this point, another approach to predict water table fluctuation had to be developed. The development of a method similar to the one that had been used by the Bureau of Reclamation (Dumm, 1964; Dumm and Winger, 1964) for drainage design in irrigated areas was considered. The method considers the transient regimen of the groundwater recharge and discharge. Hence, it was assumed that the daily water table height above the tile bottom halfway between tile lines could be computed as follows

\[ H(N) = H(N-1) + \frac{\text{Exc}}{f} - 9.42\left(\frac{k}{f}\right)[H(N-1)/S]^{2.381} \]  

(22)

where

- \( H(N) \) = water table height at the end of the Nth day,
- \( H(N-1) \) = water table height at the end of the previous day, and
- \( \text{Exc}/f \) = instantaneous buildup of the water table from each recharge increment (excess of soil water in the soil profile divided by drainable porous space).

The third term on the right hand side of Equation (22) accounts for the water table drawdown at the Nth day, and corresponds to Equation (20) solved for the drainage rate (\( R \)) and divided by \( f \).

It was desired to compare the daily water table heights obtained from the analytical procedure given in Equation (22) with those generated by the glassbeads-glycerol drainage model. To make this comparison possible, the design of the model (time scale and rate of application) had to be established first.
Model design

To make a comparison between predicted daily water table heights for a certain field situation (prototype) with those results obtained from the drainage model, a time scale was set up by solving Equation (17) for time as follows:

\[
\frac{t}{t_m} = n \frac{K_m}{K} \frac{f}{f_m}
\]  

(23)

where \( m \) stands for model and \( n = S/S_m \) is the length scale. For convenience, the subscript \( p \) denoting the prototype was deleted.

A scale for rate of fluid application to the model was established by rearranging Equation (18) as

\[
R_m = \frac{K_m}{K} R
\]  

(24)

Predicted water table heights compared with model results

Hypothetical soil moisture excess within a period of 62 days was used as input to the system. The days with soil moisture excess and its corresponding amount are given in Table 3.

To evaluate the time and the rate of fluid application scales, arbitrary field conditions were selected consisting of a hydraulic conductivity of 50 cm/day and a drainable porosity of 6.7 percent. A length scale (\( n \)) of 10 was also selected. These values, along with the drainable porosity of the model (0.46) and its hydraulic conductivity at the time of each run, were applied to Equation (23). The relationship was such that when \( t \) was one day, \( t_m \) was 6.5 and 7.0 minutes for \( K_m \) values of 71.72 and 76.42 m/day, respectively. The rates of fluid application were easily determined by using Equation (24). These values,
Table 3. Hypothetical daily soil moisture excess

<table>
<thead>
<tr>
<th>Day number</th>
<th>Excess, R (cm/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.62</td>
</tr>
<tr>
<td>2</td>
<td>1.91</td>
</tr>
<tr>
<td>11</td>
<td>0.90</td>
</tr>
<tr>
<td>15</td>
<td>0.61</td>
</tr>
<tr>
<td>16</td>
<td>1.67</td>
</tr>
<tr>
<td>17</td>
<td>0.80</td>
</tr>
<tr>
<td>21</td>
<td>0.35</td>
</tr>
<tr>
<td>22</td>
<td>4.78</td>
</tr>
<tr>
<td>34</td>
<td>0.45</td>
</tr>
<tr>
<td>41</td>
<td>0.82</td>
</tr>
<tr>
<td>42</td>
<td>2.92</td>
</tr>
</tbody>
</table>

multiplied by the surface area of the model, gave the volumes of fluid to be applied to the model. The application of each volume was made following the procedure described by Vaigneur (1965).

Model tile-spacings of 50, 100, 200, 300 and 400 cm were used in the experiment. The observed water tables were converted to field scale and plotted with those predicted by Equation (22) for comparison. The agreement between observed and calculated water table heights was not good, as can be observed in Figure 12 for a tile spacing of 40 m.

The last term on the right side of Equation (22) was changed by the one corresponding to Equation (21) solved for the drainage rate R
Figure 12. Water table fluctuation for 40 m tile spacing, with tiles laid on the impervious layer, as found by model and Equation (22)
and divided by f. Then Equation (22) became

\[ H(N) = H(N-1) + \left( \frac{\text{Exc}}{f} \right) - 4\left( \frac{K}{f} \right)\frac{H(N-1)}{S}^2 \] (25)

The same comparisons were made using this equation, but the agreement between observed and predicted water tables still was not satisfactory.

Drawdown curves for each drainage geometry have the same pattern provided other factors influencing water table behavior (as evapotranspiration) are kept constant. Based on this fact an attempt was made to calibrate Equation (25) to fit model data. Thus, for each drain spacing being considered, the coefficient 4 in the last term of Equation (25) was replaced by the number which gave the best agreement between observed and predicted water table heights. Therefore, Equation (25) was affected by a different coefficient to best simulate water table heights in each case. Fortunately, by plotting the modified coefficients versus the corresponding tile spacing studied on logarithmic paper, it was observed that a straight line could be drawn. A regression analysis was made and the following equation, with a correlation coefficient of 0.9999, was obtained:

\[ C = 0.2093 S^{0.359} \] (26)

where

- \( C \) = dynamic coefficient to replace constant 4 in the last term of Equation (25)
- \( S \) = drain spacing in centimeters

Replacing the constant 4 in the last term of Equation (25) by the right side of Equation (26) yields the following empirical equation:
\[ H(N) = H(N-1) + \frac{\text{Exc}}{f} - 0.2093 \frac{K \left[ H(N-1) \right]^2}{f 1.641} \]  (27)

where \( H \) and \( S \) are in centimeters, \( \text{Exc} \) and \( K \) are in centimeters per day, and \( f \) is a dimensionless variable. Equation (27) compared to Equation (25) predicts a slow drawdown when drain spacing is reduced and vice-versa. In other words, when the value of \( C \) (Equation 26) is less than 4 Equation (27) simulates a slower water table drawdown than Equation (25). For values of \( C \) greater than 4, the water table drawdown predicted by Equation (27) is greater than the one simulated by Equation (25).

Comparison between the observed water tables and those predicted with Equation (27) are shown in Figures 13 through 17. Consistent agreement for the three widest tile spacings can be observed. The lack of the same close agreement for tile spacings 5 and 10 m wide can be explained. For all spacings, the model was operated with the same depth of the porous medium or tile depth, which was 25 cm. Therefore, the model responded better to the inputs applied when it was operating with wide spacings, because the water table was consistently high, thus reducing the delay of time to buildup the water table. When the model tile spacings were 50 and 100 cm, part of the input applied reached the water table in the next period of time (the following day in the model). This caused a reduction in the peaks in the hydrographs of the observed data. Furthermore, as observed before, the minimum water table height in the model at complete drawdown was 1.4 cm. Below 2.0 cm the
Figure 13. Water table fluctuation for 40 m tile spacing, with tiles laid on the impervious layer, as found by model and Equation (27)
Figure 14. Water table fluctuation for 30 m tile spacing, with tiles laid on the impervious layer, as found by model and Equation (27)
Figure 15. Water table fluctuation for 20 m tile spacing, with tiles laid on the impervious layer, as found by model and Equation (27)
Figure 16. Water table fluctuation for 10 m tile spacing, with tiles laid on the impervious layer, as found by model and Equation (27)
Figure 17. Water table fluctuation for 5 m tile spacing, with tiles laid on the impervious layer, as found by model and Equation (27)
effect of the capillary fringe on the water table curves was noticed. These facts explain the discrepancy between the observed and predicted water tables when the drawdown curves reached a height less than 20 cm above the tile bottom (2 cm in the model). Therefore, it was concluded that the analytical development given in Equation (27) could be used to accurately calculate water-table fluctuations as found in the physical model. It was further assumed that the physical model satisfactorily predicted the water-table behavior for field conditions.

**Water balance approach for simulating water table depths**

From the literature reviewed, the approaches to predict water fluctuation for subsurface drainage design can be separated into two distinct categories. The first, as used by van Schilfgaarde (1965) and others (Vaigneur and Johnson, 1966; Young and Ligon, 1972; Wiser et al., 1974; and Wendte et al., 1977), can be divided into two steps: (1) determination of excess soil water using a water balance, and (2) application of the excess water as input to the van Schilfgaarde's equation to simulate water-table heights for a specified drainage geometry. The second approach, as used by Skaggs (1975a), and others (Bhattacharya et al., 1977; Chieng et al., 1978; and Ravelo et al., 1978) is a water balance integrated with the drainage geometry being studied. Therefore, a soil water balance is computed for each drainage geometry.

When a water balance is calculated separately from the computation of the water table movement (as in the first category described), the
excess of water, when it exists, is assumed to be removed from the soil profile before the next day (if the time interval used is a day). In reality, such excess of water is used to build up the water table. An excess of water of 40 mm will rise the water table 10 mm above the soil surface in a soil with a drainable porosity of 5 percent and an impervious layer 60 cm deep. It is assumed in this case that drainage facilities do not exist or drain spacings are not closer than 30 cm. Assume that no precipitation occurs on day 2. The water balance will show some depletion in the maximum water holding capacity of the soil profile due to évapotranspiration when, in reality, it is saturated with water. This situation happened when the above method was used in this investigation. To avoid erroneous conclusions, this approach was abandoned and the water balance was computed by integrating it with the drainage geometry.

Water balance development In developing a water balance for use in this study, an attempt was made to incorporate the best reported procedures compatible with available data. Thus, parts of the procedures are essentially the same as those used in the cited studies. Modifications and adaptations were made to meet the particular requirements of this work.

This method applies to a flat\(^1\) tile-drained cropland in which tile lines are laid on an existing impermeable layer located near the soil

\(^1\)Slope ranging from 0 to 5 percent.
the soil surface. The following assumptions were made:

1. Soybeans were grown annually from November 15 to about April 10. Natural pastures (grass or grass-clover mixture) were assumed to be grown during the remaining part of the year.

2. Water was removed from the soil profile only by subsurface drainage and evapotranspiration. Hence, no deep percolation was assumed to occur. This assumption is supported by the work done by Goulart (1975).

3. The water balance was restricted to the soil profile above the impervious layer. Thus, upward movement of moisture from the impermeable layer or below due to soil water potential gradient was not assumed to occur.

Basically, the water balance developed can be separated into two main parts. In the first part, the soil water excess is computed. This excess is one of the required inputs for the second part which is the determination of the water table height. These two parts are discussed in the following subsections.

Determination of soil water excess        The basic balance for the entire effective soil profile can be expressed as

\[ SW(N) = SW(N-1) + P(N) - ET(N) - SRO(N) \]  

where \( SW(N) \) and \( SW(N-1) \) represent the soil water contents at the end of day \( N \) and day \( (N-1) \), respectively. \( P(N) \) is the precipitation, \( ET(N) \) the actual evapotranspiration, and \( SRO(N) \) the surface runoff, all
for day \( N \).

When the soil water content was equal to 100 percent of the available water-holding capacity of the soil (field capacity, FC), additional water added by precipitation was declared excess water (Exc). This is water that occupies the drainable pore space (assumed constant) causes the formation of a water table. The surface drainage condition was also taken into account. Thus, if precipitation persisted after the drainable pore space \( f \) was filled and the surface-depression storage \( SD \) was satisfied, the precipitation was designated as surface runoff. In this case, the maximum excess of water is given by:

\[
\text{Exc}(N) = (\text{SAT} + \text{SD}) - \text{FC}
\]

where

\[
\text{SAT} = \text{FC} + (\text{PROF} \times f/100)
\]

in which PROF is the depth of the impervious layer and \( f \) is given in percent.

During the experiments conducted by Goulart \textit{et al.} (1976) and Lago \textit{et al.} (1978) to determine the effects of high water table level on soybean yield, supplemental irrigation water was applied when 1/3 of FC had been depleted. Since those data were used in the present study, the possibility of irrigation was also considered in the balance. Therefore, according to the findings reported by Grissom \textit{et al.} (Henderson, 1967), it was decided to irrigate when the available water holding capacity dropped below 2/3 of FC. The net amount of water to be added to the soil profile by irrigation was calculated as follows:

\[
\text{IRR}(N) = \text{FC} + \text{ET}(N) - \text{SW}(N-1)
\]

All symbols have been previously defined except \( \text{IRR}(N) \), the net amount
of irrigation water needed in day $N$. By using this equation, the soil profile will be at FC at the end of day $N$.

Daily actual evapotranspiration (ET) was obtained from daily potential evapotranspiration (PET) by correcting for soil moisture content, according to an approximation used by Thorntwaite and Mather (1955). This procedure assumes that the ratio ET/PET decreases linearly from FC to the wilting point (WP) percentage. The following relation was used:

$$ \text{ET}(N) = \left( \frac{\text{SW}(N-1)}{\text{FC}} \right) \text{PET}(N) $$  \hspace{1cm} (31)

Class A open-pan evaporation was the basic factor used for estimating daily potential evapotranspiration (PET) through the year. However, this factor was estimated from the relationship between the ratio class A open-pan evaporation to Piche evaporation (pan EV/Piche EV) and daily Piche EV. This procedure was used because recorded pan EV data were available only for the last 4 years from a total of 29 years of daily recorded climatological data from Pelotas, Rio Grande do Sul, South Brazil. The relationship was developed by using monthly average values of pan EV and Piche EV. A graphic representation is shown in Figure 18, which includes similar relationships developed for Israel and United Arab Republic as reported by Gangopadhyaya et al., (1966).

Two different methods were used to estimate PET throughout the year. For soybeans the relationship between PET and the pan EV (PET/pan EV ratio) throughout the entire plant growth cycle as reported by
Figure 18. Variations of the ratio class A open-pan evaporation to pan evaporation during the year.

- □ Pelotas, RS - Brazil (4-yr avg.)
- △ Israel (6-yr avg.)
- ○ United Arab Republic (5-yr avg.)
Berlato and Bergamaschi (1976) and reproduced in Figure 19 was used. Thus, the pan EV was adjusted by a factor which was dependent upon the stage of crop development. For natural pastures, however, PET was estimated by using the linear regression equation suggested by Pruitt (1966), which relates PET for grass or grass-clover mixture with pan EV as follows:

\[ \text{PET} = 0.8 \text{ pan EV} \quad (32) \]

Surface runoff (SRO) was estimated according to the procedure developed by Buss and Shaw (1960), which was based on the method of Kohler and Linsley (1951). The variables involved in the original method were: basin recharge, antecedent-precipitation index (API), season or weeks of the year, storm duration and storm rainfall (P). By using the late June period for the entire growing season and a duration of zero hours, Buss and Shaw (1960) reduced the original graphical method of determining runoff to one family of curves that give runoff as a function of daily total rainfall and the antecedent precipitation index. Detailed information about this procedure is given by Buss and Shaw (1960) and Shaw (1963). The procedure is applicable to several types of soil, including the Edina soil which is "somewhat poorly drained because of flat topography and tight B horizon" (Buss and Shaw, 1960). This study is addressed to soils with similar physic characteristics of the Edina Soil. Thus, the use of Buss and Shaw's procedure seems to be justified. Furthermore, Shaw (1963) used it for "sites with little or no slope".
Figure 19. Soybean potential evapotranspiration to pan evaporation ratio as a function of growing season.
**Determination of water table depths** Once determined, daily soil water excess (Exc) was used as input for calculating water table height (H) above the impervious layer at the midpoint between drains, according to the drainage geometry being considered. However, as surface depressional storage (SDS) conditions were taken into account in this analysis, the computation of H(N) was performed by Equation (27), or Equation (33), or Equation (34), depending on the value of H(N-1). The last two equations mentioned are a slight modification of Equation (27) to adjust the computation of H(N) when SDS is greater than zero. These equations are expressed as

\[
H(N) = H(N-1) + \frac{Exc}{f} - q 
\]  \hspace{1cm} (33)

and

\[
H(N) = H(N-1) + \frac{Exc}{f} - \frac{(q-SDS)}{f} 
\]  \hspace{1cm} (34)

All symbols have been previously defined, except q, the rate of drainage, which is given by

\[
q = 0.2093 \frac{K[H(N-1)]^{2.0}}{S^{1.641}} 
\]  \hspace{1cm} (35)

Equation (33) was used when q was equal to or less than SDS. Otherwise, Equation (34) was used. The values of SDS were determined according to the value of H(N-1). If H(N-1) were greater than or equal to DMAX, SDS was equalled to the maximum surface detention. DMAX is given by the depth of the impervious layer (PROF) plus the maximum surface detention. If H(N-1) were less than DMAX and greater than PROF, SDS was defined as
SDS = H(N-1) - PROF \quad (36)

The values of H(N) range from zero to DMAX. If H(N) were greater than zero and equal to or less than PROF, the depth of the water table (WT) was determined by

\[ WT = PROF - H(N) \quad (37) \]

If H(N) were greater than PROF, WT was set equal to zero. Before determining WT for the day being considered however, the value of H(N) must be reevaluated. The analysis and procedure to perform such re-evaluation of H(N) is now described.

