An hourly water balance model of a tile drained brookston clay soil.

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AN HOURLY WATER BALANCE MODEL
OF A
TILE DRAINED BROOKSTON CLAY SOIL.

A THESIS

Submitted to the Faculty of Graduate Studies through the Department of Civil Engineering in Partial Fulfilment of the requirements for the Degree of Master of Applied Science at the University of Windsor.

BY

NORMAN A. BIRD

B. S. A., University of Toronto, 1960.

Windsor, Ontario, Canada.

1969
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SUMMARY

An hourly water balance model containing the
C. W. Thornthwaite soil moisture budget and an empirical relationship
between mid spacing water table height and tile drain runoff was
developed and programmed for an IBM 360/40 digital computer. One
half of the data from an eleven year field study of tile drainage
performance on Brookston Clay soil was used to develop the model.
The other half of the data was used to check the model. The
relationship used to predict tile runoff rates was found to be quite
accurate, and would predict the shape of tile runoff hydrographs
under a varying precipitation pattern. The ability to accurately
predict the soil moisture levels was the primary limiting factor
in the model performance. The continuity of the water balance
provided information on the extent of surface runoff, and horizontal
seepage to surface drains. These two items accounted for approximately
one third of the total runoff. The continuity of the ground water and
drainage portion of the water balance provided an indication of the
seepage patterns, the effective hydraulic conductivities and the
drainable porosity.
ACKNOWLEDGEMENTS

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NOTATION

\( A \)  reservoir coefficient (T)
\( a \)  constant in Luthin Worstell equation
\( A_c \)  field capacity of accessible soil moisture storage zone (L)
\( A_r \)  soil moisture retention in accessible zone (L)
\( \Delta E \)  daily actual evapotranspiration (L)
\( B \)  depth of aquifer (L)
\( b \)  depth of drain axis below ground surface (L)
\( b' \)  depth of drain axis below ponded water surface (L)
\( c \)  water table flux factor
\( D \)  \( d + m_\theta/z \) (L)
\( d \)  depth of impermeable layer below drain axis (L)
\( d_e \)  equivalent depth of impermeable layer below drain axis (L)
\( F \)  infinite series function
\( f \)  drainable porosity
\( f_a \)  average drainable porosity
\( F_C \)  field capacity (L)
\( G \)  function in the Kirkham ponded water equations (L)
\( H_0 \)  height of mid-spacing water table above impermeable layer (L)
\( h_0 \)  height of water table above impermeable layer at drain (L)
\( h \)  piezometric head (L)
\( fi \)  assumed constant mean water table height (L)
\( i \)  rainfall intensity (L/T)
K  hydraulic conductivity (L/T)
1  daylength factor
m  height of mid-spacing water table above drain axis (L)
m_0  initial value of m (L)
m_f  final value of m (L)
P  daily precipitation (L)
PE  daily potential evapotranspiration (L)
Q  drain discharge per foot of length (L^2/T)
Q_1  Q/2 (L^2/T)
q  (b' - r)/G (L)
R  drain runoff rate (L/T)
r  drain radius (L)
S  drain spacing (L)
s  slope of Thornthwaite retention relationship
T(t)  arbitrary function of t (T)
T_m  mean daily temperature
T_r  transmissivity (L^2/T)
t  time (T)
U  incomplete beta function
w_T  water table height (L)
X(x)  arbitrary function of x (L)
x  horizontal distance co-ordinate (L)
y  horizontal distance co-ordinate (L)
z  vertical distance co-ordinate (L)
\Phi  potential function (L)
\Psi  stream function (L)
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CHAPTER I
INTRODUCTION

The soils of Essex, Kent and Lambton Counties in south-western Ontario are primarily level clay soils formed under Lake Warren during recession of the glaciers of the Wisconsin glaciation. Today these soils support intensive agricultural production, the primary crops being corn and soybeans. Subsurface drainage is necessary on these soils in order to lower the water table rapidly in the spring and to permit the soil to dry to tillable condition and to warm rapidly to suitable germination temperatures. During the growing season, the root zone must not be allowed to remain water logged for more than a few hours, or severe root damage will occur. In the fall, efficient drainage is necessary in order to facilitate field harvesting operations.

Subsurface drains are found to be an effective means of removing water ponded on the surface in low areas, and are not an obstruction to field operations as are surface drains.

A subsurface drainage system for this area consists
Typically of a series of parallel 4" diameter tile drains spaced about 40 feet apart and installed at a depth of 26 to 36 inches and a slope of 0.001. They may be up to 2000 feet long and drain into an outlet ditch or header drain. The selection of this spacing is based primarily on experience and the depth is controlled by the depth of outlets and the capacity of trenching machines.

Header mains are designed for a drainage rate of $\frac{1}{2}$ inch per day. This, as with other design criteria is based on experience and accepted practice.

In 1957, a field experiment was initiated by the Ontario Agricultural College in order to collect data that would assist in improving the design criteria for drainage systems. Ten years of records of tile drain discharge and rainfall were collected.

The purpose of this study is to develop a mathematical model that would simulate the drain discharge hydrographs using hourly precipitation as input. Such a model could then be used to compute discharge hydrographs for a greater number of years than the ten for which drain discharge records were taken using rainfall records available from other stations in the area.

The model also, could be used to test the feasibility of irrigation on the level clay soils in the area. The soil moisture budget would provide the information to determine the need for irrigation and the water table elevations could be used to determine the probability of crop damage as a result of an irrigation schedule superimposed on the precipitation pattern.
CHAPTER II
LITERATURE SURVEY

The response of drain discharge to precipitation involves a water balance which includes infiltration, surface runoff, interflow, evapotranspiration, deep seepage, soil moisture storage, ground water storage, and ground water seepage to a system of parallel drains. This chapter reviews and summarizes briefly the theoretical, laboratory and field drainage studies and developed evapotranspiration and water balance models that provide a basis for the development of this model.

2.1 DRAINAGE STUDIES

The performance of systems of parallel tile drains have been extensively studied. For some problems, mathematical models based on theory have been devised that are exact. For others, models based on approximating assumptions have been proposed. Laboratory models and field studies have yielded empirical relationships, and have been used to verify mathematical models.
2.1.1. THEORETICAL STUDIES

The seepage of unconfined ground water can be conveniently divided into steady and unsteady flow situations.

C. E. Jacob (1) demonstrates that the development of fundamental equations from Darcy's law leads to the Laplace equation,

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = 0 \quad \ldots (2.1)$$

for steady conditions and the following non-linear partial differential equation for the unsteady case:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = f \frac{\partial h}{\partial y} + T_T \frac{\partial^2 h}{\partial t^2} \quad \ldots (2.2)$$

In these equations, $h$ is piezometric head, $x$ and $y$ are horizontal plane co-ordinates, $f$ and $T_T$ are the aquifer characteristics specific yield or drainable porosity and transmissivity respectively, and $t$ is time.

2.1.1.1. STEADY STATE SOLUTIONS

Dupuit, who's work is reported by van Schilfgaarde, et al. (2) assumed that:

1. Stream lines in a system of gravity seepage toward a shallow sink are horizontal.

2. The velocity along a stream line is proportional to the slope of the free surface.

3. The velocity is uniform from top to bottom of the seepage depth.

van Schilfgaarde (3) pointed out that the assumptions of Dupuit, when consistently followed are contradictory. In addition, he
pointed out that in the use of these assumptions to describe a problem, seepage above the water table and a surface of seepage are ignored.

Nevertheless, the Dupuit theory is widely used and when applied to seepage problems where vertical velocities will be small compared to horizontal ones, the results have been found to agree with experiments. Several researchers independently applied the Dupuit assumptions and Darcy's law to the problem of uniform, steady rainfall falling on an area drained with parallel ditches penetrating to a shallow impermeable layer. The result is an equation describing an ellipse, and Hooghout (4) who's work is reported by van Schilfgaarde et al. (2) developed it in the form:

\[ S = 2K \frac{(H_0^2 - h_0^2)}{Q_1} \]  

...(2.3)

where \( S \) is the drain spacing, \( K \) is the hydraulic conductivity, \( Q_1 \) is half of the total discharge of each drain per unit length, and \( h_0 \) and \( H_0 \) are as illustrated in Fig. 2.1.

In discussing the application of this equation, van Schilfgaarde et al. (2) pointed out that it has been used for ditches that are not fully penetrating and also for tile drains. Both cases require that the effect of convergence of flow near the drains be neglected. However, the authors suggest that since the backfill over tile drains is often more permeable, the error in applying the equation is small. The error caused by convergence below the drains depends on the depth of the impermeable layer below the drain. Hooghnout (5) as reported by van Schilfgaarde et al. (2) provided a table of equivalent depths to correct for convergence effect. His ellipse equation, written in the notation of Fig. 2.2 and including his equivalent depth is as follows:
Fig. 2.1 GEOMETRY OF DITCH DRAINAGE SYSTEM
Fig. 2.2 GEOMETRY OF TILE DRAINAGE SYSTEM
where $R$ is the drainage rate.

For steady state drainage problems to which the Dupuit assumptions did not apply, Hooghout developed further approximate solutions. He assumed radial flow and used image drains to solve the case of a deep impermeable layer and assumed a combination of radial and horizontal flow for intermediate cases.

van Schilfgaarde et al. (2) report that a number of researchers including van Doemter (6), Gustafsson (7) and Engelund (8) used the hodograph method to solve the Laplace equation for both potential and stream functions and derive exact solutions to their steady state problems. The most general case, solved by van Doemter included deep seepage or artesian effect. He assumed the drain radius to be zero.

Toksoz and Kirkham (9) developed from potential theory the steady state solution:

$$m = \frac{SR}{K}\frac{1}{1 - \frac{R}{K}} F\left(\frac{r}{S}, \frac{d}{S}\right)$$

where the function $F$ is evaluated from graphs or tables.

In addition to steady state situations induced by steady rainfall infiltrating to a curved water table, there is the case of water ponded on the surface and a flat water table. Kirkham (10) obtained an exact solution to the ponded water case using the method of images and a complex variable. For the case of an impermeable layer at shallow depth, he obtained the following equations to calculate the
potential, stream function, and the flow per unit drain length respectively:

\[ \Phi = q \sum_{n=-\infty}^{\infty} \ln \left[ \frac{\cosh \frac{\pi}{2B} (x - nS) - \cos \frac{\pi z}{2B}}{\cosh \frac{\pi}{2B} (x - nS) + \cos \frac{\pi z}{2B}} \right] \cosh \frac{\pi}{2B} (x - nS) - \cos \frac{\pi (2b - z)}{2B} + b' \]

\[ \Psi = -2q \sum_{n=-\infty}^{\infty} \left( \tan^{-1} \left\{ \frac{\sinh \frac{\pi}{2B} (x - nS)}{\sin \frac{\pi z}{2B}} \right\} \right) \]

\[ + \tan^{-1} \left\{ \frac{\sinh \frac{\pi}{2B} (x - nS)}{\sin \frac{\pi (2b - z)}{2B}} \right\} \]

\[ Q = 4\pi Kq \]

where \( q = (b' - r)/G \)

and

\[ G = 2\ln \frac{\tan \frac{\pi (2b - r)}{4B}}{\tan \frac{\pi r}{4B}} + 2 \sum_{n=1}^{\infty} \ln \left[ \frac{\cosh \frac{\pi nS + \cos \frac{\pi x}{2B}}{2B}}{\cosh \frac{\pi nS - \cos \frac{\pi x}{2B}}{2B}} \right] \cosh \frac{\pi nS - \cos \frac{\pi (2b - r)}{2B}}{2B} \cosh \frac{\pi nS + \cos \frac{\pi (2b - r)}{2B}}{2B} \]

In these equations, \( B \) is the depth of the aquifer, \( b \) is the depth of the drains and \( b' \) is the depth of the drains plus the depth...
of ponded water.

2.1.1.2. SOLUTIONS OF TRANSIENT DRAINAGE PROBLEMS

Since steady state drainage problems occur in limited regions and the problem of a water table fluctuating in response to intermittent rainfall is more common, the latter has been extensively studied.

van Schilfgaarde (11) gives the equation of continuity for a system of equally spaced drains over an impermeable boundary, based on the Dupuit assumptions as:

\[ K \frac{\partial}{\partial x} \left( h \frac{\partial h}{\partial x} \right) = f \frac{\partial h}{\partial t} \quad \ldots (2.11) \]

Glover, as reported by Dumm (12) linearized this equation by assuming h is a constant compared to h/т to give:

\[ h K \frac{\partial^2 h}{\partial x^2} = f \frac{\partial h}{\partial t} \quad \ldots (2.12) \]

Assuming an initially flat water table, he obtained the following solution:

\[ h - d = \lim_{n=1,3,5} \sum_{n=1}^{\infty} \sin \left( \frac{n \pi x}{n} \right) \exp \left( -\frac{n^2 \pi^2 K D t}{f S} \right) \]

\[ \ldots (2.13) \]

This equation can be approximated with less than 4 percent error by:

\[ S^2 = \frac{n^2 K D t}{\pi \ln \frac{h_0}{m_t}} \quad \ldots (2.14) \]

in which D is the initial average depth of seepage.

Tapp and Moody, as reported by Dumm (13) solved equation (2.12) for an initially parabolic water table and obtained a solution similar to equation (2.13) except that the factor 4 in equation (2.13)
was 3.7 in their solution. This equation represents more nearly the actual water table shape at the start of drawdown.

van Schilfgaarde (3) pointed out that since the above two solutions assume that \( h \) is a constant, they are limited to cases in which \( h \) is large relative to \( m \). However, he further pointed out that since convergence near the drains is not taken into account, the error due to convergence increases with an increase in \( h \) relative to \( m \).

Glover (12) solved equation 2.11 without linearization for the case of drains on the impermeable layer by assuming that the variables are separable, or,

\[
h(x,t) = X(x) T(t) \quad \ldots(2.15)
\]

His solution is:

\[
S^2 = \frac{2}{\int} \frac{K t}{f} \frac{m_o m_t}{m_o - m_t} \quad \ldots(2.16)
\]

van Schilfgaarde (14) used a similar method to solve equation 2.11 for an initially parabolic water table and the drains above the impermeable layer. His solution is:

\[
\frac{K t}{f} = 2 \frac{S^2 (m_o - m_t)}{u^2 (m_t + de)(m_o + de)} \quad \ldots(2.17)
\]

where \( u \) is an incomplete beta function but \( u^2 \) may be approximated within 3 percent error by the expression:

\[
1 - \left[ \frac{de}{de + m_o} \right]^2
\]

In addition to the falling water table problem, investigators have been interested in the more general transient water table problem that includes recharge patterns.
Werner (15) and Maasland (16) modified equation 2.11 by adding a term \( P \) to the right hand side, representing a recharge rate. Werner linearized the equation by substituting \( y \) for \( h^2 \) and taking \( \frac{y^3}{3} \) as a constant.

De Zeeuw and Hellinga (17) applied a varying precipitation pattern to the steady state ellipse equation and Krayenhoff, as reported by van Schilfgaarde (11) applied one to equation 2.13. Since both analyses were based on the Dupuit assumptions, the results were similar.

Dagan (18) and (19) developed a falling water table equation for deep isotropic and anisotropic soils from potential theory. His solution used a step recharge input.

### 2.1.2. EMPIRICAL STUDIES

Bouwer and van Schilfgaarde (20) proposed that a steady state equation could be integrated with respect to time to provide a transient drainage equation. Some assumptions were necessary:

1. The water table falls without change in shape, and therefore the flux per unit area of water table is uniform between the drains.

2. The instantaneous drainage rate is the same as the steady state drainage rate for a particular mid-point water table height.

These two assumptions permit the authors to write:

\[
\frac{d_m}{dt} = -R
\]

\[\ldots(2.18)\]

Since, as the authors point out, the water table initially falls more rapidly near the drains, and later, more rapidly at the mid-point,
the above equation is modified to include a constant representing the ratio of the average flux to the flux at the mid-point. The modified equation is:

$$ R = -\int c \frac{dm}{dt} $$  ...(2.19)

This equation, the authors suggest, can be integrated over a distance of water table drop for which $c$ is a constant. Any known relationship between successive steady states of $m$ and $R$ can be used. As two examples, the authors integrated equation 2.4 to yield:

$$ \frac{K t}{f} = 2.3 c S^2 \log_{10} \frac{m_0 (m_t + 2d_e)}{m_t (m_0 + 2d_e)} $$  ...(2.20)

and equation 2.5 to yield:

$$ \frac{K t}{f} = c S \ln \frac{m_0}{m_t} F(r/S, d/S) $$  ...(2.21)

van Schilfgaarde (11) notes that equation 2.21 was also derived by Kirkham (21) using potential theory for a model that included fictitious frictionless membranes.

Bouwer and van Schilfgaarde (20) compared the results of integrated steady state equations with other transient flow equations. They found quite close agreement between equations (2.20) and (2.17).

In a discussion of the factor $c$, the authors report briefly on a number of studies that suggest that $c$ drops rapidly to 1 from a value of about 3 following ponding, and drops below 1 for $m/S$ values less than 0.15. For $m/S$ values between 0.02 and 0.08, a value of 0.8 for $c$ is suggested.

Dylla (22) used the technique of Bouwer and van Schilfgaarde
to integrate the ellipse equation. He developed a set of drain spacing prime curves for various distances from the drains to the impermeable layer. van Schilfgaarde also integrated equation (2.5) using the above method but applying a forcing function that represents an impulse.

The solution is:

$$m_N = \frac{A}{f} \left[ \exp(1/A) - 1 \right] \sum_{n=1}^{N} \frac{nP \exp \left[ - \frac{(N - n + 1)/A}{A} \right]}{n}$$  ...(2.22)

where \( n \) is a selected time increment. \( P \) is a steady precipitation rate for the time increment. \( A \) equals \( fF/S/K \) and can be considered to be a reservoir coefficient.

Luthin (23) proposed an empirical equation for the falling water table based on some observed relationships in field and model studies. These four relationships used were:

1. The rate of flow into a drain is directly proportional to the height of the water table above the tile lines.

2. The rate of flow into a drain is independent of the spacing for equal heights of the water table at the mid point.

3. The rate of flow is independent of drain diameter.

4. The drop of the water table close to the drains is a negligible volume compared to the total volume between the drains.

The equation, further modified by Luthin and Wortell (24) to conform to an elliptical water table is:

$$\frac{Kt}{fa} = S \left[ \ln \frac{m_0}{m_t} \right] \frac{\pi}{\ln a}$$  ...(2.23)

where \( a \) is the slope of the linear relationship between mid spacing water table height and the rate of flow, and \( fa \) is the average drainable
pore space.

2.1.3. STUDIES THAT INCLUDE THE EFFECT OF THE CAPILLARY FRINGE

Laboratory models have been constructed by a number of researchers to study parallel drain systems. Models using porous materials and electric analogues have been helpful in determining the contribution of the capillary fringe to drainage and also the manner in which the soil pores are drained.

Inthin and Worstell (25) using a full scale sand tank simulating a twenty foot drain spacing found that the seepage in the capillary zone was significant.

Grover and Kirkham (26) reported on a glass bead - glycerol model in which 2 mm. diameter beads were treated with silicone to minimize the capillary fringe. Nevertheless, a fringe thickness of 0.75 cm. existed and which compared to a capillary fringe of 0.75 feet in fine sandy soil. The height to the surface of saturation was measured rather than the water table height in the results of tests. Dimensionless equations were derived from the model data which can be used to solve field problems.

Bouwer (27) used an electrical resistance network to study flow above the water table in the drainage of shallow homogeneous soil. He reasoned that since the depth of the capillary zone added a greater cross-section for flow but did not add to the head producing flow, the effect of this zone was greater for shallow soils than for soils having a deep impermeable layer. He suggested that the effect of the capillary fringe could be taken into account by lowering the impermeable layer an amount equal to the fringe thickness. He pointed
out that the contribution of flow in the capillary fringe when it extends into the topsoil would be magnified because of the greater hydraulic conductivity of this layer. With the mid-spacing water table at the top of the subsoil and the capillary fringe extending everywhere to the surface, Bouwer (28) found the effect of the flow in the capillary fringe to be sufficient to increase the drainage coefficient from 1.09 to 1.73 cm. per day for a topsoil five times more permeable than the subsoil.

2.1.4. FIELD STUDIES

Field studies have been carried out under many soil and climatic conditions.

Two studies on lake bed soils in Ohio have been extensively analysed and reported.

Goins (29) reported a study carried out on Napanee Silt Loam near Tiffin, Ohio, in which drain depths of two and three feet and spacings of thirty and sixty feet were compared. Significant differences in tile flow were found for different crops. Drain runoff for the deep-narrow arrangement was twice the runoff for the shallow-wide arrangement. The shallow-narrow and deep-wide arrangements resulted in similar runoffs. It was found that when soil moisture was replenished, tile flow response to rainfall was immediate, and the rising limb of the hydrograph was linear with time except for low or variable rainfall.

Goins and Taylor (30) reporting on the same study noted that the shallow drainage systems were equally effective in draining the soil rapidly following storms. They also found that the hydrograph
peaks immediately following a period of low soil moisture were
apparently affected by a rapid drainage of water through shrinkage

The authors found an approximately linear relationship
between water table height and tile flow for each arrangement when
flow was greater than two cubic feet per foot of drain per day.

The hydraulic conductivity was estimated using an electric
analog. Applying boundary conditions from field data, the estimated
conductivities were approximately four times those obtained by the
auger hole method. The average estimated conductivity was 0.88 inches
per hour.

Taylor and Goins (31) reported a study carried out on
Toledo Silty Clay Loam near Sandusky, Ohio. The site was drained
with a system of parallel drains forty feet apart and thirty inches
deep. A water table was established near the surface on four occasions
using sprinkler irrigation, and the water table recessions were
recorded. Water table depths measured 6, 12, and 20 feet from the
drains differed significantly for only two of twenty-nine profile
measurements, indicating that it was essentially flat in this region.
The authors suggested that the tendency of the backfill to act like
an open ditch, and the effect of deep seepage contributed to the
flatness of the water table.