As pointed out in the literature review, the water content of the unsaturated zone of a soil does not dry below its field capacity (FC) as long as the water table is above some limiting depth. In this case, the potential evapotranspiration rate is assured and the total water consumed in the process is supplied by the upward movement from the water table. This fact causes an additional drawdown of the water table in soils with subsurface drainage facilities.

If the water table is at a level below the limiting depth, water will still move upward from the water table, but at a rate less than the PET demand. When this occurs, the supplemental water to meet the total demand is removed from the unsaturated zone, starting the drying process. Under these conditions, water table drawdown is also influenced by its contribution to the evapotranspiration process. If no recharge to the water table occurs during this period, the water table
will reach a depth at which the root zone will no longer be supplied with the upward movement of water from it. A good example of this process is given by Skaggs (1978).

Limiting depths can be approximated using the numerical methods of Whisler et al. for the steady state case, and, for some hydraulic conductivity functions, by the methods given by Gardner (Skaggs, 1975a). Analytical determination of limiting depths was desired in this study; however, the available data from the soils being considered did not provide the required informations for that. Therefore, an empirical approach had to be developed.

From Goulart's (1975) experimental data (see Figures 3 through 5), an approximate method to reevaluate the predicted water table height was developed. It was assumed that the evaporation rate (ET) will be equal to the potential evapotranspiration rate (PET) so long as the water table is present above the impermeable layer on which the tiles are laid. Otherwise, ET will be calculated according to Equation (31).

Furthermore, it was assumed that the PET demand will be supplied from the water table until it reaches a depth of 45 cm. This depth represents a static limiting depth. The correction factor (CF) for re-evaluating H(N) is then given by

\[ CF = \frac{PET}{f} \]  

(38)

where CF and PET are expressed in cm and f (drainable porosity) is dimensionless.

Between the depths of 45 cm and 60 cm, it was assumed that the
water table contributes to the PET process according to the following function:

\[ CF = 0.04 \times H(N) \times \frac{PET}{f} \]  

(39)

in which \( H(N) \) is the water table height computed previously. At this point, the remaining difference to complete the PET demand is taken from the unsaturated zone which starts to dry. When the water table is between the depths of 60 cm and 70 cm (depth of the impermeable layer), the correction factor was assumed to be given as

\[ CF = 0.4 \left( \frac{PET}{f} \right) \]  

(40)

A general expression for reevaluating previously computed water table heights can be given as

\[ H(N)_c = H(N) - CF \]  

(41)

where \( c \) stands for corrected. This approximated method was used to predict those recorded water table heights taken from Goulart (1975) as shown in Figures 3 through 5. A comparison between predicted and recorded water table depths is shown in Figures 20 through 22. A fairly good agreement was achieved, mainly during the growing season of corn. In fact, this is the most important period. Therefore, it was concluded that Equation (27), adjusted by a correction factor, could be used to accurately simulate water table fluctuations.

The approximated method for reevaluating water table heights was developed considering an impermeable layer at 70 cm from surface. This was because the experimental data used from Goulart (1975) refer to a
Figure 20. Water table drawdown curves for 8 m spacing tile drained soil with tiles laid on the impervious layer.

- Recorded
- Predicted

- 30% corn growing season
- Corn harvesting

S = 8 m
K = 14.4 cm/day
f = 2.53%
Figure 21. Water table drawdown curves for 12 m spacing tile drained soil with tiles laid on the impervious layer.
Figure 22. Water table drawdown curves for 16 m spacing tile drained soil with tiles laid on the impervious layer.
soil with an impervious layer at 70 cm from its surface. However, in this study the impermeable layer is assumed to be at a depth of 60 cm. Thus, a slight modification of the correction factor for water table depths between 45 cm and 60 cm had to be made. The modified correction factor can be expressed as

\[ CF = [0.4 + 0.04 H(N)]_{PET/f} \] (42)

As previously mentioned, this method assumes that the evapotranspiration process will be equal to the PET rate as long as the water table is present above the impervious layer. Furthermore, it assumes that the unsaturated zone starts to dry only after the water table has receded to a depth below 45 cm. Because of these assumptions, checks of the previously calculated value of soil moisture content (Equation 28) and actual evapotranspiration rate (Equation 31) have to be performed, and reevaluation made when applicable.

Simulation of Soybean Yield Reduction Due to Fluctuation of High Water Tables

According to the literature review, soybeans have the capacity to perform well under conditions of temporarily high water tables; even though in general, the yield reduces as the duration of high water tables prolongs. Experimental data reported by Goulart et al. (1976), Lago et al. (1978), and Barni and Costa (1978) were grouped and are shown in Table 4. These data refer to soybean yield reductions for different durations of water table within the first 10 cm soil depth. However,
Table 4. Soybean yield losses due to high water conditions at 4 different periods of the growing season

<table>
<thead>
<tr>
<th>Duration of high water table, days</th>
<th>Emergence stage</th>
<th>20 days after emergence</th>
<th>Flowering stage</th>
<th>Grain formation stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>7</td>
<td>2</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>10</td>
<td>8</td>
<td>5</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>15</td>
<td>9</td>
<td>8</td>
<td>32</td>
<td>13</td>
</tr>
<tr>
<td>20</td>
<td>13</td>
<td>16</td>
<td>46</td>
<td>14</td>
</tr>
<tr>
<td>30</td>
<td>-</td>
<td>-</td>
<td>65</td>
<td>-</td>
</tr>
</tbody>
</table>

Water table was maintained within the first 10 cm soil depth.

Information on yield losses due temporary water tables at depths below 10 cm was needed. Based on the methods developed by Wiser et al. (1974) and Bhattacharya and Broughton (1979), this information was obtained. A detailed description of the methodology is given below.

Development of the model

The soybean yield data for unirrigated plots subjected to various static water table conditions, as reported by Williamson and Kriz (1970) and shown in Table 1, are plotted in Figure 23. In the absence of more definite data, it was decided to extend the visual best fit line for the data points between the coordinates (61, 100) and (30, 63) to a point representing 60 percent of the maximum yield and extend
Figure 23. Step curve relating depths of permanent water table with soybean yield losses

Data from Williamson and Kriz (1970)
it to (10, 0); therefore, assuming that there is no crop yield when the water table is maintained constant at a 10 cm depth of soil. Also, to simplify the computation, the losses for a 10 cm interval of water table depths have been assumed as is shown by the step curve in Figure 23. A similar procedure for alfalfa and for corn was used by Wiser et al. (1974) and Bhattacharya and Broughton (1979), respectively.

Based on the information contained in Figure 23, the first two columns of Tables 5 through 8 could then be developed. The figures in the first row of these tables (from columns 3 to 7 or 8) were taken from the corresponding column of Table 4. Assuming that there is a negative linear relationship between crop yield loss and water table depth, the remaining rows (from columns 3 to 7 or 8) were completed with the information then available in each table. Thus, for each duration of the water table, the remaining crop yield reduction values were computed proportionally to those in the second column of each table. For example, the crop yield loss for a water table remaining 20 day in the depth range of 10-20 cm from surface, as shown in Table 5, was calculated as follows:

\[(13 \times 85)/100 = 11.05\%\]

where the values 100 and 85 were taken from column 2 and the value 13 from the first row of the third column. A graphic representation of the data in Tables 5 through 8 is shown in Figures 24 to 27.
Table 5. Soybean yield reduction, in percent of the maximum yield, as a function of various water table depths and durations, during the crop emergence period

<table>
<thead>
<tr>
<th>Water table depth range (cm)</th>
<th>Consecutive Durations of Water Table (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Permanent 20 15 10 5 0</td>
</tr>
<tr>
<td>0-10</td>
<td>100 13.0 9.0 8.0 7.0 0</td>
</tr>
<tr>
<td>10-20</td>
<td>85 11.1 7.7 6.8 6.0 0</td>
</tr>
<tr>
<td>20-30</td>
<td>55 7.2 5.0 4.4 3.9 0</td>
</tr>
<tr>
<td>30-40</td>
<td>34 4.4 3.1 2.7 2.4 0</td>
</tr>
<tr>
<td>40-50</td>
<td>20 2.6 1.8 1.6 1.4 0</td>
</tr>
<tr>
<td>50-60</td>
<td>7 0.9 0.6 0.6 0.5 0</td>
</tr>
<tr>
<td>&gt;60</td>
<td>0 0.0 0.0 0.0 0.0 0</td>
</tr>
</tbody>
</table>

Table 6. Soybean yield reduction, in percent of the maximum yield, as a function of water table depths and durations, during the period starting 20 days after emergence

<table>
<thead>
<tr>
<th>Water table depth range (cm)</th>
<th>Consecutive Durations of Water Table (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Permanent 20 15 10 5 0</td>
</tr>
<tr>
<td>0-10</td>
<td>100 16.0 8.0 5.0 2.0 0</td>
</tr>
<tr>
<td>10-20</td>
<td>85 13.6 6.8 4.3 1.7 0</td>
</tr>
<tr>
<td>20-30</td>
<td>55 8.8 4.4 2.8 1.1 0</td>
</tr>
<tr>
<td>30-40</td>
<td>34 5.4 2.7 1.7 0.7 0</td>
</tr>
<tr>
<td>40-50</td>
<td>20 3.2 1.6 1.0 0.4 0</td>
</tr>
<tr>
<td>50-60</td>
<td>7 1.1 0.6 0.4 0.1 0</td>
</tr>
<tr>
<td>&gt;60</td>
<td>0 0.0 0.0 0.0 0.0 0</td>
</tr>
</tbody>
</table>
Figure 24. Soybean yield reduction due to depth and duration of the water table during the emergence period.
Figure 25. Soybean yield reduction due to depth and duration of water table during the period starting 20 days after emergence.
Table 7. Soybean yield reduction, in percent of the maximum yield, as a function of water table depths and durations, during the flowering period

<table>
<thead>
<tr>
<th>Water table depth range (cm)</th>
<th>Consecutive Durations of Water Table (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Permanent 30 20 15 10 5 0</td>
</tr>
<tr>
<td>0-10</td>
<td>100 65.0 46.0 32.0 11.0 5.0 0</td>
</tr>
<tr>
<td>10-20</td>
<td>85 55.3 39.1 27.2 9.4 4.3 0</td>
</tr>
<tr>
<td>20-30</td>
<td>55 35.8 25.3 17.6 6.1 2.8 0</td>
</tr>
<tr>
<td>30-40</td>
<td>34 22.1 15.6 10.9 3.7 1.7 0</td>
</tr>
<tr>
<td>40-50</td>
<td>20 13.0 9.2 6.4 2.2 1.0 0</td>
</tr>
<tr>
<td>50-60</td>
<td>7 4.6 3.2 2.2 0.8 0.4 0</td>
</tr>
<tr>
<td>&gt;60</td>
<td>0 0.0 0.0 0.0 0.0 0.0 0</td>
</tr>
</tbody>
</table>

Table 8. Soybean yield reduction, in percent of the maximum yield, as a function of water table depths and durations, during the grain formation stage

<table>
<thead>
<tr>
<th>Water table depth range (cm)</th>
<th>Consecutive Durations of Water Table (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Permanent 20 15 10 5 0</td>
</tr>
<tr>
<td>0-10</td>
<td>100 14.0 13.0 11.0 9.0 0</td>
</tr>
<tr>
<td>10-20</td>
<td>85 11.9 11.1 9.4 7.7 0</td>
</tr>
<tr>
<td>20-30</td>
<td>55 7.7 7.2 6.1 5.0 0</td>
</tr>
<tr>
<td>30-40</td>
<td>34 4.8 4.4 3.7 3.1 0</td>
</tr>
<tr>
<td>40-50</td>
<td>20 2.8 2.6 2.2 1.8 0</td>
</tr>
<tr>
<td>50-60</td>
<td>7 1.0 0.9 0.8 0.6 0</td>
</tr>
<tr>
<td>&gt;60</td>
<td>0 0.0 0.0 0.0 0.0 0</td>
</tr>
</tbody>
</table>
Figure 26. Soybean yield reduction due to depth and duration of water table during the flowering period.
Figure 27. Soybean yield reduction due to depth and duration of water table during the grain formation period.
The crop yield reduction values thus far available (Tables 5 through 8), are not presented in a workable form for computing the soybean yield losses under field conditions. To arrange such data in an easier form for computation, it was assumed that crop yield losses were additive and linearly distributed within each 5 days period of water table duration. Thus, the net crop yield reduction values, ascribed to each day of a continuous duration of the water table at each of the depth ranges, were determined and are shown in Tables 9 through 12. These modifications simplified the computation of soybean yield losses when water tables fluctuate randomly. The procedure developed for such computation is now described.

Operation of the model

To calculate the total crop yield reduction, the length of the entire soybean growing season as well as the length of each period studied had to be defined. Based on the studies reported by Goulart et al. (1976), Berlato and Bergamaschi (1976), Bergamaschi et al. (1976) and Lago et al. (1978), all developed in South Brazil, Table 13 could be prepared. Assuming November 15 as the planting date, and a growing season length of about 145 days, the four periods for crop yield reduction computation were defined as follows:

1. Emergence - November 21 to December 14
2. 20 days after emergence - December 15 to January 5
3. Flowering - January 6 to February 10
4. Grain formation - February 11 to March 28
Table 9. Net crop yield reduction ascribed to each depth range (in percent of maximum yield), as a function of a continuous water table stay in each depth range, for the period of November 21 to December 14.

<table>
<thead>
<tr>
<th>Duration of water table (days)</th>
<th>Water table depth range (cm)</th>
<th>0-10</th>
<th>11-20</th>
<th>21-30</th>
<th>31-40</th>
<th>41-50</th>
<th>51-60</th>
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<tbody>
<tr>
<td>1</td>
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<td>0.20</td>
<td>0.42</td>
<td>0.30</td>
<td>0.20</td>
<td>0.18</td>
<td>0.10</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>0.40</td>
<td>0.84</td>
<td>0.60</td>
<td>0.40</td>
<td>0.36</td>
<td>0.20</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>0.60</td>
<td>1.26</td>
<td>0.90</td>
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Table 10. Net crop yield reduction ascribed to each depth range (in percent of maximum yield), as a function of a continuous water table stay in each depth range, for the period of December 15 to January 5

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Table 11. Net crop yield reduction ascribed to each depth range (in percent of maximum yield), as a function of a continuous water table stay in each depth range, for the period of January 6 to February 10

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Table 12. Net crop yield reduction ascribed to each depth range (in percent of maximum yield), as a function of a continuous water table stay in each depth range, for the period of February 11 to March 28.

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<th>Water Table Depth Range (cm)</th>
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Table 13. Range of each specific soybean growing period

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<th>Growing period, days November-December 5(^a)</th>
<th>December 30(^a)</th>
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<td>29-51</td>
<td>24-43</td>
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<td>51-87</td>
<td>43-73</td>
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<td>Grain formation</td>
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<td>87-131</td>
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<td>131-145</td>
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</table>

\(^a\) Planting date.