In discussing water removal rates, the authors could not
fully explain the high drainage rate when the water table was near
the surface in terms of seepage below the water table.

Schwab et al. (32) described a field experiment also near
Sandusky, Ohio, and on Toledo Silty Clay soil. This study, initiated in 1957 consisted of four replicates of four drainage treatments, namely, no drainage, surface drainage, surface and tile drainage, and tile drainage. The depth and spacing of parallel drains was respectively, three feet and forty feet. Sprinkler irrigation was used to simulate rainfall and raise the water table. Equipment was installed to measure precipitation, tile flow, surface runoff, water table profiles and soil moisture.

Hoffman and Schwab (33) used equation (2.17) and data from the above experiment to compute the effective hydraulic conductivity for various water table heights. In applying this equation, an impermeable layer was assumed to exist six feet below the ground surface, and the water table was assumed to be essentially flat. A method using the same equation was outlined to obtain the required drain spacing for a different rate of water table draw down. Curves of tile flow versus mid spacing water table height, tile flow versus time after stop of irrigation and mid spacing water table height versus time were presented.

Schwab and Fouss (34) reporting on the above experiment noted that the crop grown had a considerable effect on tile flow and surface runoff. In their study, they found that runoff from corn was less for surface drained plots than for tile drained plots whereas runoff from fescue was about equal for the two methods of drainage. They also noted that surface and tile drainage complemented each other giving the highest total runoff. Hoover and Schwab (35) conducted a statistical analysis of sixteen years of records from the drainage experiment near Tiffin, Ohio. Their analysis showed that
daily flow rates for corn preceded by oats was higher than corn preceded by second year meadow, suggesting that the previous years crop could affect drainage. No significant difference was found between the two foot and three foot depth of drains. However, the seasonal runoff was fifty percent greater for the 30 foot than for the 60 foot spacing.

Tu and Broughton (36) reported on an experiment in which drain depths of 2.5, 3.5 and 4.5 feet were compared at 20, 60 and 120 foot spacings on sandy loam and 20, 100 and 200 foot spacings on clay soil.

In comparing draw down times with mathematical theory, the authors found that both the ellipse equation (equation 2.3) and Glover's equation (equation 2.14) predicted a narrower spacing than actual. Their plotted water table profiles indicate that the water tables drop with little change in shape. The greatest change in shape being in the first four hours following ponding for all spacings.

Hore and Gray (37) measured some physical properties of Brookston clay loam on a site near Chatham, Ontario. Using the piezometer method, they found hydraulic conductivity values for the first and second foot to be 2.4 and 4.3 inches per hour respectively. Corresponding values of non capillary porosity found were 0.089 and 0.067.

W. R. Johnston et al. (38) compared four falling water table equations with field data taken on silty clay soil in the San Joaquin Valley, California, where tile drain spacings varied from 187 to 1200 feet.
They found that the van Schilfgaarde equation (2.17) gave the best prediction of actual draw down times. The Luthin and Worstell equation (2.23) underestimated the time except for the first period following ponding, and the integrated Toksoz and Kirkham equation (2.21), and integrated Hooghoudt equation (2.20) overestimated the draw down time by 60 to 70 percent. The authors suggest that water is likely lost to the capillary fringe and to evapotranspiration when the water table is near the root zone. This would explain an apparent higher draw down rate at high water table stages.

2.2 WATER BALANCE MODELS

A depth of soil can be considered to provide two storages for water, gravitational and non gravitational. Gravitational storage includes ground water below the water table plus gravitational water in the capillary fringe. Non gravitational storage holds water that will not drain out by gravity and the non gravitational storage capacity is the field capacity of the soil. Drainage studies that are concerned with the response of a drainage system to a continuing precipitation pattern must keep an account of the water stored in these two storages.

Ayers (39) discusses soil moisture and the problems of accounting for it in these two storages. He notes that in terms of the volume of water stored in non gravitational storage, the wilting point is a satisfactory lower limit to this storage capacity. Although some vegetation can remove water at greater tension than the fifteen atmospheres of tension associated with the wilting point, the amount of water removed is negligible. On the other hand, he points
out that the field capacity level is not a clearly defined division between gravitational and non-gravitational water. Some water may be in transition between non-gravitational and gravitational storage, and could at a later time or different location, replenish depleted non-gravitational storage. The amount of water stored between the wilting point and field capacity is termed "available moisture" for plants. However, plants may also use water from transient storage or gravitational storage and conversely, all "available moisture" may not be accessible to plants due to limited root development.

Ayers suggests that water in transient storage affects infiltration rates and therefore also surface detention and overland flow.

2.2.1. SOIL MOISTURE BUDGETS

If the non-gravitational storage is assumed to be replenished before water goes to gravitational or transitional storage then a budgeting system can be employed to keep account of the soil moisture in this storage. In addition to precipitation, the actual evapotranspiration rate must be known.

Penman (40) proposed an empirical method for the computation of evaporation from open water. His equations include the drying effect of the air and the solar energy received. He related the air drying effect to daily run of the wind at three meters high and the saturated vapour pressure of the air at mean air temperature and mean dew point temperature. The solar energy received was found to be related to the radiation that would be received in the absence of an atmosphere; the radiation lost; the daily hours of bright sunshine
and the saturated vapour pressure of the air at mean dew point.

The potential evapotranspiration rate was found to be related to the open water evaporation rate by a factor that ranges between 0.6 and 0.8 depending upon the time of year.

Shaw (I41) studying evapotranspiration under corn in Iowa found an empirical relationship between actual evapotranspiration and class "A" pan evaporation that gave good results for the portion of the season after June 7. Prior to this date he found that an accurate budget could be maintained by assuming a daily evapotranspiration rate of 0.1 inch.

Thornthwaite and Mather (I42) provide a method to compute potential evapotranspiration using mean temperatures, day length and geographical location. This relationship which they give in tabular form can be expressed for a latitude of 42° N as:

\[
\begin{align*}
PE &= 0.0033 \times l \times (T_m - 32) \quad 32 \leq T_m \leq 56 \\
PE &= 0.001423 \times l \times (T_m - 37) \quad 56 \leq T_m 
\end{align*}
\]

(2.2kl)

(2.25)

where PE is potential evapotranspiration in inches per day, l is a day length factor, and T_m is mean daily temperature in °F.

Thornthwaite and Mather also provided a water budgeting method that related soil moisture retention to accumulated potential evapotranspiration. This relationship, also given in tabular form is illustrated in Fig. 2.3 in graphical form. It is based on an assumed logarithmic reduction in actual evapotranspiration with reduced soil moisture retention.

A modified version of equation 2.24 was shown to be capable of predicting soil moisture levels in a test carried out in
Fig. 2.3 THORNTHWAIT MOISTURE RETENTION RELATIONSHIPS
South Western Quebec by Lake (43). Lake assumed that the actual evapotranspiration rate was equal to the potential rate until one half of the available soil moisture was depleted, at which point, evapotranspiration ceased.

The effect of soil moisture levels on evapotranspiration rate is difficult to determine as pointed out by Veihmeyer et al. (44). In their lysimeter studies they were not able to correlate evapotranspiration with soil moisture levels above the permanent wilting percentage.

Pistor (45) compared the potential evapotranspiration computed by three methods at Harrow, Ontario. Included were the Penman and Thornthwaite methods described above and the Holmes-Robertson method which related potential evapotranspiration to evaporation from a black bellani plate atmometer. He found a low correlation between the computed values of daily potential evapotranspiration but a high correlation between the computed monthly values. For example, he obtained a correlation coefficient of .913 for the monthly potential evapotranspiration computed by the Penman and Thornthwaite methods.

He applied the Thornthwaite daily bookkeeping method and computed five day, ten day and thirty day actual evapotranspiration with the three methods. Highest correlation between computed and measured actual evapotranspiration was obtained with the Thornthwaite method.

Wiser and van Schilfgaarde (46) used the method described by Thornthwaite and Mather in conjunction with equation (2.22) in
order to compute daily water table heights using daily precipitation records. Precipitation in excess of available soil moisture storage capacity was used as input to equation (2.22).

Vaigneur and Johnson (47) carried out a similar study using the water budget of Shaw (41) in place of that of Thornthwaite and Mather.

Taylor and Watts (48), using data from a field study in the Willamette Valley, Oregon, developed a drainage mathematical model which included daily evapotranspiration and computed changes in water table height for time intervals of from one to four hours using an empirical relationship which was obtained from measured water table recession curves.
CHAPTER III
THE FIELD EXPERIMENT

In 1957, the Agricultural Engineering Department of the Ontario Agricultural College (now the School of Agricultural Engineering of the University of Guelph), initiated a field drainage study on a Brookston Clay soil near Merlin, Ontario. The plan of the site is shown in Fig. 3.1. The area contained three inch diameter tile drains at a spacing ranging from 60 to 79 feet. The outlet ditch was such that the water level in it would seldom rise to the level of the drain outlets.

The discharge from the five drains numbering 1 to 5 was recorded for the frost free period for eleven years from 1957 to 1967. This was recorded using Cassella flow meters equipped with proportioning weirs for which discharge varies linearly with stage. (see Fig. 3.2) Rainfall at the site was recorded with one Bendix Fries weighing recorder. The flow meters were equipped with seven-day clocks and charts, and the rain recorder with a twelve hour chart. However, the rain recorder chart was normally changed at two or three
Fig. 3.1 SITE PLAN OF DRAINAGE EXPERIMENT
Fig. 3.2 CASELLA RECORDING FLOW METER
In 1961, the area drained by drain number 3 was reduced by installing drain A and drain B. This, of course, also reduced the area drained by drains 2 and 4. At the same time, equipment was installed to record the mid spacing water table height between drains 4 and 5 and between drains A and 3. These recording wells were 8 inches in diameter and 36 inches deep. The casings were surrounded with a 2 inch thick sand filter and a fibreglass filter. The water level was recorded with a float activated recorder having a seven day chart.

A typical drain profile is shown in Fig. 3.3 together with a profile of the soil horizons.

An analysis of the soil profile and particle size distribution was carried out by the Department of Soil Science, Ontario Agricultural College. The soil was found to be uniform over the area and representative of the Brookston Clay as it occurs in Kent and Essex counties. The profile description and particle size distribution for one of two locations studied on the site is given in table 3.1.
<table>
<thead>
<tr>
<th>Horizon</th>
<th>% Sand</th>
<th>% Silt</th>
<th>% Clay</th>
<th>Textural Class</th>
<th>Depth (in.)</th>
<th>Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ac</td>
<td>19.2</td>
<td>31.6</td>
<td>49.2</td>
<td>Clay</td>
<td>0 - 8</td>
<td>Crumb</td>
</tr>
<tr>
<td>G1</td>
<td>15.0</td>
<td>25.8</td>
<td>59.2</td>
<td>Clay</td>
<td>8 - 18</td>
<td>Massive Plastic</td>
</tr>
<tr>
<td>G2</td>
<td>15.8</td>
<td>23.6</td>
<td>60.6</td>
<td>Clay</td>
<td>18 - 28</td>
<td>Massive Plastic</td>
</tr>
<tr>
<td>C</td>
<td>14.0</td>
<td>27.6</td>
<td>58.4</td>
<td>Clay</td>
<td>28 +</td>
<td>Clay Till, Massive</td>
</tr>
</tbody>
</table>

TABLE 3.1
SOIL PROFILE DESCRIPTION
CHAPTER IV
THEORY AND DEVELOPMENT OF THE DRAINAGE MODEL

4.1 FIELD DATA SELECTION

Of the five original drains that were equipped with flow meters, the area drained by No. 1 and No. 5 remained unchanged for the duration of the record period. Mid-span water table readings were taken adjacent to drain No. 5 for the years 1964 to 1967 inclusive, and therefore it was decided to model this drain.

In order to verify the model, it was necessary to reserve a portion of the data to be used only as a check on the final computer model. In selecting the check data, important characteristics were selected to be represented in both model development and check data. Table 4.1 lists these characteristics and the selection made. The tile flow records for 1957 were not available until after the development period and therefore were chosen as check data. The 1958 data contained no runoff events.
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Water table records available.</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Tile runoff rates in excess of 0.42 inches per hour.</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Late summer and fall tile runoff.</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Dry periods preceding runoff events.</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Multiple peak events</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Crops</td>
<td>tomatoes wheat soybeans soybeans oats wheat corn soybeans oats wheat corn alfalfa alfalfa alfalfa corn soybeans oats wheat alfalfa</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other remarks</td>
<td>missing data</td>
<td>missing data</td>
<td>missing data</td>
<td>missing data</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Selection</td>
<td>Check Model Model Check Check Check Check Model Check Check Model Model</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.2 THE DRAINAGE MODEL WATER BALANCE

In order to simplify the very complex soil moisture regime, it was assumed that the water balance could be described in terms of two major reservoirs or storage phases. That is, available soil moisture storage and ground water storage. Between these two phases would exist the unsaturated capillary fringe, and at times there would be water in transient storage above the water table. In general, the available soil moisture phase would be balanced by the addition of precipitation and subtraction of evapotranspiration with the excess going to ground water storage. The losses from ground water storage would include deep seepage, seepage to other drains, and tile drain runoff. Limiting of infiltration or the filling to capacity of ground water storage would result in surface runoff. Fig. 4.1 illustrates this general water balance model.

![Diagram of Water Balance Model](image)

**Fig. 4.1 GENERAL WATER BALANCE MODEL**

4.3 THE DEVELOPMENT OF THE RATING CURVE

The steady state drainage problem is one of a water table in equilibrium with steady rainfall and tile runoff. A curve formed by
a succession of points relating mid-spacing water table height to tile runoff rate would constitute a rating curve for a drainage system functioning in steady state.

Bouwer and van Schilfgaarde (20) have shown that if the flux is uniform between the drains, then a transient water table can be approximated by a series of steady state relationships between mid-spacing water table height and tile runoff rate.

The field data for the years 1964 and 1957 contain corresponding readings of mid-spacing water table height and tile runoff rate. These were plotted as shown in Fig. 1.2 and a rating curve was drawn. It has a shape quite similar to one reported by Hoffman and Schwab (32) for a similar soil.

This rating curve was developed from hydrograph recessions that were not affected by precipitation. If the mid-spacing flux was less than the flux near the drains for the portions of the hydrographs used, then the curve would include the flux factor described by Bouwer and van Schilfgaarde. If this were the case, the rating curve would over-estimate steady tile flow at high water table levels. This problem was left to be resolved by subsequent tests which failed to give evidence of an included flux factor effect.

The rating curve was described by four straight lines which could easily be adopted to a computer programme. The concept of a rating curve described by two linear relationships between mid-spacing water table height and tile flow for the cultivated zone and the subsoil zone was reported by Luthin (23) as suggested to him by Taylor.

The development data did not include tile runoff rates that
Fig. 4.2 DRAIN NO. 5 RATING CURVE

- Extrapolated portion
Data from 1964 and 1967
would verify the rating curve in the zone above 0.03 inches per hour. The maximum runoff rate was arbitrarily limited by the dashed line shown in Fig. 4.2.

4.4 A THEORETICAL PHYSICAL MODEL OF THE FIELD DRAINAGE SYSTEM

In order to further study the rating curve on a theoretical basis and also to complete the mathematical model of the drainage system, it was necessary to formulate a theoretical physical model that could be expected to be very nearly equivalent to the actual field drainage system.

Drain No. 5, situated slightly off centre of a 72 foot drainage width was approximated by a drain in the centre of a 70 foot width in the theoretical model.

It is known from hydraulic conductivity measurements on similar soils that the conductivity decreases with depth. Hore and Gray (37) found this to be so for Brookston clay loam as did Taylor and Goins (31) for Toledo silty clay loam. If an impermeable layer is assumed to exist just below the zone that contributes significantly to seepage to the drains, then a hydraulic conductivity can be assigned to the zone that is equivalent to a diminishing hydraulic conductivity with depth and a deeper impermeable layer. Hoffman and Schwab (33) assumed an impermeable layer at a depth of 6 feet in their study. In this study, an impermeable layer was assumed at a 50 inch depth. Because of the change in the rating curve between the subsoil and cultivated zones, it was decided to consider these as two separate zones in the theoretical model. The theoretical model is shown in Fig. 4.3.

An attempt was made to compute the drainable porosity of
the two zones using the method outlined by Taylor (19). By selecting an increment of water table drop and dividing the distance of the drop into the depth of water removed, the drainable porosity of that increment of soil is determined. This method was applied to the June 1964 runoff event to obtain a value of 0.023 for the subsoil. A corresponding value for the cultivated zone could not be obtained using this method for the following reasons.

1. Water levels in the recording well would lag a rapidly rising or falling water table.

2. There were no records of a water table height near the top of the cultivated zone.

3. The computed drainable porosity would be influenced by the development of a capillary fringe as the water table fell from the surface.

4. The average water table height which was not known should be used to eliminate the error due to non uniform flux between the drains.

5. Although the water table is expected to be essentially flat between the drains, it would not be entirely in the cultivated zone except at high mid spacing levels.

Another procedure to estimate the drainable porosity of the cultivated zone was attempted. Some hydrograph peaks were selected for which a water balance could be computed by adding precipitation and subtracting tile runoff. It was found that tile runoff accounted for approximately half of the total runoff for the peaks selected. Using the rating curve to predict the water table heights for the June 1960
event, the drainable porosities indicated by the rise and fall of the water table were 0.23 and 0.115 respectively. Due to the uncertainties of the method it was decided that it would be necessary to arrive at the drainable porosity by trial and error with the completed mathematical model, starting with a trial value of 0.12.

Equation 2.4, the ellipse equation was considered to apply to seepage in the subsoil zone since the zone is shallow and wide. Substituting the values of \( h, 28, 0.0024 \) and \( \theta I 0 \) for \( m, d, R \) and \( S \) respectively yields a value for \( K \) of 0.002 inches per hour. This value compares favourably with computed and measured values reported by Hoffman and Schwab (33) for Toledo silty clay soil.

Assuming that this computed value for the hydraulic conductivity is a good estimate of both the horizontal and vertical conductivities, the maximum possible tile flow under ponded conditions can be calculated using equations 2.8 and 2.9. Since these equations yield a maximum runoff rate of 0.0025 inches per hour it must be concluded that runoff rates ranging up to 0.05 inches per hour occur due to horizontal seepage in the cultivated zone and vertical seepage near the drains in a zone of apparent high vertical conductivity.

Taylor and Coins (31) performed calculations to show that the cultivated zone could not support a horizontal seepage rate that would substantiate this drainage mechanism. However, Bower (27) demonstrated that seepage in the unsaturated zone is quite significant and it could be reasoned that the effective depth of flow is 8 inches. Taking the head producing flow as 10 inches by adding two inches of favourable land elevation difference, a length of 35 feet and a flow
of 0.05 inches per hour, Darcy's law yields a hydraulic conductivity of 110 inches per hour.

The assumption of a constant depth of flow is consistent with a linear rating curve since the horizontal seepage rate varies linearly with piezometric head.

4.5 TEST OF THE DRAINAGE WATER BALANCE

Since rainfall data was available on an hourly basis and since hourly changes in the tile runoff hydrographs were measurable, it was decided that the drainage water balance should be computed on an hourly basis.

In order to test this decision and test the principle of the use of a rating curve, a simplified computer programme was written. Using the computed values for drainable porosity, the programme made hourly water table adjustments by adding precipitation and subtracting tile runoff. Constant deep seepage and evapotranspiration rates were chosen arbitrarily and subtracted on a daily basis. The justification for a constant daily evapotranspiration rate was found in the work of Shaw (41). He found that a constant rate of 0.1 inch per day was the best estimate for bare soil in Iowa in the months of April and May.

The performance of this model on a portion of the development data confirmed that the principle of hourly computations was sufficiently accurate and the use of the rating curve was sound.

4.6 THE COMPLETE WATER BALANCE DEVELOPMENT

Since soil moisture is replenished before additions to ground water occur, the error in estimate of soil moisture retention is added to the error in estimate of ground water storage. Errors in these
estimates are self compensating in time, but in order to accurately predict the first peak of a hydrograph following a dry period, the soil moisture balance is of critical importance.

Existing water balance models have been reviewed in Chapter II. All of these require climatological data at the site that is not available for this study. The Thornthwaite method requires mean daily temperature only, and this could be estimated at the site by averaging the mean daily temperatures taken at Chatham and Leamington. The site is approximately halfway between these two stations and the proximity to Lake Erie is equal to the average proximity of the stations.

The widespread use of the Thornthwaite method and the favourable comparisons found by Pistor (45) suggested that it would yield results of comparable accuracy to any other method.

The Thornthwaite water balance method assumes that actual evapotranspiration is reduced according to a logarithmic relationship with reduced moisture retention.

In order to compute the available moisture retained, one must know the storage capacity for available moisture that is accessible to plant roots or to the forces of evaporation.

Webber and Tel (50) give percentages of available moisture by depth for Brookston Clay Loam. These were combined with typical bulk density measurements as reported by Hore and Gray (36) to obtain available moisture in inches. They are summarized in table 4.2.

It was decided to represent this available moisture distribution by two zones each holding 2 inches of available moisture, but since Shaw (41) considered rooting depths to 5 feet, a third zone
holding 2 inches of available moisture was added to represent the depth of the theoretical physical model.