Therefore, any high water table before November 21 and after March 28, is considered to have no influence on the yield of soybeans.

The methodology used to calculate crop yield losses can be better understood through an example. A hypothetical case will be given. Suppose the total crop yield reduction due to the water table height distribution during the growing season of soybeans, as shown in Figure 28, is to be determined. The first step is to draw in the figure five vertical lines to define exactly the range ascribed to each of the four periods previously mentioned. This is necessary because the counting process must be performed independently in each defined growing period. The second step then is to count the maximum number of continuous days that the water table remained in each depth range within each of the
Figure 28. Hypothetical water table fluctuation in the growing season of soybeans
four periods, as shown in Figure 28. With this information, crop yield losses are taken directly from Tables 9 through 12, depending on the period being considered. The expected soybean yield losses for the example water table fluctuation are summarized in Table 14. The total yield reduction would be 20.18 percent, which corresponds to the summation of the total losses in each period. The crop yield loss method reported by Bhattacharya and Broughton (1979) over-estimated the losses since they did not take into account the relative crop loss due to each water depth range.

Computer Program to Simulate Daily Water Table Fluctuation with Subsurface Drainage Facilities and Soybean Yield Response to Drainage

Structure and operation

A computer program was developed in Fortran IV G level language, which integrates the water balance approach for simulating water table depths under subsurface drainage facilities. The model also predicted the consequent soybean yield responses. The program performs a computation of the daily soil water balance for each year. This was necessary since there was no information about the soil water status at the beginning of the soybean growing season each year for each drainage alternative studied. To start the water balance computation the soil water was initialized to field capacity. However, the computation of crop yield reductions were executed only during the period of November 21 to March 28. A slight modification can make this program appropriate
Table 14. Soybean yield losses for the water table hydrograph shown in Figure 28

<table>
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<th>Water table depth range (cm)</th>
<th>Nov. 21-Dec. 14</th>
<th>Dec. 15-Jan. 5</th>
<th>Jan. 6-Feb. 10</th>
<th>Feb. 11-Mar. 28</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>W.T. duration</td>
<td>Crop loss (%)</td>
<td>W.T. duration</td>
<td>Crop loss (%)</td>
</tr>
<tr>
<td></td>
<td>(days)</td>
<td></td>
<td>(days)</td>
<td></td>
</tr>
<tr>
<td>0-10</td>
<td>3</td>
<td>0.60</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>11-20</td>
<td>5</td>
<td>2.10</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>21-30</td>
<td>8</td>
<td>1.62</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>31-40</td>
<td>13</td>
<td>1.22</td>
<td>7</td>
<td>0.46</td>
</tr>
<tr>
<td>41-50</td>
<td>15</td>
<td>1.20</td>
<td>21</td>
<td>2.10</td>
</tr>
<tr>
<td></td>
<td>18(^a)</td>
<td>3.68(^a)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>51-60</td>
<td>16</td>
<td>0.60</td>
<td>22</td>
<td>1.10</td>
</tr>
<tr>
<td></td>
<td>36</td>
<td>4.60</td>
<td>12</td>
<td>0.84</td>
</tr>
<tr>
<td>TOTAL</td>
<td>7.40</td>
<td>3.66</td>
<td>8.28</td>
<td>0.84</td>
</tr>
</tbody>
</table>

\(^a\)18 = 13+5 and 3.68 = 3.08+0.60.
to other growing season periods and different depths of the impervious layer.

A general flow chart of the main program is depicted in Figure 29. In the first part, 7 arrays are stored in the computer memory. The arrays are:

1. Runoff, which is given as a function of the actual precipitation (PRC) and the antecedent precipitation index (API).
2. Crop coefficient, obtained as a function of the ratio potential evapotranspiration to pan evaporation (PET/PAN EV), and day of the growing season.
3. Evaporation coefficient, given as a function of time and the ratio pan evaporation to piche evaporation (PAN EV/PICHE EV). It is needed to transform piche evaporation input data into pan evaporation.
4. Crop yield reduction (YRED), which is given as a function of the depth and duration of the water table. There are 4 arrays, one for each period considered in the computation of YRED.

Sequentially the program reads the year, the month, and the number of days (NDAY) in that month. Then, daily piche evaporation (EV) and precipitation (PRC) are read. The next step is to compute PET. At this point, the first subroutine (RUNOFF) is called to calculate the surface runoff in the day being considered. Then a certain tile spacing is specified and 3 subroutines are called. The first is the subroutine EXCESS which computes daily soil water excess. This excess is used as
Figure 29. Flow chart of the main program
input in the subroutine (WDEPTH) that gives the depth of the water table according to the tile spacing under consideration. This subroutine also reevaluates, when necessary, the value of the actual evapotranspiration and available soil water status previously calculated in subroutine EXCESS. The next subroutine called WTSTAY, which counts the number of days the water table remained continuously at a certain depth range. When the process is interrupted, a nested subroutine named DATE is then called. This subroutine is in charge of the computation of the crop yield reduction (YRED). The calculated total daily YRED is returned to the main program. The next program step is to print the daily output. The complete program listing is given in Appendix D.

Input and output

Climatological input data Precipitation and evaporation, on a daily basis, were the only required weather data to perform the water balance. Twenty-nine years (1951-1979) of records were used for this investigation. These data were recorded at Pelotas, Rio Grande do Sul, Brazil. According to Mota et al. (1971), weather data recorded at Pelotas can be extrapolated for other locations within what they call a homogeneous micro-region. This micro-region is formed by seven counties, corresponding to 5.6% of Rio Grande do Sul state's area.

Soil input data The purpose of this study was to select the optimum subsurface drainage system design to successfully grow soybeans in soils with an impervious layer near its surface. The range of the physical characteristics of the soils was obtained from Arruda and
Dias da Costa (1961), Sombroek (1969), Winkler and Goedert (1972), Goulart (1975) and Kämpf and Klamt (1977). The available physical characteristics which could be of interest in this study are given in Table 15.

Table 15. Some physical characteristics of shallow soils in Rio Grande do Sul, South Brazil

<table>
<thead>
<tr>
<th>Depth of impervious layer (cm)</th>
<th>Maximum water holding capacity (cm/cm)</th>
<th>Hydraulic conductivity (cm/day)</th>
<th>Drainable porosity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>0.10</td>
<td>30</td>
<td>6.8&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>0.15</td>
<td>20</td>
<td>5.0&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>0.29</td>
<td>10</td>
<td>2.5</td>
</tr>
<tr>
<td>60&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.10&lt;sup&gt;a&lt;/sup&gt;</td>
<td>30&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6.8&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>0.15&lt;sup&gt;a&lt;/sup&gt;</td>
<td>20&lt;sup&gt;a&lt;/sup&gt;</td>
<td>5.0&lt;sup&gt;a,b&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>0.20</td>
<td>10</td>
<td>2.5</td>
</tr>
<tr>
<td>80</td>
<td>0.10</td>
<td>30</td>
<td>6.8&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>0.15</td>
<td>20</td>
<td>5.0&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>0.20</td>
<td>10</td>
<td>2.5</td>
</tr>
</tbody>
</table>

<sup>a</sup>Inputs to the computer program used in this study.

<sup>b</sup>Determined according to Dylla (1966).

It would be ideal to work with all of the combinations shown in Table 15. However, due to computer time limitation, only one alternative was used. Thus, the combination representing the average soil physical characteristics was selected.
Crop input data. As indicated before, an annual crop rotation with soybeans and natural pastures (grass and grass-clover mixture) was assumed in this study. The entire soybean growing season was taken as beginning on November 15 and ending on about April 10, corresponding to a length of 145 days. Natural pastures were assumed to cover the soil surface during the remaining part of the year. This is a common agricultural practice in that region of South Brazil. The selection of the optimum subsurface drainage design was based exclusively on the economic importance of soybeans. Therefore, the soybean yield response to depth and duration of high water table was another crop input data. Finally, the crop coefficients used to compute the potential evapotranspiration for soybeans and natural pastures can be included in this category of input data.

Drainage system input data. The system input data used in this investigation were drain spacing, drain depth, and the depth of surface depressional storage. A parallel drain tube subsurface drainage system was considered. Nine different drain spacings were used (4, 8, 12, 16, 20, 30, 40, 50 and 200 m). The 200 m drain spacing was included to simulate an undrained field situation. Skaggs (1974) has quantified surface drainage by means of surface depressional storage measurements on several soils of North Carolina. He classified surface drainage conditions in good, medium, and poor, when surface detention was 0.25, 1.25, and 2.50 cm, respectively. Based on the surface drainage conditions of soils used in this study, it was assumed reasonable to use a surface detention of 1.25 cm.
Other input data   To run the computer program, initial values had to be assigned to the following variables: (1) available soil water (SW), (2) antecedent precipitation index (API), (3) number of days water table remained at each depth range until the previous day, and (4) the water table height above the impermeable layer halfway between drains (HW). Therefore, on January 1 of 1951 (when computation began) the SW was initialized to field capacity (FC). The last three variables were initialized to zero. These assumptions probably caused some error during the first months of that year. However, that error was very likely eliminated by the end of the winter (September), since rainfall in this season repeatedly brings the water table to the soil surface. Moreover, the first complete soybeans growing season begins on November 15 of the same year.

The output consists of the daily printouts, from November 1 to March 31, giving a summary of the computations performed. It lists the inputs used each day and all the variables computed. A sample of outputs is given in Appendix E.

Optimization of System Design

It was defined previously (Introduction chapter) that the best criterion for selecting optimum subsurface drainage systems is the one based on an economic analysis of the design alternatives. The discounting technique used to perform this analysis was the Annual-cost method (James and Lee, 1971), in which the best alternative is the one that maximizes the returns.
System benefits

The value of a crop reaches a maximum under optimum conditions. If damaging events occur, yield will be reduced from this maximum. By simply subtracting the reduction from the maximum yield, annual values of yield can be obtained. An average of all these values provides an estimate of the average annual value of the yield.

The annual benefit due to the system is not simply the average annual yield because without any system at all some yield would generally be obtained. Therefore, the average annual benefit due to drainage was obtained by subtracting the average annual no-system value from the average annual yield for the given system.

Obviously, other benefits in addition to the benefit of increased yield, result from subsurface drainage system (Schwab et al., 1966). The economic benefit of tile drainage from increased mobility of agricultural machinery was reported by Aldabagh and Beer (1975). Wendte et al. (1977) determined the average annual timeliness benefit of subsurface drainage for two Illinois soils. Although such benefits are often significant in determining whether or not to install a system, their quantification has not been attempted herein. Thus, they were not considered in this study.

System costs

System cost is generally a function of the tile diameter (if drain tubes are used) and system geometry. It consists of the fixed cost of the system itself together with annual costs such as maintenance costs
and crop production costs.

To determine the fixed costs for a tile drainage system, three principal items were considered: material, installation, and engineering costs (Schwab et al., 1966).

**Material costs**  As previously mentioned, (Introduction chapter), the purpose of this study was to determine the optimal subsurface drainage system (if any) to grow soybeans in fields before used to grow rice under submerged irrigation conditions. Therefore, those fields have some drainage facilities. In general, they are provided with open ditches about 500 m apart. Considering that such existing drainage facilities could work as the main system (collectors), only the costs related with the relief drains were taken into consideration in this analysis.

Since the cost of tile increases as its diameter increases, it was desirable to know the minimum clay tile diameter to carry out the design flow without back pressure in a distance of 500 m. The design flow was determined based on the maximum drainage rate for a tile spacing of 4 m, and the drain discharge capacity according to the Manning's equation. Detailed computation is presented in Appendix F. It was concluded that inside tile diameter as small as 2 inches could be used. These tiles, generally 60 cm length, costs about $0.42 per meter, while one with 3 inches in diameter costs $0.72 per meter.

**Installation costs** The installation cost which includes ditching, laying the tile, blinding and backfilling, was determined based on work done by hand. Thus, the installation cost in South Brazil is about $0.50
engineering costs  These costs normally vary from 5 to 10 percent of the total cost. Engineering services include the preliminary survey, designing the system, staking the line, and controlling the grade during the installation.
RESULTS AND DISCUSSION

The purposes of this chapter are: (1) to present the results obtained from computer simulations of soybean yield reductions versus drain tile spacings, (2) to perform an economic analysis of the drainage design alternatives, and (3) to discuss the simulation procedures used in this study and the results obtained from the economic analysis.

Results from Computer Simulations

Soybean yield reductions associated with nine different drain spacings were continuously simulated for 28 years (1952 to 1979). Tile drains were assumed to be laid on an impermeable layer located at 60 cm from the soil surface. The hydraulic conductivity and the drainable porosity were 20 cm/day and 5%, respectively. A level of surface drainage corresponding to a surface detention of 1.25 cm was used. The results obtained from computer simulations are shown in Table G1 in Appendix G. The annual average crop yield reduction associated with each drain spacing is also included in Table G1. A drain spacing of 200 m was used to simulate a field condition with no subsurface drainage. Figure 30 shows the relationship between average annual crop yield reduction and drain spacing. Yield reductions for both the driest and the wettest crop growing seasons are also shown. The average annual crop yield reduction is given as a function of the maximum expected yield
Figure 30. Soybean yield reduction as a function of tile spacing
of soybeans as reported by Lago et al. (1978). This yield corresponds to a 3-year average of two soybean varieties obtained from the experimental check plots. All of the plots used in the experiment were separated by open ditch drains which were constructed 2 m apart.

Economic Analysis

No attempt has been made to include the effect of inflation on various cost items. It is assumed that inflation equally influences the cost of the system and the selling price of the crop. Therefore, it has no overall significant effect.

System benefits

The production cost of soybeans in South Brazil for the growing period 1979/1980 was calculated as $216.44 per hectare. Under optimum conditions, the maximum expected yield of soybeans is 2,935 kg/ha. This was the maximum 3-year average yield reported by Lago et al. (1978) obtained from the check plots. As shown in Table 16, the average annual crop yield reduction for 200-m drain spacing (or no-drainage system) is 25.09 percent. Therefore, an average yield of 2,198.61 kg/ha is assured without subsurface drainage. The average selling price of soybeans in South Brazil is about $12.50 per sac of 60 kg (or 20.83 cents per kg). Thus, the average annual no-system value corresponds to $458.04 per hectare. The average annual net return from the no-drainage system is $241.60 per hectare.

1 According to the Federação das Cooperativas Brasileiras de Trigo e Soja Ltda.
As shown above, an average annual benefit of $241.60 per hectare is obtained if soybeans are grown in a field without any subsurface drainage. Hence, the average annual benefit due to drainage must be obtained by subtracting the average annual no-system value from the average annual yield value for the given system. The results of the computations are presented in Table 16.

**Table 16. Average annual crop yield reduction and benefit as a function of drain spacings**

<table>
<thead>
<tr>
<th>Drain spacing (m)</th>
<th>Average annual yield reduction (kg/ha)</th>
<th>Average annual benefita ($/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>294.09</td>
<td>91.65</td>
</tr>
<tr>
<td>8</td>
<td>483.39</td>
<td>51.90</td>
</tr>
<tr>
<td>12</td>
<td>571.15</td>
<td>33.47</td>
</tr>
<tr>
<td>16</td>
<td>613.12</td>
<td>24.65</td>
</tr>
<tr>
<td>20</td>
<td>647.46</td>
<td>17.44</td>
</tr>
<tr>
<td>30</td>
<td>678.87</td>
<td>10.85</td>
</tr>
<tr>
<td>40</td>
<td>692.07</td>
<td>8.07</td>
</tr>
<tr>
<td>50</td>
<td>713.50</td>
<td>3.58</td>
</tr>
<tr>
<td>200b</td>
<td>736.39</td>
<td>0.00</td>
</tr>
</tbody>
</table>

*a Obtained by subtracting each average annual yield reduction (column 3) from 153.41 dollars per hectare.

b Assumed to be the no-drainage system.
System costs

A clay tile with 2 inches inside diameter was found to be adequate to carry the design flow (see Appendix F). The cost per meter of this tile and the system installation cost per meter are $0.42 and $0.50, respectively (see the last section in the Procedures chapter). Considering an engineering cost of 5 percent of the previous costs ($0.42 + $0.50), the total initial cost of drainage per meter is $0.966.

A length of one meter of lateral drains corresponds to an area of 1xS square meters, where $S$ is the drain spacing in meters. Hence, the total length of laterals required per hectare is given by 10,000/S, in which 10,000 is the amount of square meters per hectare. The total initial cost per hectare for each drain spacing is (10,000/S)0.966.

For comparison with annual yields, the fixed system cost must be converted to an annual basis. This requires computation of the capital recovery factor (an uniform annual series factor) which is based on the estimated life of the system and the interest rate. System life and interest rate are difficult to establish and are generally defined arbitrarily (Wiser et al., 1974). An effective life of the tile drains equal to 20 years and an interest rate of 12 percent was assumed in performing this analysis. For an economic life of 20 years and an interest rate of 12 percent, the capital recovery factor is 0.133879. Multiplying this factor by (10,000/S)0.966 gives the total annual initial cost of the system. When added to the assumed annual cost of $2.47 per hectare for maintenance, the total annual cost is
obtained (Table 17).

Table 17. Total initial and annual cost of drainage systems

<table>
<thead>
<tr>
<th>Drain spacing, S (m)</th>
<th>Total initial cost ($/ha)</th>
<th>Total annual cost ($/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>2,415.00</td>
<td>325.79</td>
</tr>
<tr>
<td>8</td>
<td>1,207.50</td>
<td>164.13</td>
</tr>
<tr>
<td>12</td>
<td>805.00</td>
<td>110.24</td>
</tr>
<tr>
<td>16</td>
<td>603.80</td>
<td>83.31</td>
</tr>
<tr>
<td>20</td>
<td>483.00</td>
<td>67.13</td>
</tr>
<tr>
<td>30</td>
<td>333.00</td>
<td>47.05</td>
</tr>
<tr>
<td>40</td>
<td>241.50</td>
<td>34.80</td>
</tr>
<tr>
<td>50</td>
<td>193.20</td>
<td>28.34</td>
</tr>
</tbody>
</table>

\( ^a \)Total initial cost (column 3) plus the maintenance cost ($2.47/ha).

\( ^b \)\((10,000/S)0.966.\)

\( ^c \)(10,000/S)0.966 x 0.133879.

Annual net return

The annual net return is obtained by subtracting the annual cost from the annual benefit. However, in this analysis the annual net returns are negative for all drain spacing studied using 12 percent interest rate and 20 years of system life. A graphic representation of these two functions is shown in Figure 31.
Figure 31. Average annual drainage and benefit costs as a function of tile spacing.
Under the assumptions made in this analysis, the installation of tile drainage systems proved to be infeasible. Thus, drainage systems entirely formed by open ditches were considered. This requires the assumption that the same crop yield reductions would result if open ditches were used. The total annual cost of drainage systems by open ditches is given in Appendix H. The following were not taken into account in this analysis: (1) the decrease in crop production due to the reduction of the net farmed area, and (2) the probable increase in the cost of machinery operation. In spite of these omitted costs, the same results were reached. That is, the installation of subsurface drainage systems was infeasible.

Discussion

The drainage system design technique requires a large number of assumptions. Some of these assumptions were introduced for simplicity, and can be replaced by models that most closely reflect a well-understood physical behavior. Other assumptions, however, are required because the information which they replace is not now available.

Simulation of water table fluctuation

The water balance was restricted to the soil profile above the impermeable layer. This limitation was made because no information referring to the upward movement of moisture (unsaturated conditions) from the impervious layer or below it was available. If this movement does exist, it probably lengthens the drying process of the soil
profile above the impermeable layer. Consequently, the need for irrigation will be reduced, thereby reducing the total amount of crop yield losses. Additional crop yield reduction is likely to occur when rainfall takes place after an irrigation (say in the next day). Thus, because the irrigation raised the soil water status to its field capacity, a small amount of rainfall entering the soil profile will build up the water table to some depth. This water table would affect to some extent the crop yield.

The relationship used to transform Piche evaporation data to pan evaporation was determined by using data from the same location for which this study was made. However, the results would be more realistic if sufficient pan evaporation data were available.

Simulation of plant response

The water balance model computes the height of the water table at the midpoint between drains. For simplicity this height has been assumed to control the crop yield over the entire drain spacing. Because this will not be true unless the field is completely flooded, the result is to overestimate the crop damage.

During the beginning of the soybean growing season, the root system has not extended to the entire depth of the soil profile. Thus, no yield reduction is expected to occur for water table heights below the depth of the soybean root system. However, no attempt was made in the crop yield response model to take this fact into account. It was assumed that the plant root system was completely developed at the
beginning of the growing season. Although this fact causes an overestimation of the crop damage, this overestimation, had it occurred, would probably have been very small. This affirmation is based on the soybean yield reduction pattern during the period (see Figure 25).

Experimental data relating soybean yield responses to duration of water tables at depths greater than 10 cm from soil surface were not available. This information was obtained from experimental data reported in the literature. Therefore, the true crop yield responses when the water table depths are greater than 10 cm were unknown. They could be either greater or smaller than those given by the approach used.

Surface-depression storage was assumed to exist in this investigation. However, the effects of the duration of some surface detention of water upon the crop yield were not available. To compute the yield reduction when surface detention was greater than zero, the depth of the water table was assumed to be zero.

Economic factors

The development of the optimum design technique is relatively simple and straightforward. Assumptions required for this part of the solution are more realistic than those required to obtain the soybean damage distribution. Even expecting, on the average, an annual crop yield reduction of 25%, the best alternative is to grow soybeans without a subsurface drainage system. It should be observed that a low engineering cost was assumed in performing the economic analysis. If an effective life of the tile drains equal to 50 years and an interest rate
of 5-1/2 percent had been assumed in this analysis, the results would also do not have favored the installation of subsurface drainage.

As shown in Figure 30, the differences between the average annual crop yield reductions associated with the tile spacings used and the no-drainage system are small. This is likely one of the factors responsible for the results achieved in this analysis. Such differences would be expected to increase when soils with higher hydraulic conductivity values (greater than 20 cm/day) are considered. As the hydraulic conductivity increases, the drainage system will be more efficient in eliminating the excess soil water. Therefore, there is a hydraulic conductivity value from which an economic net return will be obtained.

This study would be more complete if the economic benefits from increased mobility of agricultural machinery were taken into account. These additional benefits would possibly change the results of the economic analysis. In addition, a winter crop with economic importance as wheat could replace the natural pastures considered in this study. However, the effects of durations and depths of water tables upon the wheat yield were not available.

Carter and Camp (1978) conducted a field experiment to determine soybean yield responses to subsurface drainage in the alluvial clay soils of the lower Mississippi. An economic analysis of the feasibility of subsurface drainage was performed. They concluded that the relatively small yield increase due to drainage and the current market price for soybeans did not favor the installation of subsurface drainage
at that time. If machine trafficability were considered along with the other benefits, however, the economics of subsurface drainage could be more favorable. On the other hand, Colwell and Bolton (1979) found it to be economically feasible to reduce existing drain spacings on the Brookston clay soils of Southern Ontario, Canada to grow soybeans and corn. When tile spacings were reduced from 24- to 6 m, the yields were increased 20- and 40 percent for soybeans and corn, respectively. These findings correspond to two year average soybean yield and four year average corn yield. In spite of these results, the greatest internal rates of return were obtained when tile spacing were reduced from 24- to 12 m and from 18- to 9 m.

The above works reported by Carter and Camp (1978) and Colwell and Bolton (1979) deal with the economic feasibility of installing subsurface drainage to soybeans grown in some clay soils. Although this study deals with the same purpose, a meaningful comparison of the findings reached in this investigation with those described above was not possible. This was because those investigators did not describe at least two important factors: (1) the saturated hydraulic conductivity of the soils they worked on, and (2) the depth of the impermeable layer of those soils.
SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

A study has been made to determine the degree of drainage which maximizes the net return from growing soybeans in soils with an impervious layer close to the surface. To achieve this purpose, the drainage system performance and the crop yield response to each system alternative had to be determined.

To simulate the performance of each drainage geometry, two main steps were followed. First, a laboratory investigation using a glass-beads-glycerol drainage model was carried out. The objective was to find and test an equation for predicting water table heights when drains are laid on an impervious layer. Second, a water balance approach to simulate daily water table depths under subsurface drainage facilities was developed. This water balance integrates the determinations of daily excess of soil water and water table depth associated with the drainage geometry being considered.

From available experimental data reported in the literature, a soybean yield reduction pattern as a function of various depths and durations of the water table was established. A methodology for simulating crop yield reduction due to water table fluctuation associated with subsurface drainage facilities was also developed.

A computer program was developed in Fortran IV G level language. This program integrates the water balance approach for simulating water table depths under subsurface drainage facilities with the model to predict soybean yield responses. Climatological records for a 28-year
period for Pelotas, Rio Grande do Sul, South Brazil were used to simulate soybean yield responses for different degrees of drainage.

An economic analysis was performed to establish the relationship between levels of drainage investments versus benefits from different degrees of drainage. The results obtained in this study are for the region of Pelotas, Rio Grande do Sul, South Brazil. The methodology herein developed, however, can be applied to other humid regions provided that: (1) the drains are assumed laid on the impermeable layer, (2) local soil, crop and climatological data are used, and (3) the basic informations to perform the economic analysis are also from the region being considered.

On the basis of this study, the following conclusions were drawn:

1. When the drainage system is the only element responsible for the water table drawdown, Equation (27) can be used to accurately predict water table fluctuations. This equation applies when the tile drains are laid on an impermeable layer.

2. To predict water table fluctuations under field conditions, Equation (27) must be adjusted by a correction factor to account for other factors affecting the water table drawdown. This correction factor must be determined for each different type of soil.

3. The proposed drainage crop response model, as defined in this study, is meant to be used only in humid areas where the groundwater is low in salts.
4. The results of the economic analysis do not favor the installation of subsurface drainage. The low hydraulic conductivity (20 cm/day) used in this study was probably the most important factor leading to this conclusion.

Based on the experience of this study, the following suggestions are offered:

1. This methodology should be applied using values of hydraulic conductivity greater than 20 cm/day and different depths of the impervious layer.

2. A check of the water balance methodology developed in this study with field data is recommended.

3. The crop yield response model should be improved. To accomplish this, crop yield responses for different depths and durations of the water table must be investigated. Also, the effect of some surface detention on crop yield should be determined.

4. This methodology would be improved if the economic benefits from increased mobility of agricultural machinery could be included in the analysis.

5. Other crop rotation patterns should be investigated. A crop with high economic value as wheat could be used during the winter. However, a wheat yield response model must be developed.
REFERENCES


Murphy, Glen. 1950. Similitude in engineering. The Ronald Press, New York, N.Y.


Tovey, Rhys. 1964. Alfalfa growth as influenced by static and fluctuating water tables. Am. Soc. Agr. Engr., Trans. 7:310-312.


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Finally, deep appreciation is expressed to my wife Ligia and my children Alessandra and Rodrigo, who provided immeasurable understanding, moral support and encouragement up until the completion of this work. To them this dissertation is dedicated.
APPENDIX A: CALIBRATION DATA FROM FLUID APPLICATOR AND DISTRIBUTOR
Table A1. Discharge (ml/min) measured from each tube of the fluid applicator

<table>
<thead>
<tr>
<th>Run no.</th>
<th>Tube number</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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<th></th>
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<tbody>
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<td>1.95</td>
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<td>1.72</td>
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<td>1.80</td>
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<td>1.75</td>
<td>1.90</td>
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<tr>
<td>Average</td>
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<td>1.76</td>
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<td>1.72</td>
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<td>1.79</td>
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<td>1.78</td>
<td>1.92</td>
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<td>1.71</td>
<td>1.78</td>
<td>1.72</td>
<td>1.80</td>
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</table>
Table A2. Average volume (ml) collected from each of the fluid distributor

<table>
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<th>Compartment</th>
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<td>10.25</td>
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<td>9.78</td>
<td>9.45</td>
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<td>9.70</td>
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APPENDIX B: DRAINAGE MODEL DATA
Table B1. Experimental data gathered when the glassbeads-glycerol drainage model was being operated under steady-state conditions

<table>
<thead>
<tr>
<th>S^a (cm)</th>
<th>H^b (cm)</th>
<th>R^c (cm/day)</th>
<th>K^d (cm/day)</th>
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</thead>
<tbody>
<tr>
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<td>3.3</td>
<td>4215.0</td>
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<tr>
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<td>5979.0</td>
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<td>24.4</td>
<td>71.1</td>
<td>5287.0</td>
</tr>
</tbody>
</table>

^aTile spacing.

^bWater table height above the impervious layer.

^cUniform rainfall entering the porous medium.

^dHydraulic conductivity.
APPENDIX C: GLOSSARY OF VARIABLES FOR WATER BALANCE AND CROP YIELD RESPONSE MODEL USED IN THE COMPUTER PROGRAM
<table>
<thead>
<tr>
<th>SYMBOL</th>
<th>DEFINITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>APA(A,B)</td>
<td>Crop yield reduction array during period A (November 21 to December 14) as a function of the depth and duration of the water table</td>
</tr>
<tr>
<td>APB(C,D)</td>
<td>Crop yield reduction array during period B (December 15 to January 5) as a function of the depth and duration of the water table</td>
</tr>
<tr>
<td>APC(E,F)</td>
<td>Crop yield reduction array during period C (January 6 to February 10) as a function of the depth and duration of the water table</td>
</tr>
<tr>
<td>APD(G,H)</td>
<td>Crop yield reduction array during period D (February 11 to March 28) as a function of the depth and duration of the water table</td>
</tr>
<tr>
<td>API(6)</td>
<td>Row vector antecedent precipitation index</td>
</tr>
<tr>
<td>ARR(PP,API)</td>
<td>Surface runoff array as a function of rainfall and API</td>
</tr>
<tr>
<td>CLA</td>
<td>Crop yield reduction ascribed to the water table depth A (0-10 cm)</td>
</tr>
<tr>
<td>CLB</td>
<td>Crop yield reduction ascribed to the water table depth B (10-20 cm)</td>
</tr>
<tr>
<td>CLC</td>
<td>Crop yield reduction ascribed to the water table depth C (20-30 cm)</td>
</tr>
<tr>
<td>CLD</td>
<td>Crop yield reduction ascribed to the water table depth D (30-40 cm)</td>
</tr>
<tr>
<td>CLE</td>
<td>Crop yield reduction ascribed to the water table depth E (40-50 cm)</td>
</tr>
<tr>
<td>CLF</td>
<td>Crop yield reduction ascribed to the water table depth F (50-60 cm)</td>
</tr>
<tr>
<td>DDPA(B)</td>
<td>Depth of the water table during period A (November 21 to December 14)</td>
</tr>
<tr>
<td>DDPB(D)</td>
<td>Depth of the water table during period B (December 15 to January 5)</td>
</tr>
<tr>
<td>DDPC(F)</td>
<td>Depth of the water table during period C (January 6 to February 10)</td>
</tr>
<tr>
<td>SYMBOL</td>
<td>DEFINITION</td>
</tr>
<tr>
<td>------------</td>
<td>---------------------------------------------------------------------------</td>
</tr>
<tr>
<td>DDPD(H)</td>
<td>Depth of the water table during period D (February 11 to March 28)</td>
</tr>
<tr>
<td>DEPTH</td>
<td>Depth of the water table</td>
</tr>
<tr>
<td>DMX</td>
<td>Maximum water table height</td>
</tr>
<tr>
<td>DSO</td>
<td>Depth of the impermeable layer</td>
</tr>
<tr>
<td>ET1 to ET9</td>
<td>Actual evapotranspirations. Each symbol refers to the water balance computed for a specific drain spacing</td>
</tr>
<tr>
<td>EV</td>
<td>Daily evaporation</td>
</tr>
<tr>
<td>EXCl to EXC9</td>
<td>Excess soil water. Each symbol refers to the water balance computed for a specific drain spacing</td>
</tr>
<tr>
<td>FC</td>
<td>Field capacity</td>
</tr>
<tr>
<td>HUMID</td>
<td>Soil water plus rainfall minus surface runoff</td>
</tr>
<tr>
<td>HW1 to HW9</td>
<td>Height of the water table. Each symbol refers to the water balance computed for a specific drain spacing</td>
</tr>
<tr>
<td>INDEX</td>
<td>Antecedent precipitation index</td>
</tr>
<tr>
<td>IRR1 to IRR9</td>
<td>Amount of irrigation water. Each symbol refers to the water balance computed for a specific drain spacing</td>
</tr>
<tr>
<td>K</td>
<td>Saturated hydraulic conductivity</td>
</tr>
<tr>
<td>KCROP</td>
<td>Crop coefficient to adjust pan evaporation to crop potential evapotranspiration</td>
</tr>
<tr>
<td>KEV</td>
<td>Evaporation coefficient to adjust Piche evaporation to pan evaporation</td>
</tr>
<tr>
<td>KEVAP(NO,NBM)</td>
<td>Evaporation coefficient array</td>
</tr>
<tr>
<td>MXSAT</td>
<td>Maximum amount of water in the soil (SAT+SD)</td>
</tr>
<tr>
<td>NBA1 to NBA9</td>
<td>Duration (days) of water table in level A (0-10 cm). Each symbol refers to the water balance computed for a specific drain spacing</td>
</tr>
</tbody>
</table>
NBB1 to NBB9  Duration (days) of water level B (10-20 cm). Each symbol refers to the water balance computed for a specific drain spacing