**TABLE 4.2**

**AVAILABLE MOISTURE IN BROOKSTON CLAY LOAM SOIL**

<table>
<thead>
<tr>
<th>Depth (inches)</th>
<th>Bulk density</th>
<th>Available moisture (%)</th>
<th>Available moisture (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 6</td>
<td>1.39</td>
<td>19.0</td>
<td>1.6</td>
</tr>
<tr>
<td>6 - 12</td>
<td>1.39</td>
<td>13.0</td>
<td>1.1</td>
</tr>
<tr>
<td>12 - 18</td>
<td>1.46</td>
<td>7.0</td>
<td>0.6</td>
</tr>
<tr>
<td>18 - 24</td>
<td>1.46</td>
<td>6.0</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>TOTAL 3.8</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A computer programme was written that included the Thornthwaite potential evapotranspiration model (equations 2.24 and 2.25) and the equation describing the Thornthwaite moisture retention curve for a storage capacity of 2 inches. Three zones of accessible soil moisture storage of 2 inches available moisture each were included in the model. The addition or reduction in the number of zones was arbitrarily chosen according to stage of crop development.

The testing of this programme on the development data yielded promising results but indicated that a further refinement was necessary. The evapotranspiration model overestimated actual evapotranspiration or bare soil. This was not surprising since both Shaw (41) and Pistor (45) reported difficulties in estimating actual evapotranspiration during May.

It was necessary to further reduce the accessible zone during this period, but since there were two fields, each with a different crop, it was deemed necessary to maintain a separate water

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balance for each field. This improvement made it possible to account for such crop effects as the harvesting of grain and hay crops in early summer.

A relationship was found between the slopes of the moisture retention curves shown in Fig. 2.3. This equation and the general equation for the moisture retention family of curves are as follows:

\[
s = \frac{1.06}{A_c} \quad \ldots(4.1)
\]

\[
AE = Ar_2 - Ar_1 \quad \ldots(4.2)
\]

\[
\ln Ar_2 = \ln Ar_1 - s(PE) \quad \ldots(4.3)
\]

where \( s \) is the slope of the logarithmic retention line, \( A_c \) is the moisture storage capacity in the accessible zone, \( PE \) and \( AE \) are potential and actual evapotranspiration respectively. \( Ar_1 \) and \( Ar_2 \) are soil moisture retention values in the accessible zone before and after subtraction of \( AE \).

With these equations, it was not necessary to maintain a separate water balance in separate zones. A water balance was maintained for the accessible zone and for the total soil moisture phase. The accessible zone was adjusted in increments of 0.5 inches of available moisture depending on stage of crop development.

4.7 MODEL IMPROVEMENTS BASED ON PERFORMANCE

All further improvements to the model were based on its performance in predicting the tile flow hydrographs in the development data. For each consistent weakness in the model performance, adjustments were proposed. Table 4.3 lists the weaknesses and adjustments considered.
### TABLE 4.3

**MATHEMATICAL MODEL WEAKNESSES OF PERFORMANCE**

<table>
<thead>
<tr>
<th>Weakness</th>
<th>Proposed Corrections</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Under-estimated peaks and recession curve too flat.</td>
<td>Reduce drainable porosity.</td>
</tr>
<tr>
<td>4. Over-estimated second peaks of multiple peak storms.</td>
<td>Limit infiltration capacity. Reduce flux factor to 1.0 or less.</td>
</tr>
<tr>
<td>8. Under-estimated peak in warm weather.</td>
<td>Add precipitation to soil before subtracting evapotranspiration. Provide seepage to drains from transient storage.</td>
</tr>
</tbody>
</table>
It is evident that some of the weaknesses are inter-related and some of the proposed corrections are beneficial to more than one problem. Proposed corrections that were not of consistent benefit generally were not implemented.

In order to positively correct the weaknesses, it was necessary to consider them in an order so that one could be sure that they were being properly identified. They could be identified in the order in which they appear in the table, and are discussed below.

1. Over-estimated tile runoff.

This error is isolated from an error in estimating soil moisture retention since the latter error could be computed at the start of an event. It was quite consistent and therefore indicated that either surface runoff or horizontal seepage was occurring. Introducing surface runoff would affect the water table peak and tile runoff peak rate. Increasing deep seepage would accomplish little since the drainage water balance error was occurring over too short a time period. Also, increasing deep seepage would adversely affect weakness #3. Introducing horizontal seepage to surface drains appeared to be the best solution.

It has been shown that horizontal seepage in the cultivated zone is a significant part of the flow mechanism and the rate of seepage is directly proportional to the water table height in this zone. There are small surface ditches perpendicular to the tile drains at an unspecified but wider spacing. The seepage rate to these drains would be proportional to the seepage rate to the tile drains. A horizontal
seepage runoff rate of 0.4 times tile drain runoff rate was selected and applied to tile runoff at all depths.

Evidence of this horizontal seepage loss is also found in the work of Hoffman and Schwab (33). They found that the water table dropped more rapidly on plots with surface drainage and the increased rate of drop extended to a depth of 1.5 feet.

An additional correction that was applied and is helpful with other weaknesses, is the allowing of replenishment of the soil moisture phase from the capillary fringe. Studies such as that carried out by Bouwer (27) give evidence that the distance above the water table for which the capillary fringe would have a significant capillary conductivity would be as much as one foot. Assuming, then, that the capillary fringe could supply water at a rate equal to the evapotranspiration rate to a height of one foot, the mathematical model was revised to permit the replenishment of a fraction of the daily potential evapotranspiration approximately equal to the percent of the root zone depth within the capillary fringe.

2. Under-estimated peaks, and recession curves too flat.

These are clearly the symptoms of too low a drainable porosity, provided that the flat recession curve is not related to weakness #1, or the under-estimation of the peak related to an under-estimation of soil moisture retention.

A drainable porosity of .116 for the cultivated zone gave the best results.

3. Under-estimated peaks following intense rainfall on low water table.

A few events fell into this category and were diagnosed
as the effect of a rapid rise of a flat water table resulting in a high, flat water table which in turn fell with greater flux near the drains than at mid spacing. A combined water table shape factor and flux factor was devised such that it had the value of 1.1 at low water table levels, a value of approximately 0.5 when at the top of the subsoil zone and increased in value upon the rise of the water table in the cultivated zone in proportion to the rise in this zone. It could achieve a peak value of approximately 1.5 and returned to 1.1 in approximately five hours of water table recession. It functioned as a flux factor only in the cultivated zone. An example of this problem and the improvement with the flux factor is shown in Fig. 4.4.

4. Over-estimated second peaks of multiple peak storms.

This problem was first thought to be related to the non-uniform flux problem, but could only be diagnosed as the effect of a reduced infiltration capacity of a wet soil. Some improvement was obtained by applying an arbitrary infiltration capacity of 0.15 inches per hour for selected periods of time as indicated by rainfall patterns. An example of the effect of limiting infiltration is shown in Fig. 4.5.

5. Under-estimated soil moisture retention in early spring.

This problem and the revisions of the model to permit a reduced accessible soil zone have been discussed in section 4.6. This was not, however, the complete solution. During periods when the moisture retention was maintained at a high level by frequent rains the accessible zone size had little effect on the actual evapotranspiration rate. Based on the discovery by Shaw (41) that the field capacity of the soil in April was higher than in June, and reduced as the soil
warmed up, the starting values of field capacity were increased an amount that ranged from 0.25 to 0.75 inches, depending on the March mean temperature. This increment was permitted to decrease at a rate proportional to the daily potential evapotranspiration until the base value was reached. The result was that the soil could remain close to field capacity for a period without precipitation occurring.

6. **Under-estimated soil moisture retention in summer.**

The maximum available soil moisture was reduced from 6 inches to 5 to improve the prediction of summer runoff events.

7. **Under-estimated slope of recession in hot weather.**

There was evidence that the slope of hydrograph recession curves increased during mid day in hot weather. The replenishment of soil moisture by the capillary fringe was further justified.

8. **Under-estimated peak in warm weather.**

The Thornthwaite method of keeping the moisture budget subtracts the daily potential evapotranspiration from the daily precipitation before adding the balance to the soil. This resulted in some hydrograph peaks being under-estimated. To more accurately simulate the true situation, a surface retention storage was added such that the amount retained on the surface would not exceed the daily potential evapotranspiration. The maximum retention capacity ranged from 0.05 to 0.15 depending on the stage of crop development.

There was evidence in a few events that tile runoff was caused by seepage from transient storage. No attempt was made to account for this in the model.
The complete water balance model after all revisions were made is as shown in Fig. 4.6. The three storage phases are surface retention, available soil moisture storage and ground water storage. The available soil moisture phase contains the accessible zone which varies with the stage of crop development and for which a separate budget is maintained. This soil moisture phase may be larger in early spring than later in the year as represented by the additional area under the broken line in Fig. 4.6.

The capacity of the surface retention phase is related to the stage of crop development, and is assumed not to exceed the daily potential evapotranspiration.

The movement of water and the gains and losses are shown on the diagram. The precipitation is added, filling each zone in turn. If all of the zones are filled, the excess is surface runoff which is a loss from the system. The other losses are evaporation from surface retention; surface runoff of hourly precipitation in excess of the infiltration capacity; actual evapotranspiration loss from the accessible zone; horizontal seepage, deep seepage and tile runoff.

Not shown on the water balance diagram is the slow release of water from the soil moisture storage zone to ground water storage in early spring.

A flow diagram of the computer programme is shown in Fig. 4.7. The computer programme was written in the FORTRAN IV language for an IBM 360/40 computer system, and is shown in the appendix, together with the notation used.
Fig. 4.6 WATER BALANCE OF DRAINAGE MODEL
Initial water budget values and initial values of programme constants were provided at the beginning of a period for computation, usually the period from April to October of one year. By selecting a known starting point such as the beginning of the first runoff event of the year, the values of soil moisture and ground water retention could be determined. Initial values of field capacity were selected as described in section 4.7 and the adjustment of the accessible soil moisture was based on a knowledge of the normal planting dates and maturity or harvesting dates of the crops grown.

Input on a daily basis included the daily mean temperature, day length factor, and daily precipitation for computing PE and P – PE. Indexing was provided for adjustment of the accessible zone.

The computations proceed as outlined on the flow chart. All water balance computations are made in units of hundredths of inches.
Fig. 4.7 COMPUTER PROGRAMME FLOW DIAGRAM

Start

Read initial storage values and constants.

Read daily input.

Compute daily PE, \((P - PE)\). Adjust field capacity (spring).

Subtract daily deep seepage. Add excess water from soil moisture storage to ground water (early spring). Compute water table height. Adjust root zone.

Repeat for each field.

Read hourly precipitation.

Tile flow not possible, \((P - PE) - ve\)

Compute daily AE. Subtract AE from accessible storage.

Repeat for each field.

Tile flow possible

Tile flow not possible, \((P - PE) + ve\)

Add daily \((P - PE)\) to soil moisture phase. Add excess to ground water.

Repeat for each field.

Print daily values. Stored quantities, \(P, PE\).
Repeat for each field.