NBC1 to NBC9  Duration (days) of the water level C (20-30 cm). Each symbol refers to the water balance computed for a specific drain spacing

NBD1 to NBD9  Duration (days) of the water level D (30-40 cm). Each symbol refers to the water balance computed for a specific drain spacing

NBE1 to NBE9  Duration (days) of the water level E (40-50 cm). Each symbol refers to the water balance computed for a specific drain spacing

NBF1 to NBF9  Duration (days) of the water level F (50-60 cm). Each symbol refers to the water balance computed for a specific drain spacing

NBMES(NBM) Month of the year

NDAY Total number of days of the month being considered

NUMERO(NO) Day of the month

PET Potential evapotranspiration

PLANT(NO,NBM) Crop coefficient array

P, PRC Daily precipitation

PP(52) Column vector precipitation

Q Rate of drainage

SAT Soil saturation

SD, SDS Surface detention

SM1 to SM9 Soil moisture. Each symbol refers to the water balance computed for a specific drain spacing

SRO Surface runoff

STPA Stay of water table during period A (November 21 to December 14)

STPB Stay of water table during period B (December 15 to January 5)
<table>
<thead>
<tr>
<th>SYMBOL</th>
<th>DEFINITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>STPC</td>
<td>Stay of water table during period C (January 6 to February 10)</td>
</tr>
<tr>
<td>STPD</td>
<td>Stay of water table during period D (February 11 to March 28)</td>
</tr>
<tr>
<td>SUM1 to SUM9</td>
<td>Summation of crop yield reduction. Each symbol refers to the water balance computed for a specific drain spacing</td>
</tr>
<tr>
<td>TFC</td>
<td>One-third of FC</td>
</tr>
<tr>
<td>THETA</td>
<td>Drainable porosity</td>
</tr>
<tr>
<td>TS</td>
<td>Tile spacing</td>
</tr>
<tr>
<td>WTABLE</td>
<td>Water table depth</td>
</tr>
<tr>
<td>WTB1 to WTB9</td>
<td>Water table depth. Each symbol refers to the water balance computed for a specific drain spacing</td>
</tr>
<tr>
<td>YRED</td>
<td>Crop yield reduction</td>
</tr>
</tbody>
</table>
APPENDIX D: LISTING OF WATER BALANCE AND CROP YIELD REDUCTION COMPUTER MODEL
INTEGER A,B,C,D,E,F,G,H,I,J,M,N,T,X,Y,NDAY,NO,NBMES(12),NBMT,MONTH,
  YEAR,DIST,NEA1(2),NEB1(2),NEC1(2),NBD1(2),NEF1(2),NBA2(2),
  INB2(2),NBE2(2),NBD2(2),NBE2(2),NBF2(2),NBA3(2),NBA4(2),NBS
  IA6(2),NBA17(2),NBA6(2),NBA9(2),NBB3(2),NBB4(2),NBS5(2),NBB6(2),NBB7
  I(2),NBB8(2),NBB9(2),NBC3(2),NBC4(2),NBS5(2),NBC6(2),NBC7(2),NBC8(2
  1),NBC9(2),NBD3(2),NBD4(2),NBD5(2),NBD6(2),NBD7(2),NBD8(2),NBD9(2),
  NBE3(2),NBE4(2),NBE5(2),NBE6(2),NBE7(2),NBE8(2),NBE9(2),NBF3(2),NB
  F4(2),NBF5(2),NBF6(2),NBF7(2),NBF8(2),NBF9(2),NUMERO(31),STPA(20),
  STPB(20),STPC(30),STPD(20),DDPA(6),DDPB(6),DDPC(6),DDPD(6)
REAL P(6),PRC(6),PP(52),API(7),ARR(52,7),PLANT(31,12),KEVAPC(31,12)
1,SAT,MXSAT,KCRP,SD,DSO,FC,SD0,KEV,K,APA(20,6),APB(20,6),APC(30,6)
1,APD(20,6),PET,EV,DMX,TS,WTABLE,WTB1,WTB2,WTB3,WTB4,WTB5,WTB6,WTB7
  ,WTB8,WTB9,HTM(2),HWM(2),HWM(2),HD(2),HD(2),HD(2),HD(2),HD(2)
1,HW9(2),THETA,SM1(6),SM2(6),SM3(6),SM4(6),SM5(6),SM6(6),SM7(6),SM8
  (6),SM9(6),IMR1,IMR2,IMR3,IMR4,IMR5,IMR6,IMR7,IMR8,IMR9,ET1,ET2,ET
  3,ET4,ET5,ET6,ET7,ET8,ET9,EXC1,EXC2,EXC3,EXC4,EXC5,EXC6,EXC7,EXC8,
  EXC9,SUM1,SUM2,SUM3,SUM4,SUM5,SUM6,SUM7,SUM8,SUM9
K=20
THETA=0.05
DSO=60.0
SD=12.5
FC=90.
SAT=120.
MXSAT=SAT+SD
DMX=DSO+0.1*SD
T=6
X=2
SM1(T-1)=FC
SM2(T-1)=FC
SM3(T-1)=FC
SM4(T-1)=FC
SM5(T-1)=FC
SM6(T-1)=FC
SM7(T-1)=FC
SM8(T-1)=FC
READ AND PRINT SURFACE RUNOFF AS A FUNCTION OF THE ANTECEDENT PRECIPITATION INDEX AND THE ACTUAL RAINFALL

WRITE(6,8)
8 FORMAT('1', 29X, 'SURFACE RUNOFF (INCHES)')
WRITE(6,18)
18 FORMAT('0', 7X, 'PCP', 10X, 'ANTECEDENT PRECIPITATION INDEX (INCHES 1)')

READ(5,2) (PP(I), I=1,52)
2 FORMAT(18(F3.1,1X)/18(F3.1,1X)/16(F3.1,1X))
READ(5,4) (API(J), J=1,7)
4 FORMAT(7(F3.1,1X))
WRITE(6,38) (API(J), J=1,7)
38 FORMAT('0', 5X, '(INCHES)', 3X, 7(F3.1,5X))
WRITE(6,39)
39 FORMAT('0', ')
DO 32 I=1,52
READ(5,6) (ARR(I,J), J=1,7)
6 FORMAT(7(F4.2,1X))
32 CONTINUE
DO 23 I=1,52
WRITE(6,28) PP(I), (ARR(I,J), J=1,7)
READ AND PRINT CROP COEFFICIENT

WRITE(6,121)
121 FORMAT('1',7X,'CROP COEFF.= POT. EVAPOTRANSPIRATION/PAN EVAPORATION')
READ(5,123) (NUMERO(NO),NO=1,31)
123 FORMAT(24(I2,1X)/7(I2,1X))
READ(5,127) (NBMES(NBM),NBM=1,12)
127 FORMAT(12(I2,1X))
WRITE(6,128)
128 FORMAT('0',8X,'MONTH')
WRITE(6,129) (NBMES(NBM),NBM=1,12)
129 FORMAT('0',2X,'DAY',2X,12(I2,3X))
WRITE(6,131)
131 FORMAT('0',9X)
DO 133 NO=1,31
    READ(5,137) (PLANT(NO,NBM),NBM=1,12)
137 FORMAT(12(F4.2))
133 CONTINUE
DO 139 NO=1,31
    WRITE(6,141) NUMERO(NO),(PLANT(NO,NBM),NBM=1,12)
141 FORMAT('3X,I2',12(1X,F4.2))
139 CONTINUE

READ AND PRINT PAN EVAPORATION/PICHE EVAPORATION COEFFICIENT

WRITE(6,143)
143 FORMAT('1',7X,'EVAPORATION COEFF.= PAN EVAPORATION/PICHE EVAPORATION')
READ(5,123) (NUMERO(NO),NO=1,31)
READ(5,127) (NBMES(NBM),NBM=1,12)
WRITE(6,128)
WRITE(6,129) (NBMES(NBM),NBM=1,12)
WRITE(6,131)
DO 147 NO=1,31
READ(5,137) (KEVAP(NO,NBM),NBM=1,12)
147 CONTINUE
DO 149 NO=1,31
WRITE(6,141) NUMERO(NO),(KEVAP(NO,NBM),NBM=1,12)
149 CONTINUE

READ AND PRINT CROP YIELD REDUCTION AS A FUNCTION OF THE WATER
TABLE STAY IN EACH DEPTH RANGE

WRITE(6,3)
3 FORMAT('1',7X,'NET CROP YIELD REDUCTION, AS PERCENT OF MAXIMUM YIELD'
1,'/','7X,'FOR A CONTINUOUS WATER TABLE STAY IN EACH DEPTH RANGE'
1,'/','7X,'FOR THE PERIOD NOVEMBER 21 TO DECEMBER 14'
WRITE(6,5)
5 FORMAT('0',7X,'CONTINUOUS WT',2X,'WATER TABLE DEPTH RANG'
1,'/','7X,'IE'
READ(5,7) (STPA(A),A=1,20)
7 FORMAT(20(I2,1X))
READ(5,9) (DDPA(B),B=1,6)
9 FORMAT(6(I1,1X))
WRITE(6,11) (DDPA(B),B=1,6)
11 FORMAT('0',7X,'STAY (DAYS)',4X,I1,5(5X,I1))
WRITE(6,13)
13 FORMAT('0',')
DO 17 A=1,20
READ(5,19) (APA(A,B),B=1,6)
19 FORMAT(6(F4.2,1X))
17 CONTINUE
   DO 191 A=1,20
   WRITE(6,21) STPA(A), (APA(A,B), B=1,6)
21 FORMAT(' ',13X,'7X,'F5.2,5(1X,F5.2))
191 CONTINUE

WRITE(6,213)
213 FORMAT('1',7X,'NET CROP YIELD REDUCTION, AS PERCENT OF MAXIMUM YIELD'/' FOR A CONTINUOUS WATER TABLE STAY IN EACH DEPTH RANGE'/' FOR THE PERIOD DECEMBER 15 TO JANUARY 05')
WRITE(6,5)
READ(5,7) (STPB(C), C=1,20)
READ(5,9) (DDPB(D), D=1,6)
WRITE(6,11) (DDPB(D), D=1,6)
WRITE(6,13)
   DO 27 C=1,20
   READ(5,19) (APB(C,D), D=1,6)
27 CONTINUE
WRITE(6,21) STPB(C), (APB(C,D), D=1,6)
31 CONTINUE

WRITE(6,33)
33 FORMAT('1',7X,'NET CROP YIELD REDUCTION, AS PERCENT OF MAXIMUM YIELD'/' FOR A CONTINUOUS WATER TABLE STAY IN EACH DEPTH RANGE'/' FOR THE PERIOD JANUARY 06 TO FEBRUARY 10')
WRITE(6,5)
READ(5,14) (STPC(E), E=1,30)
14 FORMAT(24(I2,1X)/6(I2,1X))
READ(5,9) (DDPC(F), F=1,6)
WRITE(6,11) (DDPC(F), F=1,6)
WRITE(6,13)
DO 37 E=1,30
   READ(5,22) (APC(E,F),F=1,6)
22 FORMAT(F4.2,5F5.2)
37 CONTINUE
DO 41 E=1,30
   WRITE(6,21) STPC(E),(APC(E,F),F=1,6)
41 CONTINUE

WRITE(6,43)
43 FORMAT(*15X,'NET CROP YIELD REDUCTION, AS PERCENT OF MAXIMUM YIELD'
      / '*15X,'FOR A CONTINUOUS WATER TABLE STAY IN EACH DEPTH RANGE'
      / '*15X,'FOR THE PERIOD FEBRUARY 11 TO MARCH 28')
   WRITE(6,5)
   READ(5,7) (STPD(G),G=1,20)
   READ(5,9) (DDPD(H),H=1,6)
   WRITE(6,11) (DDPD(H),H=1,6)
   WRITE(6,13)
   DO 47 G=1,20
      READ(5,19) (APD(G,H),H=1,6)
47 CONTINUE
DO 49 G=1,20
   WRITE(6,21) STPD(G),(APD(G,H),H=1,6)
49 CONTINUE

C
C COMPUTE DAILY SOIL MOISTURE EXCESS UNDER SUBSURFACE DRAINAGE
C FACILITIES AND THE CORRESPONDING CROP YIELD REDUCTION
C
C
DO 200 Y=1,29
   READ(5,250) YEAR
250 FORMAT(I4)
C
DO 300 M=1,12
READ(5,350) MONTH,NDAY
350 FORMAT(A3,I2)
   IF(.NOT.((M.GE.11).OR.(M.LE.03))) GO TO 8500
   WRITE(6,400) YEAR
400 FORMAT(" 49X*YEAR = '*,I4)
   WRITE(6,450) MONTH
450 FORMAT(" 48X*MONTH = '*,A3,8X)
   WRITE(6,600)
600 FORMAT(*0*,*DAY RAIN EVAP KEV* KCROP PET* ET SRO SM I
   IRR* EXC* K F SPACING HW WTD* YRED SUM*)
   WRITE(6,601)
601 FORMAT(* 6*)
   WRITE(6,602)
602 FORMAT(*0*,')

8500 DO 500 N=1,NDAY
   READ(5,550) EV,P(T)
550 FORMAT(F4.1,F4.0)
   KCROP=PLANT(N,M)
   KEV=KEVAP(N,M)
   PET=KCROP*KEV*EV
   PRC(T)=P(T)
   CALL RUNOFF (SRO,PRC,6,API,PP,ARR,52,7)
C
TS=100*4.
   CALL EXCESS (EXC1,SM1,6,P,FC,MXSAT,PET,IRR1,SRO,ET1)
   CALL WDEPTH (HW1,2,WTB1,EXC1,TS,THETA,K,DSO,DMX,ET1,P,6,SM1,FC,PET 1)
   WTABLE=WTB1
   IF(.NOT.((M.GE.11).OR.(M.LE.03))) GO TO 905
   CALL WTSTAY (M,N,WTABLE,YRED,STPA,DPA,APA,20,6,STPB,DPB,APB,20,6,S 1TPC,DPC,APC,30,6,STPD,DPD,APD,20,6,NBA1,NBB1,N8C1,N8D1,N8E1,N8F1,2 1)
THETA=THETA*100.