Repeat hourly:

1. **Compute retention**
   - Subtract retention from PE

2. **Hour = 12**
   - **Hour ≠ 12**
   - **Compute fraction of (P - PE) supplied by capillary fringe.**
   - **Compute daily AE.**
   - **Compute hourly AE and hourly ground water loss through capillary fringe.**

3. **Subtract hourly AE and hourly ground water loss through capillary fringe.**
   - Add hourly P loss excess of infiltration capacity in turn to surface retention; soil moisture phase; ground water until satisfied.
   - **Subtract tile runoff and horizontal seepage for previous hour.**
   - **Compute water table height.**
   - **Compute combined water table shape factor and flux factor.**
   - **Compute hourly tile runoff.**
   - **Compute accumulated tile runoff.**

4. **Print daily and hourly values.**
   - **Plot hydrographs**

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CHAPTER V
RESULTS

Results of this study include the physical properties of the soil and field drainage system that were computed during the development of the model and revealed by the analysis and adjustment phase of the model development. These are summarized in Table 5.1.

The major result of this study is the completed computer programme and its performance in predicting the tile runoff hydrographs for both the model development and check data. The predicted water balances for all of the years are summarized in Figs. 5.1 to 5.10. These graphs show the computed available soil moisture retention and water table (WT) depths below the ground surface throughout each runoff season. Double lines indicate the separate values for the separate fields. A horizontal line is drawn at the 22 inch level through the time periods of actual tile runoff. The model predicts tile runoff when mid-span water table is less than 22 inches deep, therefore, these horizontal lines show the accuracy of the model in predicting the occurrence of tile runoff.
### Table 5.1

Some indicated physical properties and characteristics of the field drainage system

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic Conductivity,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cultivated Zone</td>
<td>110 in./hr.</td>
<td>0.042 in./hr.</td>
</tr>
<tr>
<td>Subsoil Zone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drainable porosity,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cultivated Zone</td>
<td>0.116</td>
<td>0.023</td>
</tr>
<tr>
<td>Subsoil Zone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal seepage to</td>
<td></td>
<td>0.4 times tile</td>
</tr>
<tr>
<td>surface drains.</td>
<td></td>
<td>runoff rate.</td>
</tr>
<tr>
<td>Uniformity of water table</td>
<td></td>
<td>Uniform except</td>
</tr>
<tr>
<td>flux upon recession.</td>
<td></td>
<td>after a sharp</td>
</tr>
<tr>
<td></td>
<td></td>
<td>rise into the</td>
</tr>
<tr>
<td></td>
<td></td>
<td>cultivated zone</td>
</tr>
<tr>
<td></td>
<td></td>
<td>from a low level.</td>
</tr>
<tr>
<td>Field Capacity</td>
<td></td>
<td>Usually higher in</td>
</tr>
<tr>
<td></td>
<td></td>
<td>April than in</td>
</tr>
<tr>
<td></td>
<td></td>
<td>period from June to November.</td>
</tr>
<tr>
<td>Infiltration Capacity</td>
<td></td>
<td>Reduces to values</td>
</tr>
<tr>
<td></td>
<td></td>
<td>as low as 0.15 in. per hour following</td>
</tr>
<tr>
<td></td>
<td></td>
<td>an intense storm.</td>
</tr>
</tbody>
</table>
These diagrams demonstrate the important role of the soil moisture budget in the model, and the sensitive response of the water table to precipitation following replenishment of soil moisture.

The effect of replenishment of soil moisture from the capillary fringe can be seen in a number of instances where the water table in the zone below the drains recedes at a rate greater than that caused by deep seepage.

These graphs show that the runoff events occurring in June and early July are the ones most commonly missed.

Figs. 5.11 to 5.21 show the predicted and actual hydrographs for the larger runoff events together with the hourly rainfall, i, in histogram form. Shape agreement is good on most of the hydrographs considering the sensitivity of tile runoff rate to water table height and possible errors introduced by variations in rainfall patterns. Runoff events occurring after dry periods such as the 1962 events suggest that some physical properties such as drainable porosity may vary slightly. It is also possible that a dry soil permits horizontal seepage to the drains from water in transient storage. Errors in predicting the shape of hydrographs in early spring are possibly due to the effects of frost zones or melting snow.

The only event in which a ponded condition was predicted was the April 1961 event. The actual hydrograph peak for drain No. 5 was not recorded, but a steady peak similar in shape to the predicted hydrograph was recorded for another drain.

The ability of the model to predict peak runoff rates and 6 hour, 12 hour, and 24 hour average runoff rates and total runoff...
per event was analysed. The predicted and measured values are given in table 5.2. The event numbers are those used in the records. An unnumbered event results from runoff being predicted that did not occur. In some instances the first event of the year could not be predicted due to the lack of a starting point to set the starting values. The columns in this table have been totalled to indicate possible trends in the errors of prediction.

In addition to the error in computing the water balance, and error in relating water table height to tile flow, the error in predicting the quantities include the error in measurement of precipitation and tile runoff rates and the error in assuming uniform areal distribution of rainfall.

The standard deviation of the errors in prediction were computed. These are tabulated in Table 5.3 for the model development data, check data and combined data. Since the errors did not appear to be related to the size of the quantity measured, the actual rather than percentage error was used. However, errors in predicting runoff tended to be greater for events of long duration than events that were shortened because of a following event. It is expected that the error in measurement of runoff for long periods of low runoff rates could be much larger than the error for short events.

Although the variations between drains is affected by other factors such as the area drained, and the topography of the area drained, a comparison between drain No. 1 and No. 5 was made to give an indication of the inherent variability in the physical system. Drain No. 1 performance was assumed to be an estimate of drain No. 5
performance and the standard deviations of the errors between these two drains were computed and are also given in table 5.3. The standard error in predicting the peak and average runoff rates with drain No. 5 was approximately one half of the standard error using the model. The standard errors in predicting the total runoff quantities were very similar.
### TABLE 5.2
MEASURED AND PREDICTED RUNOFF RATES AND QUANTITIES

<table>
<thead>
<tr>
<th>Year and Event</th>
<th>Peak Runoff Rate in./100 hr.</th>
<th>Average Runoff Rates in./100 hr.</th>
<th>Total Runoff in./100</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M*</td>
<td>P**</td>
<td>M</td>
</tr>
<tr>
<td>1957 1</td>
<td>2.64</td>
<td>2.50</td>
<td>2.63</td>
</tr>
<tr>
<td>2</td>
<td>3.02</td>
<td>3.20</td>
<td>2.92</td>
</tr>
<tr>
<td>3</td>
<td>0.59</td>
<td>0.50</td>
<td>0.51</td>
</tr>
<tr>
<td>4</td>
<td>0.81</td>
<td>0.50</td>
<td>0.62</td>
</tr>
<tr>
<td>5</td>
<td>0.15</td>
<td>0.20</td>
<td>0.15</td>
</tr>
<tr>
<td>6</td>
<td>2.23</td>
<td>2.90</td>
<td>2.59</td>
</tr>
<tr>
<td>7</td>
<td>2.56</td>
<td>2.10</td>
<td>2.18</td>
</tr>
<tr>
<td>8</td>
<td>2.06</td>
<td>1.90</td>
<td>1.74</td>
</tr>
<tr>
<td>9</td>
<td>1.90</td>
<td>3.20</td>
<td>1.67</td>
</tr>
<tr>
<td>10</td>
<td>0.66</td>
<td>0.00</td>
<td>0.59</td>
</tr>
<tr>
<td>11</td>
<td>1.76</td>
<td>0.00</td>
<td>1.28</td>
</tr>
<tr>
<td>12</td>
<td>2.70</td>
<td>0.10</td>
<td>2.06</td>
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<tr>
<td>13</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>14</td>
<td>2.60</td>
<td>2.10</td>
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</tr>
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<tr>
<td>16</td>
<td>2.79</td>
<td>0.10</td>
<td>2.48</td>
</tr>
<tr>
<td>17</td>
<td>2.12</td>
<td>1.00</td>
<td>2.25</td>
</tr>
<tr>
<td></td>
<td>**</td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td></td>
<td>31.68</td>
<td>23.10</td>
<td>23.67</td>
</tr>
</tbody>
</table>

* - M - measured  
** - P - predicted
### TABLE 5.2 - CONTINUED

<table>
<thead>
<tr>
<th>Year and Event</th>
<th>Peak Runoff Rate in./100 hr.</th>
<th>Average Runoff Rates in./100 hr.</th>
<th>Total Runoff in./100</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M*</td>
<td>P**</td>
<td>M</td>
</tr>
<tr>
<td>1959</td>
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<tr>
<td>2</td>
<td>1.76</td>
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<td>1.37</td>
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<td>1.61</td>
<td>1.70</td>
<td>1.16</td>
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<tr>
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<td>0.04</td>
<td>0.30</td>
<td>0.03</td>
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<td>6</td>
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<td>1.68</td>
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<td>0.64</td>
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<td>1.00</td>
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<td>2.72</td>
<td>0.20</td>
<td>1.94</td>
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<td>Year and Event</td>
<td>Peak Runoff Rate in./100 hr.</td>
<td>Average Runoff Rates in./100 hr.</td>
<td>Total Runoff in./100</td>
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<tr>
<td>----------------</td>
<td>-------------------------------</td>
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</tr>
<tr>
<td></td>
<td>M**</td>
<td>P**</td>
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</tr>
<tr>
<td></td>
<td>M</td>
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<tr>
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<td>0.60</td>
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<td>0.51</td>
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<td>2.50</td>
<td>2.72</td>
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<td>0.50</td>
<td>0.60</td>
</tr>
<tr>
<td>9</td>
<td>0.30</td>
<td>0.80</td>
<td>0.26</td>
</tr>
<tr>
<td>10</td>
<td>2.32</td>
<td>2.60</td>
<td>1.94</td>
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<tr>
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<td>1</td>
<td>1.35</td>
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<td>0.79</td>
</tr>
<tr>
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<td>0.84</td>
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<td>0.53</td>
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<td>0.20</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>2.32</td>
<td>1.20</td>
<td>1.46</td>
</tr>
<tr>
<td>Year and Event</td>
<td>Peak Runoff Rate in./100 hr.</td>
<td>6-Hour</td>
<td>12-Hour</td>
</tr>
<tr>
<td>---------------</td>
<td>-------------------------------</td>
<td>--------</td>
<td>---------</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>P</td>
<td>M</td>
</tr>
<tr>
<td>1963</td>
<td>5.10</td>
<td>1.52</td>
<td>0.10</td>
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<td>Year and Event</td>
<td>Peak Runoff Rate in./100 hr.</td>
<td>Average Runoff Rates in./100 hr.</td>
<td>Total Runoff in./100</td>
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<tr>
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<td>-----------------------------</td>
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<tr>
<td></td>
<td>M†</td>
<td>P‌*‡</td>
<td>M</td>
</tr>
<tr>
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<td>0.97</td>
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<td>10</td>
<td>0.93</td>
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<td>10.54</td>
<td>11.14</td>
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<td>---------------</td>
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<td>------------------</td>
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<td></td>
<td>Peak Runoff Rate in./100 hr.</td>
<td>Average Runoff Rates in./100 hr.</td>
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<td></td>
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<td>6 - Hour</td>
<td>12 - Hour</td>
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<tr>
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<td>0.696</td>
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<td>0.613</td>
<td>0.539</td>
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<tr>
<td>Combined</td>
<td>0.700</td>
<td>0.592</td>
<td>0.498</td>
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<tr>
<td>1959 - 1967</td>
<td>0.385</td>
<td>0.217</td>
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<tr>
<td>Drains 1 and 5</td>
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<tr>
<td></td>
<td>Average of Measured Runoff Rates and Quantities 1957 - 1967</td>
<td>1.55</td>
<td>1.29</td>
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</table>

Table 5.3
STANDARD DEVIATIONS OF ERRORS IN PREDICTING RUNOFF EVENTS
Fig. 5.2 PREDICTED WATER BALANCE 1959
Fig. 5.5 PREDICTED WATER BALANCE 1962
Fig. 5.11 MEASURED AND PREDICTED HYDROGRAPHS 1957
Fig. 5.12 MEASURED AND PREDICTED HYDROGRAPHS 1957 AND 1959
Fig. 5.13 MEASURED AND PREDICTED HYDROGRAPHS 1960
Fig. 5.16 MEASURED AND PREDICTED HYDROGRAPHS 1963
Fig. 5.21 Measured and Predicted Hydrographs 1967
CHAPTER VI
CONCLUSIONS

1. An hourly water balance model of a tile drainage system can be developed based on an empirical relationship between the mid-spacing water table height and tile flow and a soil moisture budget.

2. The accuracy of the model which resulted from this study depended considerably upon the accuracy of the soil moisture budget. When soil moisture levels were accurately predicted, the empirical "rating curve" predicted the drain runoff rates with good accuracy.

3. The use of a water table flux factor improved the model performance only slightly and the error caused by assuming a constant water table shape was small.

4. Water in transient storage plays an important role in the water balance. It is indicated in the apparent higher field capacity in the early spring; the replenishment of available moisture
by the capillary fringe and the short, steep runoff events that cannot entirely be explained by normal seepage of water below the water table.

5. In this study, horizontal seepage to other drains accounted for approximately 40 percent of total runoff and contributed significantly to the rate of water table drop in the top foot of soil.

6. The model developed could be used with useful accuracy to predict the frequency of water table heights for years other than the record period.
REFERENCES


(2) van Schilfgaarde, J., Kirkham, D., and Frevert, R.K., Physical and Mathematical Theories of Tile and Ditch Drainage and Their Usefulness in Design. Research Bulletin 436, Agricultural Experiment Station, Iowa State College, Feb., 1956.


(4) Hooghoudt, S.B., Bijdragen tot de kennis van unieke natuurkundige grootheden van den grond, 6, Bepaling van de doorlatendheid in gronden van de tweede soort; theoretie en toepassingen van de kwantitatieve stroming van het water in ondiep gelegen grondlagen, vooral in verband met ontwateringen - en infiltratievraagstukken, Versl. Landbouwk. Ond., No. 43, 1937.


(20) Bouwer, H., and van Schilfgaarde, J., Simplified Method of Predicting Fall of Water Table in Drained Land, Transactions, American Society of Agricultural Engineers, Vol. 6, No. 4, 1963.


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## APPENDIX

### THE COMPUTER PROGRAMME

### 1. NOTATION

<table>
<thead>
<tr>
<th>SYMBOL</th>
<th>DESCRIPTION</th>
<th>UNITS</th>
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<tbody>
<tr>
<td>AE</td>
<td>Actual evapotranspiration</td>
<td>in./100</td>
</tr>
<tr>
<td>AVFC</td>
<td>Field capacity of accessible zone</td>
<td>in./100</td>
</tr>
<tr>
<td>AVST</td>
<td>Retention in accessible zone</td>
<td>in./100</td>
</tr>
<tr>
<td>C</td>
<td>Water table shape factor</td>
<td></td>
</tr>
<tr>
<td>Cl</td>
<td>Tile flow factor based on water table shape</td>
<td></td>
</tr>
<tr>
<td>CK</td>
<td>Scale factor to compute measured tile flow</td>
<td></td>
</tr>
<tr>
<td>DATE</td>
<td>Date</td>
<td></td>
</tr>
<tr>
<td>DEF</td>
<td>FC - ST</td>
<td>in./100</td>
</tr>
<tr>
<td>DL</td>
<td>Daylength factor</td>
<td>hr/12</td>
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<tr>
<td>F</td>
<td>Drain runoff rate</td>
<td>in./100 hr.</td>
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<tr>
<td>FC</td>
<td>Field Capacity</td>
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<td>Field index</td>
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<tr>
<td>IFC</td>
<td>Previous value for FC</td>
<td>in./100</td>
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<tr>
<td>IND</td>
<td>Accessible zone index</td>
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</tr>
<tr>
<td>IP</td>
<td>Daily evapotranspiration from capillary fringe</td>
<td>in./100</td>
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<tr>
<td>IR</td>
<td>Hourly rainfall</td>
<td>in./100</td>
</tr>
<tr>
<td>IYR</td>
<td>End of year index</td>
<td></td>
</tr>
<tr>
<td>J</td>
<td>Hour index</td>
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<tr>
<td>K</td>
<td>Hour index</td>
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</tr>
<tr>
<td>K1</td>
<td>Data card index - measured flow</td>
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</tr>
<tr>
<td>K3</td>
<td>Scale factor index</td>
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<tr>
<td>KFL</td>
<td>Hourly flow meter stage</td>
<td>in./20</td>
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<td>L</td>
<td>Plotting symbol array position</td>
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</tr>
<tr>
<td>LINE</td>
<td>Plotting symbol array</td>
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<td>N</td>
<td>Field index</td>
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<td>NEXT</td>
<td>Data card index - hourly rainfall</td>
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<tr>
<td>P</td>
<td>Daily rainfall</td>
<td>in./100</td>
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<tr>
<td>PE</td>
<td>Daily potential evapotranspiration</td>
<td>in./100</td>
</tr>
<tr>
<td>PPE</td>
<td>P - PE</td>
<td>in./100</td>
</tr>
<tr>
<td>PR1</td>
<td>Hourly rainfall, hours 1,3,5,...</td>
<td>in./100 hr.</td>
</tr>
<tr>
<td>PR2</td>
<td>Hourly rainfall, hours 2,4,6,...</td>
<td>in./100 hr.</td>
</tr>
<tr>
<td>RAIN</td>
<td>Hourly rainfall</td>
<td>in./100 hr.</td>
</tr>
<tr>
<td>RET</td>
<td>Surface retention</td>
<td>in./100</td>
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<tr>
<td>SLOPE</td>
<td>Slope of logarithmic retention line</td>
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<tr>
<td>ST</td>
<td>Soil moisture retention</td>
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<tr>
<td>SUMFLO</td>
<td>Accumulated drain runoff</td>
<td>in./100</td>
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<tr>
<td>T</td>
<td>Input temperature readings</td>
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</tr>
<tr>
<td>TM</td>
<td>Mean daily temperature</td>
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<td>Water table height array</td>
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<td>WT1</td>
<td>Previous value of WTH</td>
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</tr>
<tr>
<td>WTH</td>
<td>Water table height</td>
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<tr>
<td>WTV</td>
<td>Ground water retention</td>
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<td>WTVET</td>
<td>Fraction of PFE supplied from WTV</td>
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2. PROGRAMME
C DRAINAGE MODEL III
C DEPT. OF CIVIL ENGINEERING UNIVERSITY OF WINDSOR DEC. 1958
C THIS IS MODEL OF DRAIN #5 EXPERIMENT AT 45 SCHOOL OF AGRICULTURAL
C ENGINEERING UNIVERSITY OF GUELPH
C MODEL DEVELOPED AND PROGRAMMED BY N. A. BIRD
C
C THIS MODEL CONTAINS THE C. W. THORNTHWAITE EVAPOTRANSPIRATION MODEL
C (DAILY BASIS) WITH MINOR REVISIONS
C
REAL WTH, F, C, SUMFLO, LINE, TM, DL, WTV, SLOPE, WTV
INTEGER RAIN, P, PPE, T, DEF, DATE, FC, AVFC, ST, AVST, N, IND, TYR, I, J,
K, L, N, RET, I7, PR1, PR2, PE, AE
DIMENSION F (24, 2), C (2), LINE (24, 60), WTV (2), RAIN (24), T (4), AVFC (2),
ST (2), AVST (2), WTH (2), SUMFLO (24), PR1 (24), PR2 (24), IND (2)
KFL (12), C1 (2)
DATA BLANK, DOT, COMMA/1H, 1H, 1H, /
3 READ 4, FC, ST (1), ST (2), AVFC (1), AVFC (2), AVST (1), AVST (2), WTV (1),
WTV (2), SUMFLO (24), F (24, 1), F (24, 2), C (1), C (2), K3
4 FORMAT (715, 7F5.0, 11)

AE = 0
IP = 0
DATA C1 (1), C1 (2)/1.1, 1.1, 1.1/
5 READ 5, DATE, (T (1), M = 1, 4), INF, P, DL, NEXT, TYR, IND (1), IND (2), K1
6 FORMAT (16, 9I2, 12, 13, F5.0, 2X, 2I1, 312)
TM = FLOAT (T (1) + T (2) + T (3) + T (4)) / 4.0

C THORNTHWAITE EQUATIONS FOR PE AT LATITUDE 42 NORTH
IF (TM - 56.0) 11, 11, 12
11 PE = DL * 0.33 * (TM - 32.0)
GO TO 14
12 PE = DL * 0.425 * (TM - 37.0)
GO TO 14
14 PPE = P - PE

C FC REDUCTION TO 600 FROM HIGHER SPRING VALUE
21 IPC = FC
FC = FC - PE / 4
IF (FC, LT, ST (1)) FC = ST (1)
IF (FC, LT, ST (2)) FC = ST (2)
IF (FC, LT, 600) FC = 600
31 DO 49 N = 1, 2
AVST (N) = AVST (N) + IPC - FC
C LOSS OF SOIL MOISTURE TO WTV WITH EARLY SPRING REDUCTION IN FC
JFC = 0
IF (FC, GT, 620) JFC = 2
C SUBTRACT DEEP SEEPAGE
WTV (N) = WTV (N) - 0.3 * JFC
IF (WTV (N), GT, 0.0) GO TO 34
WTV (N) = 0.0
C COMPUTE WTH FROM WTV AND DRAINABLE POROSITY
34 WTH (N) = WTV (N) * 0.435

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IF (WTH(N) .LE. 42.0) GO TO 41
WTH(N) = 42.0 + (WTV(N) - 97) *.087
IF (WTH(N) .GT. 50.0) WTH(N) = 50.0
C ADJUST ROOT ZONE FOR STAGE OF CROP