SUM1=SUM1+YRED

IF(.NOT.((M.EQ.03).AND.(N.GT.28))) GO TO 9001
SUM1=0.0

9001 WRITE(6,906) (N,P(T),EV,KEV,KCRP,PET,ET1,SRO,S1(T-1),IRR1,EXC1,K1,THETA,TS,HW1(X-1),WTABLE,YRED,SUM1)

906 FORMAT(' 1X,I2,2X,F4.0,2X,F4.1,2X,F4.2,2X,F4.2,2X,F4.1,2X,F4.1,1X,F5.1,2X,F5.1,1X,F5.1,2X,F4.0,3X,F3.0,5X,F3.1,3X,F4.0,3X,F5.1,3X,F4.1,3X,F6.2,3X,F6.2)

THETA=THETA/100.

905 TS=100*8.

CALL EXCESS (EXC2,SM2,6,P,FC,MXSAT,PET,IRR2,SRO,ET2)

CALL WDEPTH (HW2,2,WTB2,EXC2,TS,THETA,K,DSO,DMX,ET2,P,6,SM2,FC,PET)

WTABLE=WTB2

IF(.NOT.((M.GE.11).OR.(M.LE.03))) GO TO 907

CALL WSTAY (M,N,WTABLE,YRED,STPA,APA,20,6,STPB,DPB,APB,20,6,STPC,DPC,APC,30,6,STPD,DPD,APD,20,6,NBA2,NBB2,NC2,NBD2,NBE2,NBF2,2)

THETA=THETA*100.

SUM2=SUM2+YRED

IF(.NOT.((M.EQ.03).AND.(N.GT.28))) GO TO 9002
SUM2=0.0

9002 WRITE(6,906) (N,P(T),EV,KEV,KCRP,PET,ET2,SRO,SM2(T-1),IRR2,EXC2,K1,THETA,TS,HW2(X-1),WTABLE,YRED,SM2)

THETA=THETA/100.

907 TS=100*12.

CALL EXCESS (EXC3,SM3,6,P,FC,MXSAT,PET,IRR3,SRO,ET3)

CALL WDEPTH (HW3,2,WTB3,EXC3,TS,THETA,K,DSO,DMX,ET3,P,6,SM3,FC,PET)

WTABLE=WTB3
IF(.NOT.((M.GE.11).OR.(M.LE.03))) GO TO 908
CALL WTSTAY (M,N,WTABLE,YRED,STPA,STPA,APA,20.6,STPB,STPB,APB,20.6,S
ITPC,DPD,DPD,APD,20.6,STPA,STPA,APA,20.6,STPB,STPB,APB,20.6,S
ITPC,DPD,DPD,APD,20.6,STPA,STPA,APA,20.6,STPB,STPB,APB,20.6,S
ITPC,DPD,DPD,APD,20.6,STPA,STPA,APA,20.6,STPB,STPB,APB,20.6,S
ITPC,DPD,DPD,APD,20.6,STPA,STPA,APA,20.6,STPB,STPB,APB,20.6,S
ITPC,DPD,DPD,APD,20.6,STPA,STPA,APA,20.6,STPB,STPB,APB,20.6,S
ITPC,DPD,DPD,APD,20.6,STPA,STPA,APA,20.6,STPB,STPB,APB,20.6,S
THETA=THETA*100.
SUM3=SUM3+YRED
IF(.NOT.((M.EQ.03).AND.(N.GT.28))) GO TO 9003
SUM3=0.0
9003 WRITE(6,906) (N,P(T),EV,KEV,KCRDP,PET,ET3,SRO,SM3(T-1),IRR3,EXC3,K
1,THETA,TS,HW3(X-1),WTABLE,YRED,SUM3)
THETA=THETA/100.

908 TS=100*16.
CALL EXCESS (EXC4,SM4,6,P,FC,MXSAT,PET,IRR4,SRO,ET4)
CALL WDEPTH (HW4,2,WTB4,EXC4,TS,THETA,K,DSO,DMX,ET4,P,6,SM4,FC,PET
1)
WTABLE=WTB4
IF(.NOT.((M.GE.11).OR.(M.LE.03))) GO TO 909
CALL WTSTAY (M,N,WTABLE,YRED,STPA,STPA,APA,20.6,STPB,STPB,APB,20.6,S
ITPC,DPD,DPD,APD,20.6,STPA,STPA,APA,20.6,STPB,STPB,APB,20.6,S
ITPC,DPD,DPD,APD,20.6,STPA,STPA,APA,20.6,STPB,STPB,APB,20.6,S
ITPC,DPD,DPD,APD,20.6,STPA,STPA,APA,20.6,STPB,STPB,APB,20.6,S
ITPC,DPD,DPD,APD,20.6,STPA,STPA,APA,20.6,STPB,STPB,APB,20.6,S
THETA=THETA*100.
SUM4=SUM4+YRED
IF(.NOT.((M.EQ.03).AND.(N.GT.28))) GO TO 9004
SUM4=0.0
9004 WRITE(6,906) (N,P(T),EV,KEV,KCRDP,PET,ET4,SRO,SM4(T-1),IRR4,EXC4,K
1,THETA,TS,HW4(X-1),WTABLE,YRED,SUM4)
THETA=THETA/100.

909 TS=100*20.
CALL EXCESS (EXC5,SM5,6,P,FC,MXSAT,PET,IRR5,SRO,ETS)
CALL WDEPTH (HW5,2,WTB5,EXC5,TS,THETA,K,DSO,DMX,ET5,P,6,SM5,FC,PET
1)
TABLE=WTB5
IF (.NOT.((M.GE.11).OR.(M.LE.03))) GO TO 910
CALL WTSTAY (M,N,WTABLE,YRED,STPA,DPA,APA,20,6,STPB,DPB,APB,20,6,S
ITPC,DPC,APC,30,6,STPD,DPD,APD,20,6,NBA5,NBB5,NBC5,NBD5,NE5,NBF5,2
1)
THETA=THETA*100.
SUM5=SUM5+YRED
IF (.NOT.((M.EQ.03).AND.(N.GT.28))) GO TO 9005
SUM5=0.0
9005 WRITE (6,906) (N,P(T),EV,KEV,KCROP,PET,ETS,SM5(T-1),IRR5,EXC5,K
1,THETA,TS,HW5(X-1),WTABLE,YRED,SUM5)
THETA=THETA/100.

910 TS=100*30.
CALL EXCESS (EXC6,SM6,6,P,FC,MXSAT,PET,IRR6,SRO,ET6)
CALL WDEPTH (HW6,2,WTB6,EXC6,TS,THETA,K,DSO,DMX,ET6,P,6,SM6,FC,PET
1)
WTABLE=WTB6
IF (.NOT.((M.GE.11).OR.(M.LE.03))) GO TO 911
CALL WTSTAY (M,N,WTABLE,YRED,STPA,DPA,APA,20,6,STPB,DPB,APB,20,6,S
ITPC,DPC,APC,30,6,STPD,DPD,APD,20,6,NBA6,NBB6,NBC6,NBD6,NE6,NBF6,2
1)
THETA=THETA*100.
SUM6=SUM6+YRED
IF (.NOT.((M.EQ.03).AND.(N.GT.28))) GO TO 9006
SUM6=0.0
9006 WRITE (6,906) (N,P(T),EV,KEV,KCROP,PET,ETS,SM6(T-1),IRR6,EXC6,K
1,THETA,TS,HW6(X-1),WTABLE,YRED,SUM6)
THETA=THETA/100.

911 TS=100*40.
CALL EXCESS (EXC7,SM7,6,P,FC,MXSAT,PET,IRR7,SRO,ET7)
CALL WDEPTH (HW7,2,WTB7,EXC7,TS,THETA,K,DSO,DMX,ET7,P,6,SM7,FC,PET
1) 
  WTABLE=WTB7
  IF(.NOT.((M.GE.11).OR.(M.LE.03))) GO TO 912
  CALL WTSTAY (M,N,WTABLE,YRED,STPA,DPA,APA,20.6,STPB,DPB,APB,20.6,S
  TPC,DPC,APC,30.6,STPD,DPD,APD,20.6,NBA7,NBB7,NBC7,NBD7,NBE7,NBF7,2
  1)
  THETA=THETA*100.
  SUM7=SUM7+YRED
  IF(.NOT.((M.EQ.03).AND.(N.GT.28))) GO TO 9007
  SUM7=0.0
  9007 WRITE(6,906) (N,P(T),EV,KEV,KCROP,PET,ET7,SRO,SM7(T-1),IRR7,EXC7,K
  1,THETA,TS,HW7(X-1),WTABLE,YRED,SUM7)
  THETA=THETA/100.

  C  
  912 TS=100*50.
  CALL EXCESS (EXC8,SM8,6,P,FC,MXSAT,PET,IRR8,SRO,ET8)
  CALL WDEPTH (HW8,2,WTB8,EXC8,TS,THETA,K,DSO,DMX,ET8,P,6,SM8,FC,PET
  1)
  WTABLE=WTB8
  IF(.NOT.((M.GE.11).OR.(M.LE.03))) GO TO 913
  CALL WTSTAY (M,N,WTABLE,YRED,STPA,DPA,APA,20.6,STPB,DPB,APB,20.6,S
  TPC,DPC,APC,30.6,STPD,DPD,APD,20.6,NBA8,NBB8,NBC8,NBD8,NBE8,NBF8,2
  1)
  THETA=THETA*100.
  SUM8=SUM8+YRED
  IF(.NOT.((M.EQ.03).AND.(N.GT.28))) GO TO 9008
  SUM8=0.0
  9008 WRITE(6,906) (N,P(T),EV,KEV,KCROP,PET,ET8,SRO,SM8(T-1),IRR8,EXC8,K
  1,THETA,TS,HW8(X-1),WTABLE,YRED,SUM8)
  THETA=THETA/100.

  C  
  913 TS=100*200.
  CALL EXCESS (EXC9,SM9,6,P,FC,MXSAT,PET,IRR9,SRO,ET9)
CALL  WDEPTH (H*9,2,WTB9,EXC9,TS,THETA,K,DSO,DMX,ET9,P,6,SM9,FC,PET 1)
WTABLE=WTB9
IF(.NOT.((M.GE.11).OR.(M.LE.03))) GO TO 914
CALL  WTSTAY (M,N,WTABLE,YRED,STPA,APA,20,6,STPB,DPB,APB,20,6,S
TPC,DPC,APC,30,6,STPD,DPD,APD,20,6,NBA9,NBB9,NBC9,NBD9,NBE9,NBF9,2
1)
THETA=THETA*100.
SUM9=SUM9+YRED
IF(.NOT.((M.EQ.03).AND.(N.GT.28))) GO TO 9009
SUM9=0.0                          9009 WRITE(6,906) (N,P(T),EV,KEV,KCROP,PET,ET9,SRO,SM9(T-1)),IRR9,EXC9,K
1,THETA,TS,HW9(X-1),WTABLE,YRED,SUM9)
WRITE(6,39)
THETA=THETA/100.
914 CONTINUE
PRC(T-1)=P(T-1)
PRC(T-2)=P(T-2)
PRC(T-3)=P(T-3)
PRC(T-4)=P(T-4)
PRC(T-5)=P(T-5)
PRC(T)=P(T)
PRC(T-1)=PRC(T-2)
PRC(T-2)=PRC(T-3)
PRC(T-3)=PRC(T-4)
PRC(T-4)=PRC(T-5)
PRC(T-5)=PRC(T)
500 CONTINUE
300 CONTINUE
200 CONTINUE
STOP
END
SUBROUTINE  RUNOFF (RUN,PCP,N,APPI,RAIN,ARRAY,R,S)
INTEGER N,R,S,TP,TI
REAL  RUN,PCP(N),APPI(S),RAIN(R),ARRAY(R,S),INDEX
TP=PCP(N)
TP=IFIX(10.*0.03937*TP+.5)/10.
PCP(N)=TP
INDEX=PCP(N-1)+0.5*PCP(N-2)+0.33*PCP(N-3)+0.25*PCP(N-4)+0.20*PCP(N-5)
TI=INDEX
TI=IFIX(10.*TI+.5)/10.
INDEX=TI
IF(.NOT.(PCP(N).GE.1.0)) GO TO 35
INDEX=INDEX+0.5*PCP(N)
35 CONTINUE
IF(.NOT.(PCP(N).GT.5.1)) GO TO 34
PCP(N)=5.1
34 CONTINUE
IF(.NOT.(INDEX.GT.3.0)) GO TO 45
INDEX=3.0
45 CONTINUE
IF(.NOT.((INDEX.GE.0.0).AND.(INDEX.LT.0.3))) GO TO 17
INDEX=0.0
GO TO 27
17 CONTINUE
IF(.NOT.((INDEX.GE.0.3).AND.(INDEX.LT.0.7))) GO TO 37
INDEX=0.5
GO TO 27
37 CONTINUE
IF(.NOT.((INDEX.GE.0.7).AND.(INDEX.LT.1.3))) GO TO 47
INDEX=1.0
GO TO 27
47 CONTINUE
IF(.NOT.((INDEX.GE.1.3).AND.(INDEX.LT.1.7))) GO TO 57
INDEX=1.5
GO TO 27
57 CONTINUE
IF(.NOT.((INDEX.GE.1.7).AND.(INDEX.LT.2.3))) GO TO 67
INDEX=2.0
GO TO 27
67 CONTINUE
   IF(.NOT.((INDEX.GE.2.3).AND.(INDEX.LT.2.7))) GO TO 77
      INDEX=2.5
   GO TO 27
77 CONTINUE
   IF(.NOT.((INDEX.GE.2.7).AND.(INDEX.LE.3.0))) GO TO 27
      INDEX=3.0
27 CONTINUE
I=1
41 CONTINUE
   IF(.NOT.(PCP(N).EQ.RAIN(I))) GO TO 55
      J=1
75 CONTINUE
   IF(.NOT.(INDEX.EQ.APPI(J))) GO TO 65
      RUN=25.4*ARRAY(I,J)
   GO TO 85
55 CONTINUE
I=I+1
   GO TO 41
65 CONTINUE
J=J+1
   GO TO 75
85 CONTINUE
RETURN
END
SUBROUTINE EXCESS (EXC,SW,TT,PRC1,FC1,MAXSAT,PET1,IRR,SRO1,ET)
INTEGER TT
REAL EXC,SW(TT),PRC1(TT),FC1,MAXSAT,PET1,IRR,SRO1,ET,TFC,HUMID
TFC=FC1/3.
   IF(.NOT.(SW(TT-1).GE.FC1)) GO TO 10
100 ET=PET1
80 SW(TT)=SW(TT-1)+PRC1(TT)-ET-SRO1
   IRR=0.0
   IF(.NOT.(SW(TT).GT.FC1)) GO TO 20
IF(.NOT.(SW(TT).GE.MAXSAT)) GO TO 30
EXC=MAXSAT-FC1
GO TO 40
30 EXC=SW(TT)-FC1
40 SW(TT)=FC1
GO TO 50
20 EXC=0.0
GO TO 50
10 IF(.NOT.(SW(TT-1).GT.TFC)) GO TO 70
ET=(SW(TT-1)/FC1)*PET1
GO TO 80
70 HUMID=SW(TT-1)+PRC1(TT)-SR01
IF(.NOT.(HUMID.GT.TFC)) GO TO 90
IF(HUMID.GE.FC1) GO TO 100
ET=(HUMID/FC1)*PET1
GO TO 80
90 ET=PET1
IRR=FC1-HUMID+ET
EXC=0.0
SW(TT)=FC1
50 CONTINUE
RETURN
END