41 IF (IND(N)) 42, 49, 46
42 AVST(N) = FLOAT (AVST(N) - 50 * AVST(N) / AVFC(N)) + .5
AVFC(N) = AVFC(N) - 50
GO TO 49
46 AVST(N) = FLOAT (AVST(N)) + FLOAT (50 * (ST(N) - AVST(N))) / FLOAT (FC - 1 / AVFC(N)) + .5
AVFC(N) = AVFC(N) + 50
49 CONTINUE
N=1
IF (K1.EQ.0) GO TO 51
C READ FLOW METER STAGE DATA FOR PLOTTING ACTUAL HYDROGRAPHS
READ 50, (KFL(J), J=1, 12)
50 FORMAT (12 13)
51 IF (NEXT.EQ.0) GO TO 55
C READ HOURLY RAINFALL
READ 53, (RAIN(J), J=1, 24)
53 FORMAT (24 13)
GO TO 58
C SET HOUR 1 RAINFALL = DAILY P
55 RAIN(1) = P
DO 57 J=2, 24
57 RAIN(J) = 0
C DETERMINE IF WTH IS OR COULD BE HIGH ENOUGH FOR TILE FLOW
I7=0
58 IF (WTV(1) .GT. 56.0) I7=1
IF (WTV(2) .GT. 56.0) I7=1
IF (WTV(1) + PPE .GT. 56.0) I7=1
IF (WTV(2) + PPE .GT. 56.0) I7=1
IF (I7.EQ.1) GO TO 700
C DETERMINE IF MOISTURE TO BE ADDED OR SUBTRACTED
59 IF (PPE) 200, 500, 300
C 200 SERIES COMPUTES, SUBTRACTS AE
200 SLOPE = 1.06 / FLOAT (AVFC(N))
IF (AVST(N) .LE. 0) GO TO 500
AE = AVST(N) - EXP (ALOG (FLOAT (AVST(N))) + SLOPE * FLOAT (PPE)) + .5
AVST(N) = AVST(N) - AE
ST(N) = ST(N) - AE
GO TO 500
C 300 SERIES ADDS EXCESS P TO SOIL AND WTV
300 DEF = FC - ST(N)
IF (PPE .GT. DEF) GO TO 320
ST(N) = ST(N) + PPE
GO TO 322
320 ST(N) = FC

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321 \( WTV(N) = WTV(N) + \text{FLOAT}(PPE-DEF) \)
322 \( AVST(N) = AVST(N) + PPE \)
   IF (AVST(N) > AVFC(N)) AVST(N) = AVFC(N)
GO TO 500

C 700 SERIES CONTAINS HOURLY LOOP
C SURFACE RETENTION IS FUNCTION OF PLANT COVER,
C DOES NOT EXCEED PPE OR P
700 RET = 4 * AVFC(N) / 50
   IF (RET > P) RET = P
   IF (RET > PE) RET = PE
PPE = RET - PE
K = 24
DO 790 J = 1, 24
   IR = RAIN(J)
   IF (J.EQ.12) GO TO 210
   GO TO 708
C FOLLOWING SECTION PERFORMED AT HOUR 12
C COMPUTE FRACTION OF PPE THAT CAN BE REPLACED BY CAPILLARY FRINGE
210 WTVET = \( WTH (N) - 38.0 + 0.04 \times \text{FLOAT}(AVFC(N)) \) / \( 0.04 \times \text{FLOAT}(AVFC(N)) \)
   IF (WTVET.GT.1.0) WTVET = 1.0
   IF (WTVET.LT.0.0) WTVET = 0.0
   IF (0.5 - WTVET*PPE)
      PPE = PPE + IP
   IF (AVST(N) .LE. 0) GO TO 709
C COMPUTE AE
   SLOPE = 1.06 / \text{FLOAT}(AVFC(N))
   AE = AVST(N) - \exp(A \log(\text{FLOAT}(AVST(N))) + SLOPE \times \text{FLOAT}(PPE)) + 0.5
C SUBTRACT HOURLY AE AND IP
708 IF (AE .LE. 0) GO TO 709
   IF (AE .LT. 3) GO TO 707
   AVST(N) = AVST(N) - 2
   ST(N) = ST(N) - 2
   AE = AE - 2
   GO TO 709
707 AVST(N) = AVST(N) - 1
   ST(N) = ST(N) - 1
   AE = AE - 1
709 IF (IP .GT. 0) WTV(N) = WTV(N) - 1
   IF (RAIN(J) .LE. 0) GO TO 715
C ADD HOURLY RAIN TO RET UNTIL SATISFIED
   RAIN(J) = RAIN(J) - RET
   IF (RAIN(J) .GT. 0) GO TO 714
   RET = \text{IABS}(RAIN(J))
   RAIN(J) = 0
   GO TO 715
714 RET = 0
C ADD BALANCE TO SOIL STORAGE UNTIL SATISFIED
715 DEF = FC - ST(N)
IF (RAIN(J) .GT. DEF) GO TO 730
ST(N) = ST(N) + RAIN(J)
AVST(N) = AVST(N) + RAIN(J)
IF (AVST(N) .GT. AVFC(N)) AVST(N) = AVFC(N)
GO TO 732
730 ST(N) = FC
AVST(N) = AVFC(N)
C ADD BALANCE TO WTV (LESS EXCESS OF INFILTRATION CAPACITY)
IF(INF. .EQ. 0) GO TO 731
IF (INF. .GT. J) GO TO 731
IF (RAIN(J) - DEF. .LE. 15) GO TO 731
WTV(N) = WTV(N) + 15
GO TO 732
731 WTV(N) = WTV(N) + FLOAT(RAIN(J) - DEF)
C SUBTRACT FLOW, HORIZONTAL SEEPAGE AND COMPONENT OF DEEP
C SEEPAGE THAT IS PROPORTIONAL TO WTV FROM WTV
732 WTV(N) = WTV(N) - F(K, N) * 1.4
C IF WTV EXCEEDS CAPACITY TO SOIL SURFACE, BALANCE IS SURFACE RUNOFF
IF(WTV(N) .GT. 190.) WTV(N) = 190.
RAIN(J) = IR
K = J
WT1 = WTH(N)
C COMPUTE WTH
WTH(N) = WTV(N) * 0.435
IF (WTH(N) .LE. 42.0) GO TO 741
WTH(N) = 42.0 - (WTH(N) - 97) * 0.087
C COMPUTE WATER TABLE SHAPE FACTOR
741 IF (WTH(N) .GT. 42.0) GO TO 745
IF (WTH(N) .GT. 38.0) C(N) = C(N) - 0.05
IF (C(N) .LT. 0.5) C(N) = 0.5
C(N) = C(N) + 0.002
IF (C(N) .LT. 1.2) C(N) = 1.2
GO TO 751
745 IF (WTH(N) .LT. WT1) GO TO 749
746 IF (WT1 .LT. 42.0) GO TO 748
747 C(N) = C(N) - 0.2 + 0.13 * (WTH(N) - WT1)
GO TO 750
748 C(N) = C(N) + 0.13 * (WTH(N) - 42.0)
GO TO 750
749 C(N) = C(N) - 0.2
750 IF (C(N) .GT. 1.5) C(N) = 1.5
IF (C(N) .LT. 0.5) C(N) = 0.5
C COMPUTE TIDE FLOW FACTOR FROM WATER TABLE SHAPE FACTOR
C1(N) = C1(N) - (C1(N) - 1.) / 4.
IF (C1(N) .LT. C(N)) C1(N) = C(N)
IF (C1(N) .LT. 1.1) C1(N) = 1.1
C COMPUTE FLOW BASED ON RATING CURVE AND TIDE FLOW FACTOR
IF (WT(N) - 44.0) GT 48.0, F(J,N) = 4.0 + (WT(N) - 48.0) * C1(N) * 0.25, GO TO 761

F(J,N) = 0.6 + (WT(N) - 44.0) * C1(N) * 0.80

IF (WT(N) - 42.0) GT 48.0, F(J,N) = 0.25 + (WT(N) - 42.0) * 0.17, GO TO 761

F(J,N) = 0.0

GO TO 761

F(J,N) = 0.0178 * (WT(N) - 28.0)

C FILL ARRAY FOR PRINTING WTH

WT(J,N) = WTH(N)

CONTINUE

IP = 0

C 500 SERIES DIRECTS CONTROL TO REPEAT CALCS FOR FIELD 32

C FILLS ARRAYS FOR PRINTING AND PLOTTING

C PRINTS HOURLY VALUES, PLOTS MODEL AND ACTUAL HYDROGRAPHS

C PRINTS DAILY VALUES

IF (N.EQ.2 .AND. I7.EQ.1) GO TO 503

IF (N.EQ.1 .AND. I7.EQ.1) GO TO 501

GO TO 502

N = 2

GO TO 700

IF (N.EQ.2) GO TO 541

N = 2

GO TO 59

K = 24

DO 505 J = 1, 24

SUMFLO(J) = SUMFLO(K) + (F(J,1) + F(J,2)) / 2.0

K = J

IF (F(24,1) + F(24,2) .LE. 0.2) GO TO 541

DO 507 J = 1, 23, 2

PR1(J+1) = RAIN(J)

DO 509 J = 2, 24, 2

PR2(J) = RAIN(J)

DO 522 J = 1, 24

L = KFL(J) * CK + 1.5

LINE(J,L) = BLANK

IF (K1.EQ.0) GO TO 523

IF (K3.GT.0) GO TO 524

CK = 0.735

GO TO 525

CK = 0.845

DO 526 J = 1, 12

L = KFL(J) * CK + 1.5

LINE(J*2,L) = COMMA

DO 532 J = 2, 24, 2
\[ L = (P(J,1) + F(J,2)) \times 5.0 + 1.5 \]

532 \text{LINE} (J,L) = \text{DOT}

533 \text{DO} 537 \ J = 2, 22, 2

534 \text{PRINT} 536 \ PR1(J), PR2(J), WT(J,1), WT(J,2), SUMFLO(J), J,

\text{1(LINE(J,L),L=1,60)}

536 \text{FORMAT}(1H\,30X,2I4,3F6.1,I3,60A1)

537 \text{CONTINUE}

\text{PRINT} 538 \ DATE, AVST, ST, PE, PR1(24), PR2(24), WT(24,1), WT(24,2),

SUMFLO(24), (LINE(24,L),L=1,60)

538 \text{FORMAT}(1H\,16,8I4,3F6.1,3X,60A1)

\text{GO TO 545}

541 \text{PRINT} 542 \ DATE, AVST, ST, PE, WT, SUMFLO(24)

542 \text{FORMAT}(1H\,16,8I4,8X,3F6.1)

SUMFLO(24) = 0.0

545 \text{IF}(IYR.GT.0) \text{GO TO 3}

\text{GO TO 5}

END
VITA AUOTORIS

1937  Born in Ontario, Canada on July 8.

1955  Completed high school at Milton High School, Milton, Ontario.

1960  Received the degree of Bachelor of Science in Agriculture from the University of Toronto, Toronto, Ontario.

1961  Received the degree of Bachelor of Applied Science in Mechanical Engineering at the University of Toronto, Toronto, Ontario.

1969  Currently a candidate for the Degree of Master of Applied Science in Civil Engineering at the University of Windsor, Windsor, Ontario.