SUBROUTINE WOEPTH (HW,XX,WTBLE,EXCS,TSP,DP,KK,PROF,OMAX,ET,PRC1,TT
1,SW,FC1,PET1)
INTEGER XX,TT
REAL HW(XX),WTBLE,EXCS,TSP,DP,KK,PROF,OMAX,ET,PRC1,TT,SW(TT),FC1,
1,PET1,SDS,Q
EXCS=EXCS/10.
IF(.NOT.(HW(XX-1).GE.DMAX)) GO TO 802
HW(XX-1)=DMAX
SDS=1.25
805 Q=(0.2093*KK*(HW(XX-1)**2)/(TSP**1.641)
IF(.NOT.(Q.LE.SDS)) GO TO 801
HW(XX)=HW(XX-1)+(EXCS/DP)-Q
SUBROUTINE WTSTAY (MES, DIA, WT, CPLOSS, SPA, DRA, ARRAYA, AA, BB, SPB, DRB, IARRAYB, CC, DD, SPC, DRC, ARRAYC, EE, FF, SPD, DRD, ARRAYD, GG, HH, NDA, NDB, NDC, NDD, NDE, NDF, Z)

INTEGER MES, DIA, Z, AA, BB, CC, DD, EE, FF, GG, HH, NCA(Z), NDB(Z), NDC(Z), NDD(Z), NDE(Z), NDF(Z), NDIASA(Z), NDIASB(Z), NDIASC(Z), NDIASE(Z), NDIASF(Z), DEPTH(Z)

INTEGER SPA(AA), DRA(BB), SPB(CC), DRB(DD), SPC(EE), DRC(FF), SPD(GG), DRD(HH)

REAL WT, CLA, CLB, CLC, CLD, CLE, CLF, ARRAYA(AA, BB), ARRAYB(CC, DD), ARRAYC(EE, FF), ARRAYD(GG, HH), CPLOSS

IF (.NOT. ((WT .GE. 0.) .AND. (WT .LE. 10.))) GO TO 3001

NDA(Z) = NDA(Z-1) + 1
NDB(Z) = NDB(Z-1) + 1
NDC(Z) = NDC(Z-1) + 1
NDD(Z) = NDD(Z-1) + 1
NDE(Z) = NDE(Z-1) + 1
NDF(Z) = NDF(Z-1) + 1

CLA = 0.0
CLB = 0.0
CLC = 0.0
CLD = 0.0
CLE = 0.0
CLF = 0.0

IF (.NOT. ((MES .EQ. 12) .AND. (DIA .EQ. 14))) GO TO 3002

GO TO 3005
IF (NOT ((MES.EQ.01) AND (DIA.EQ.05))) GO TO 3003
GO TO 3005
3003 IF (NOT ((MES.EQ.02) AND (DIA.EQ.10))) GO TO 3004
GO TO 3005
3004 IF (NOT ((MES.EQ.03) AND (DIA.EQ.28))) GO TO 3051
3005 DEPTH=1
NDIASA=NDA(Z)
CALL DATE (CLA, DEPTH, NDIASA, MES, DIA, SPA, DRA, ARRAYA, 20, 6, SPB, DRB, AR
RAYB, 20, 6, SPC, DRC, ARRAYC, 30, 6, SPD, DRD, ARRAYD, 20, 6)
NDA(Z) = 0
DEPTH = 2
NDIASB=NDB(Z)
CALL DATE (CLB, DEPTH, NDIASC, MES, DIA, SPA, DRA, ARAYA, 20, 6, SPB, DRB, AR
RAYB, 20, 6, SPC, DRC, ARRAYC, 30, 6, SPD, DRD, ARRAYD, 20, 6)
NDB(Z) = 0
DEPTH = 3
NDIASC=NDIASC(Z)
CALL DATE (CLC, DEPTH, NDIASC, MES, DIA, SPA, DRA, ARAYA, 20, 6, SPB, DRB, AR
RAYB, 20, 6, SPC, DRC, ARRAYC, 30, 6, SPD, DRD, ARRAYD, 20, 6)
NDC(Z) = 0
DEPTH = 4
NDIASD=NDIASC(Z)
CALL DATE (CLO, DEPTH, NDIASC, MES, DIA, SPA, DRA, ARAYA, 20, 6, SPB, DRB, AR
RAYB, 20, 6, SPC, DRC, ARRAYC, 30, 6, SPD, DRD, ARRAYD, 20, 6)
NDD(Z) = 0
DEPTH = 5
NDIASP=NDIASE(Z)
CALL DATE (CLE, DEPTH, NDIASE, MES, DIA, SPA, DRA, ARAYA, 20, 6, SPB, DRB, AR
RAYB, 20, 6, SPC, DRC, ARRAYC, 30, 6, SPD, DRD, ARRAYD, 20, 6)
NDE(Z) = 0
DEPTH = 6
NDIASF=NDIF(Z)
CALL DATE (CLF, DEPTH, NDIASE, MES, DIA, SPA, DRA, ARAYA, 20, 6, SPB, DRB, AR
RAYB, 20, 6, SPC, DRC, ARRAYC, 30, 6, SPD, DRD, ARRAYD, 20, 6)
NDF(Z) = 0
GO TO 3051

C
C 3001 IF(.NOT.((WT.GT.10.).AND.(WT.LE.20.))) GO TO 3006
NDA(Z)=0
NDB(Z)=NDB(Z-1)+1
NDC(Z)=NDC(Z-1)+1
NDD(Z)=NDD(Z-1)+1
NDE(Z)=NDE(Z-1)+1
NDF(Z)=NDF(Z-1)+1
NDIASA=NDA(Z-1)
IF(.NOT.(NDIASA.GT.0)) GO TO 3007
DEPTH=1
CALL DATE (CLA,DEPTH,NDIASA,MES,DIA,SPA,DRA,ARRAYA,20,6,SPB,DRB,AR
1RAYB,20,6,SPC,DRC,ARRAYC,30,6,SPD,DRD,ARRAYD,20,6)
GO TO 3052
3007 CLA=0.0
3052 CLB=0.0
CLC=0.0
CLD=0.0
CLE=0.0
CLF=0.0
IF(.NOT.((MES.EQ.12).AND.(DIA.EQ.14))) GO TO 3008
GO TO 3011
3008 IF(.NOT.((MES.EQ.01).AND.(DIA.EQ.05))) GO TO 3009
GO TO 3011
3009 IF(.NOT.((MES.EQ.02).AND.(DIA.EQ.10))) GO TO 3010
GO TO 3011
3010 IF(.NOT.((MES.EQ.03).AND.(DIA.EQ.28))) GO TO 3051
3011 DEPTH=2
NDIASB=NDB(Z)
CALL DATE (CLB,DEPTH,NDIASB,MES,DIA,SPA,DRA,ARRAYA,20,6,SPB,DRB,AR
1RAYB,20,6,SPC,DRC,ARRAYC,30,6,SPD,DRD,ARRAYD,20,6)
NDB(Z)=0
DEPTH=3

161
NDIASC=NDC(Z)
CALL DATE (CLC,DEPTH,NDIASC,MES,DIA,SPA,DRA,ARRAYA,20,6,SPB,DRB,ARRAYB,20,6,SPC,ORC,ARRAYC,30,6,SPD,DRD,ARRAYD,20,6)
NDC(Z)=0
DEPTH=4
NDIasd=NDd(Z)
CALL DATE (CLD,DEPTH,NDIasd,MES,DIA,SPA,DRA,ARRAYA,20,6,SPB,DRB,ARRAYB,20,6,SPC,ORC,ARRAYC,30,6,SPD,DRD,ARRAYD,20,6)
NDD(Z)=0
DEPTH=5
NDIase=NDE(Z)
CALL DATE (CLE,DEPTH,NDIase,MES,DIA,SPA,DRA,ARRAYA,20,6,SPB,ORC,ARRAYB,20,6,SPC,ORC,ARRAYC,30,6,SPD,DRD,ARRAYD,20,6)
NDE(Z)=0
DEPTH=6
NDIASF=NDF(Z)
CALL DATE (CLF,DEPTH,NDIASF,MES,DIA,SPA,DRA,ARRAYA,20,6,SPB,ORC,ARRAYB,20,6,SPC,ORC,ARRAYC,30,6,SPD,DRD,ARRAYD,20,6)
NDF(Z)=0
GO TO 3051
C
C
3006 IF(.NOT.((WT.GT.20.) .AND. (WT.LE.30.))) GO TO 3012
NDA(Z)=0
NDB(Z)=0
NDC(Z)=NDC(Z-1)+1
NDD(Z)=NDD(Z-1)+1
NDE(Z)=NDE(Z-1)+1
NDF(Z)=NDF(Z-1)+1
NDIASA=NDA(Z-1)
IF(.NOT.(NDIASA.GT.0)) GO TO 3013
DEPTH=1
CALL DATE (CLA,DEPTH,NDIASA,MES,DIA,SPA,DRA,ARRAYA,20,6,SPB,DRB,ARRAYB,20,6,SPC,ORC,ARRAYC,30,6,SPD,DRD,ARRAYD,20,6)
GO TO 3053
3013 CLA=0.0
3053 NDIASB=NDB(Z-1)
   IF(.NOT.(NDIASB.GT.0)) GO TO 3014
   DEPTH=2
   CALL DATE (CLB,DEPTH,NDIASB,MES,DIA,SPA,DRA,ARRAYA,20,6,SPB,DRB,AR
   1RAYB,20,6,SPC,DRC,ARRAYC,30,6,SPD,DRD,ARRAYD,20,6)
   GO TO 3054
3014 CLB=0.0
3054 CLC=0.0
   CLD=0.0
   CLE=0.0
   CLF=0.0
   IF(.NOT.(MES.EQ.12).AND.(DIA.EQ.14)) GO TO 3015
   GO TO 3018
3015 IF(.NOT.((MES.EQ.01).AND.(DIA.EQ.05))) GO TO 3016
   GO TO 3018
3016 IF(.NOT.((MES.EQ.02).AND.(DIA.EQ.10))) GO TO 3017
   GO TO 3018
3017 IF(.NOT.((MES.EQ.03).AND.(DIA.EQ.28))) GO TO 3051
3018 DEPTH=3
   NDIASC=NDC(Z)
   CALL DATE (CLC,DEPTH,NDIASC,MES,DIA,SPA,DRA,ARRAYA,20,6,SPB,DRB,AR
   1RAYB,20,6,SPC,DRC,ARRAYC,30,6,SPD,DRD,ARRAYD,20,6)
   NDC(Z)=0
   DEPTH=4
   NDIASD=NDD(Z)
   CALL DATE (CLD,DEPTH,NDIASD,MES,DIA,SPA,DRA,ARRAYA,20,6,SPB,DRB,AR
   1RAYB,20,6,SPC,DRC,ARRAYC,30,6,SPD,DRD,ARRAYD,20,6)
   NDD(Z)=0
   DEPTH=5
   NDIASE=NDE(Z)
   CALL DATE (CLE,DEPTH,NDIASE,MES,DIA,SPA,DRA,ARRAYA,20,6,SPB,DRB,AR
   1RAYB,20,6,SPC,DRC,ARRAYC,30,6,SPD,DRD,ARRAYD,20,6)
   NDE(Z)=0
   DEPTH=6
NDIASF=NDF(Z)
CALL DATE (CLF, DEPTH, NDIASF, MES, DIA, SPA, DRA, ARRAYA, 20, 6, SPB, DRB, AR
IRAYB, 20, 6, SPD, DRD, ARRAYD, 20, 6)
NDF(Z)=0
GO TO 3051

C

3012 IF (.NOT.((WT.GT.30.) .AND. (WT.LE.40.))) GO TO 3019
NDA(Z)=0
NDB(Z)=0
NDC(Z)=0
NDD(Z)=NDD(Z-1)+1
NDE(Z)=NDE(Z-1)+1
NDF(Z)=NDF(Z-1)+1
NDIASA=NDA(Z-1)
IF (.NOT.((NDIASA.GT.0))) GO TO 3099
DEPTH=1
CALL DATE (CLA, DEPTH, NDIASA, MES, DIA, SPA, DRA, ARRAYA, 20, 6, SPB, DRB, AR
IRAYB, 20, 6, SPD, DRD, ARRAYD, 20, 6)
GO TO 3055

3099 CLA=0.0
3055 NDIASB=NDB(Z-1)
IF (.NOT.((NDIASB.GT.0))) GO TO 3020
DEPTH=2
CALL DATE (CLB, DEPTH, NDIASB, MES, DIA, SPA, DRA, ARRAYA, 20, 6, SPB, DRB, AR
IRAYB, 20, 6, SPD, DRD, ARRAYD, 20, 6)
GO TO 3056

3020 CLB=0.0
3056 NDIASC=NDC(Z-1)
IF (.NOT.((NDIASC.GT.0))) GO TO 3021
DEPTH=3
CALL DATE (CLC, DEPTH, NDIASC, MES, DIA, SPA, DRA, ARRAYA, 20, 6, SPB, DRB, AR
IRAYB, 20, 6, SPD, DRD, ARRAYD, 20, 6)
GO TO 3057

3021 CLC=0.0
3057 CLD=0.0
CLE=0.0
CLF=0.0
IF(.NOT.((MES.EQ.12).AND.(DIA.EQ.14))) GO TO 3022
GO TO 3025
3022 IF(.NOT.((MES.EQ.01).AND.(DIA.EQ.05))) GO TO 3023
GO TO 3025
3023 IF(.NOT.((MES.EQ.02).AND.(DIA.EQ.10))) GO TO 3024
GO TO 3025
3024 IF(.NOT.((MES.EQ.03).AND.(DIA.EQ.28))) GO TO 3051
3025 DEPTH=4
N1IASD=NDD(Z)
CALL DATE (CLD,DEPTH,NDIASD,MES,DIA,SPA,DRA,ARRAYA,20,6,SPB,DRB,8,1RAYB,20,6,SPC,DRC,ARRAYC,30,6,SPD,DRD,ARRAYD,20,6)
NDD(Z)=0
DEPTH=5
NDIASE=NDE(Z)
CALL DATE (CLE,DEPTH,NDIASE,MES,DIA,SPA,DRA,ARRAYA,20,6,SPB,DRB,8,1RAYB,20,6,SPC,DRC,ARRAYC,30,6,SPD,DRD,ARRAYD,20,6)
NDE(Z)=0
DEPTH=6
NDIASF=NDF(Z)
CALL DATE (CLF,DEPTH,NDIASF,MES,DIA,SPA,DRA,ARRAYA,20,6,SPB,DRB,8,1RAYB,20,6,SPC,DRC,ARRAYC,30,6,SPD,DRD,ARRAYD,20,6)
NDF(Z)=0
GO TO 3051
C
C 3019 IF(.NOT.((WT.GT.40.).AND.(WT.LE.50.))) GO TO 3026
NDA(Z)=0
NDB(Z)=0
NDC(Z)=0
NDD(Z)=0
NDE(Z)=NDE(Z-1)+1
NDF(Z)=NDF(Z-1)+1
NDIASA = NDA(Z-1)
IF(.NOT.(NDIASA.GT.0)) GO TO 3027
DEPTH = 1
CALL DATE (CLA, DEPTH, NDIASA, MES, SPA, DRA, ARRAYA, 20,6, SPB, DRB, AR
1RAYB, 20,6, SPC, DRC, ARRAYC, 30,6, SPD, DRD, ARRAYD, 20,6)
GO TO 3058
3027 CLA = 0.0
3058 NDIASB = NDB(Z-1)
IF(.NOT.(NDIASB.GT.0)) GO TO 3028
DEPTH = 2
CALL DATE (CLB, DEPTH, NDIASB, MES, SPA, DRA, ARRAYA, 20,6, SPB, DRB, AR
1RAYB, 20,6, SPC, DRC, ARRAYC, 30,6, SPD, DRD, ARRAYD, 20,6)
GO TO 3059
3028 CLB = 0.0
3059 NDIASC = NDC(Z-1)
IF(.NOT.(NDIASC.GT.0)) GO TO 3029
DEPTH = 3
CALL DATE (CLC, DEPTH, NDIASC, MES, SPA, DRA, ARRAYA, 20,6, SPB, DRB, AR
1RAYB, 20,6, SPC, DRC, ARRAYC, 30,6, SPD, DRD, ARRAYD, 20,6)
GO TO 3060
3029 CLC = 0.0
3060 NDIASD = NDD(Z-1)
IF(.NOT.(NDIASD.GT.0)) GO TO 3030
DEPTH = 4
CALL DATE (CLD, DEPTH, NDIASD, MES, SPA, DRA, ARRAYA, 20,6, SPB, DRB, AR
1RAYB, 20,6, SPC, DRC, ARRAYC, 30,6, SPD, DRD, ARRAYD, 20,6)
GO TO 3061
3030 CLD = 0.0
3061 CLE = 0.0
CLF = 0.0
IF(.NOT.((MES.EQ.12).AND.(DIA.EQ.14))) GO TO 3031
GO TO 3034
3031 IF(.NOT.((MES.EQ.01).AND.(DIA.EQ.05))) GO TO 3032
GO TO 3034
3032 IF(.NOT.((MES.EQ.02).AND.(DIA.EQ.10))) GO TO 3033
GO TO 3034
3033 IF(.NOT.((MES.EQ.03).AND.(OIA.EQ.28))) GO TO 3051
3034 DEPTH=5
   NDIASE=NDE(Z)
   CALL DATE (CLE,DEPTH,NDIASE,MES,DIA,SPA,DRA,ARRAYA,20,6,SPB,DRB,ARY
   IRAYB,20,6,SPC,DRC,ARRAYC,30,6,SPD,DRD,ARRAYD,20,6)
   NDE(Z)=0
   DEPTH=6
   NDIASF=NDF(Z)
   CALL DATE (CLF,DEPTH,NDIASF,MES,DIA,SPA,DRA,ARRAYA,20,6,SPB,DRB,ARY
   IRAYB,20,6,SPC,DRC,ARRAYC,30,6,SPD,DRD,ARRAYD,20,6)
   NDF(Z)=0
   GO TO 3051

3026 IF(.NOT.((WT.GT.50.).AND.(WT.LE.60.))) GO TO 3035
   NDA(Z)=0
   NDB(Z)=0
   NDC(Z)=0
   NDD(Z)=0
   NDE(Z)=0
   NDF(Z)=NDF(Z-1)+1
   NDIASA=NDA(Z-1)
   IF(.NOT.(NDIASA.GT.0)) GO TO 3036
   DEPTH=1
   CALL DATE (CLA,DEPTH,NDIASA,MES,DIA,SPA,DRA,ARRAYA,20,6,SPB,DRB,ARY
   IRAYB,20,6,SPC,DRC,ARRAYC,30,6,SPD,DRD,ARRAYD,20,6)
   GO TO 3062
3036 CLA=0.0
3062 NDIASB=NDB(Z-1)
   IF(.NOT.(NDIASB.GT.0)) GO TO 3037
   DEPTH=2
   CALL DATE (CLB,DEPTH,NDIASB,MES,DIA,SPA,DRA,ARRAYA,20,6,SPB,DRB,ARY
   IRAYB,20,6,SPC,DRC,ARRAYC,30,6,SPD,DRD,ARRAYD,20,6)
   GO TO 3063
3037 CLB=0
3063 NDIASC=NDIASC(Z-1)
   IF(.NOT.(NDIASC.GT.0)) GO TO 3038
   DEPTH=3
   CALL DATE (CLC,DEPTH,NDIASC,MES,DIA,SPA,DRA,ARRAYA,20,6,SPB,DRB,AR
   IRAYB,20,6,SPC,DRC,ARRAYC,30,6,SPD,DRD,ARRAYD,20,6)
   GO TO 3064
3038 CLC=0.0
3064 NDIASD=NDIASD(Z-1)
   IF(.NOT.(NDIASD.GT.0)) GO TO 3039
   DEPTH=4
   CALL DATE (CLD,DEPTH,NDIASD,MES,DIA,SPA,DRA,ARRAYA,20,6,SPB,DRB,AR
   IRAYB,20,6,SPC,DRC,ARRAYC,30,6,SPD,DRD,ARRAYD,20,6)
   GO TO 3065
3039 CLD=0.0
3065 NDIASE=NDIASE(Z-1)
   IF(.NOT.(NDIASE.GT.0)) GO TO 3040
   DEPTH=5
   CALL DATE (CLE,DEPTH,NDIASE,MES,DIA,SPA,DRA,ARRAYA,20,6,SPB,DRB,AR
   IRAYB,20,6,SPC,DRC,ARRAYC,30,6,SPD,DRD,ARRAYD,20,6)
   GO TO 3066
3040 CLE=0.0
3066 CLF=0.0
   IF(.NOT.((MES.EQ.12).AND.(DIA.EQ.14))) GO TO 3041
   GO TO 3044
3041 IF(.NOT.((MES.EQ.01).AND.(DIA.EQ.05))) GO TO 3042
   GO TO 3044
3042 IF(.NOT.((MES.EQ.02).AND.(DIA.EQ.10))) GO TO 3043
   GO TO 3044
3043 IF(.NOT.((MES.EQ.03).AND.(DIA.EQ.28))) GO TO 3051
3044 DEPTH=6
   NDIASF=NDIASF(Z)
   CALL DATE (CLF,DEPTH,NDIASF,MES,DIA,SPA,DRA,ARRAYA,20,6,SPB,DRB,AR
   IRAYB,20,6,SPC,DRC,ARRAYC,30,6,SPD,DRD,ARRAYD,20,6)
   NDF(Z)=0
GO TO 3051

C
C

3035 NDA(Z)=0
NDB(Z)=0
NDC(Z)=0
NDD(Z)=0
NDE(Z)=0
NDF(Z)=0
NDIASA=NDA(Z-1)
IF(.NOT.(NDIASA.GT.0)) GO TO 3045
DEPTH=1
CALL DATE (CLA,DEPTH,NDIASA,MES,DIA,SPA,DRA,ARRAYA,20,6,SPB,DRB,AR
IRAYB,20,6,SPC,DRC,ARRAYC,30,6,SPD,DRD,ARRAYD,20,6)
GO TO 3067

3045 CLA=0.0

3046 CLB=0.0

3067 NDIASB=NDB(Z-1)
IF(.NOT.(NDIASB.GT.0)) GO TO 3046
DEPTH=2
CALL DATE (CLB,DEPTH,NDIASB,MES,DIA,SPA,DRA,ARRAYA,20,6,SPB,DRB,AR
IRAYB,20,6,SPC,DRC,ARRAYC,30,6,SPD,DRD,ARRAYD,20,6)
GO TO 3068

3046 CLB=0.0

3047 CLC=0.0

3068 NDIASC=NDC(Z-1)
IF(.NOT.(NDIASC.GT.0)) GO TO 3047
DEPTH=3
CALL DATE (CLC,DEPTH,NDIASC,MES,DIA,SPA,DRA,ARRAYA,20,6,SPB,DRB,AR
IRAYB,20,6,SPC,DRC,ARRAYC,30,6,SPD,DRD,ARRAYD,20,6)
GO TO 3069

3047 CLC=0.0

3048 CLD=0.0

3069 NDIASD=NDD(Z-1)
IF(.NOT.(NDIASD.GT.0)) GO TO 3048
DEPTH=4
CALL DATE (CLD,DEPTH,NDIASD,MES,DIA,SPA,DRA,ARRAYA,20,6,SPB,DRB,AR
IRAYB,20,6,SPC,DRC,ARRAYC,30,6,SPD,DRD,ARRAYD,20,6)
GO TO 3070
3048  CLD=0.0
3070  NDIASE=NDE(Z-1)
    IF(-(NOT.(NDIASE.GT.0))) GO TO 3049
    DEPTH=5
    CALL DATE (CLE,DEPTH,NDIASE,MES,DIA,SPA,DRA,ARRAYA,20,6,SPB,DRB,ARY
    IRAYB,20,6,SPC,DRC,ARRAYC,30,6,SPD,DRD,ARRAYD,20,6)
    GO TO 3071
3049  CLE=0.0
3071  NDIASF=NDF(Z-1)
    IF(-(NOT.(NDIASF.GT.0))) GO TO 3050
    DEPTH=6
    CALL DATE (CLF,DEPTH,NDIASF,MES,DIA,SPA,DRA,ARRAYA,20,6,SPB,DRB,AR
    IRAYB,20,6,SPC,DRC,ARRAYC,30,6,SPD,DRD,ARRAYD,20,6)
    GO TO 3051
3050  CLF=0.0
C
3051  CPLOSS=CLA+CLB+CLC+CLD+CLE+CLF
    NDA(Z-1)=NDA(Z)
    NDB(Z-1)=NDE(Z)
    NDC(Z-1)=NDC(Z)
    NDD(Z-1)=NDD(Z)
    NDE(Z-1)=NDE(Z)
    NDF(Z-1)=NDF(Z)
    RETURN
END
SUBROUTINE DATE (LOSS,DPTH,KOUNT,MO,ND,STA,DA,ARRA,IA,JA,STB,DB,AR
    IRB,IB,JC,ARCC,IC,JC,STD,DD,ARRD,ID,JD)
    INTEGER MO,ND,IA,JA,IB,JC,STD,DD,ARRD,ID,JD
    REAL LOSS,ARRA(IA,JA),ARRB(IB,JB),ARRC(IC,JC),ARRD(ID,JD)
    IF(-(NOT.(MO.EQ.11).AND.(ND.GE.21))) GO TO 4000
    GO TO 4009
4000  IF(-(NOT.(MO.EQ.12))) GO TO 4001
IF(.NOT.(ND.LT.15)) GO TO 4011
GO TO 4009
4001 IF(.NOT.(MO.EQ.01)) GO TO 4003
IF(.NOT.(ND.LT.06)) GO TO 4013
GO TO 4011
4003 IF(.NOT.(MO.EQ.02)) GO TO 4005
IF(.NOT.(ND.LT.11)) GO TO 4006
GO TO 4013
4005 IF(.NOT.((MO.EQ.03).AND.(ND.LE.28))) GO TO 4007
4006 IF(.NOT.(KOUNT.GT.20)) GO TO 4008
KOUNT=20
4008 LOSS=ARRD(KOUNT,DPTH)
GO TO 4015
4009 IF(.NOT.(KOUNT.GT.20)) GO TO 4010
KOUNT=20
4010 LOSS=ARRA(KOUNT,DPTH)
GO TO 4015
4011 IF(.NOT.(KOUNT.GT.20)) GO TO 4012
KOUNT=20
4012 LOSS=ARRB(KOUNT,DPTH)
GO TO 4015
4013 IF(.NOT.(KOUNT.GT.30)) GO TO 4014
KOUNT=30
4014 LOSS=ARRC(KOUNT,DPTH)
GO TO 4015
4007 LOSS=0.0
4015 CONTINUE
RETURN
END
APPENDIX E: SAMPLE OUTPUT DATA FOR PROGRAM LISTING ON APPENDIX D
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<td>20.0</td>
<td>5.0</td>
<td>8.0</td>
<td>40.0</td>
<td>10.0</td>
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YEAR = 1957
MONTH = FEB
APPENDIX F: HYDRAULIC DESIGN OF TUBE DRAINAGE

Since the tube diameter has little effect on the rate of flow (Kirkham, 1949), the size of the drain becomes a function only of its discharge capacity and the design flow. These two factors determine the maximum length of a tile line flowing without back pressure for a specified tile diameter, coefficient of roughness, spacing, drainage rate and slope.

To obtain an equation for determining the maximum length (L), the capacity of the tile (Q) may be equated to the design flow (q).

Drain capacity can be found from Manning's equation as
\[
Q = \left(\frac{nD^2}{4}\right) \left(\frac{1}{n}\right) \left(\frac{D}{4}\right)^{2/3} s^{1/2} \times 86400
\]  \hspace{1cm} (F-1)

where
\begin{align*}
Q &= \text{maximum drain tube capacity, m}^3/\text{day/unit length} \\
D &= \text{diameter of the drain, m} \\
n &= \text{Manning's roughness coefficient} \\
s &= \text{slope of the drain tubes} \\
86400 &= \text{conversion factor from flow rate per second to flow rate per day}
\end{align*}

To determine the design flow, the following equation was used:
\[
q = RSL
\]  \hspace{1cm} (F-2)

in which
\begin{align*}
q &= \text{maximum design flow, m}^3/\text{day} \\
S &= \text{drain spacing, m} \\
L &= \text{drain length, m} \\
R &= \text{rate of drainage or drainage flux, m/day}
\end{align*}
The application of Equation (F-2) assumes a uniform flow in the drain for the drainage area under consideration. The maximum expected rate of drainage occurs when all soil profile is saturated, the maximum surface storage is satisfied and the smallest drain spacing is considered.

To compute \( R \), the following expression was used:

\[
R = 0.002093 \frac{K H^2}{S^{1.641}} \quad \text{(F-3)}
\]

where

\( R \) = rate of drainage, m/day
\( K \) = saturated hydraulic conductivity, cm/day
\( S \) = drain spacing, cm
\( H \) = water table height halfway between drains above the impervious layer, cm

The maximum value of \( L \) is then given by

\[
L \leq Q/\sqrt{SR} \quad \text{(F-4)}
\]

Clay tubes with three different inside diameters were used to determine the maximum line length. The results as well as the field conditions used are summarized in the following table.

<table>
<thead>
<tr>
<th>Tile diameter (inch)</th>
<th>( Q^1 ) (m³/day)</th>
<th>( R^2 ) (m/day)</th>
<th>( R^3 ) (m²/day)</th>
<th>( L ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
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<td>0.0337</td>
<td>801</td>
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<tr>
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<td>79.74</td>
<td>0.0084</td>
<td>0.0337</td>
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<tr>
<td>4</td>
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<td>0.0084</td>
<td>0.0337</td>
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</table>

\(^1\text{n} = 0.011, \; s = 0.1\%.

\(^2\text{K} = 20 \text{ cm/day, } H = 61.25 \text{ cm, } S = 4 \text{ m.} \)
It can be observed that, even for such reduced slope, a drain tube 2-inch inside diameter will be sufficient to carry out the design flow in a length of 500 m. This is assumed to be the maximum length of laterals, since open ditches are expected to exist at least 500 m apart.
APPENDIX G: ANNUAL SOYBEAN YIELD RESPONSE, AS A FUNCTION OF DIFFERENT DEGREES OF DRAINAGE
Table Gl. Annual soybean yield reductions (in percent of maximum yield) as a function of different drain spacings

<table>
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<tr>
<th>Year</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>16</th>
<th>20</th>
<th>30</th>
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<th>50</th>
<th>200</th>
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<td>36.18</td>
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<td>1.86</td>
<td>1.88</td>
<td>1.88</td>
<td>3.16</td>
<td>4.94</td>
<td>4.96</td>
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<td>5.86</td>
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<td>16.32</td>
<td>19.64</td>
<td>19.70</td>
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</table>

Average 10.02 16.47 19.46 20.89 22.06 23.13 23.58 24.31 25.09
APPENDIX H: TOTAL ANNUAL COSTS OF DRAINAGE SYSTEMS BY OPEN DITCHES

In this study, an impermeable layer is assumed to exist at the 60 cm from the soil surface. Therefore, open ditches with an average cross section given by a depth of 70 cm, a width of 30 cm at the bottom and side slope of 1.67 were assumed in this analysis. It was also assumed: (1) construction cost = $0.50/m, (2) engineering cost = $0.025/m, and (3) maintenance cost = $0.0614/m/year. The results of the analysis are summarized in the table below.

Table H1. Total annual costs as a function of degree of drainage

<table>
<thead>
<tr>
<th>Spacing (m)</th>
<th>Initial</th>
<th>Annual</th>
<th>Maintenance</th>
<th>TOTAL</th>
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