DRAINAGE FROM LEVEL AND SLOPING LAND

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A sand tank model study of drainage by pipe drains on level and sloping land was made in a 60-ft long, 2-ft wide, and 2-1/2-ft deep flume. The flume could be tilted to a 12 percent slope. Theoretical equations developed for steady-state drainage conditions on level land were verified. The study showed that drain spacing formulas developed for level land can be used for spacing miscoupe drains on sloping land which has a shallow impermeable barrier. Computer programs using verified formulas to determine drain spacing and maximum water table height between drains were developed and checked with data obtained from the flume study. The time-sharing computer programs have been entered into the Bureau of Reclamation Engineering Computer System (BRECS).
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by

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Flume could be tilted up to 12 percent. Photo PX-D-70132

Manometers are connected to wells installed in the soil surface to give the water table elevations between the drains. Photo PX-D-70128

Water discharging from the horizontal tile drains is collected and pumped to the water storage tank for resupply to the recharge system. Photo PX-D-70130

Figure 1a. Details of sand tank model.
Water is recirculated in the drainage system to maintain a uniform water temperature and to maintain a uniform dissolved air content in the water. Photo PX-D-70127

A uniform water recharge to the entire soil surface is obtained by distributing the flow through uniformly spaced holes in the recharge tubes. Photo PX-D-70131

Infiltration recharge is measured by using small orifices and differential manometers. Photo PX-D-70129

Figure 1b. Details of sand tank model.
PURPOSE
A sand tank model was studied to learn more about flow conditions for drainage by pipe drains on level and sloping land. The main purpose of the study was to determine how drain spacing formulas that were developed for level land could be modified for use on sloping land.

CONCLUSIONS
1. Data obtained from a sand tank model verified theoretical equations developed for steady-state drainage conditions on level land.
2. The study showed that drain spacing formulas developed for level land can also be used for mid-slope drains on sloping land. In general, downslope drains require closer spacing than on level land. Conversely, the upslope drains can be spaced farther apart.
3. Hooghoudt's equations to correct for convergence by use of an equivalent depth can be combined into the steady-state drainage equation and solved with a relatively simple computer program.
4. The maximum water table height between drains and the drain spacing can be determined for steady-state drainage conditions. Computer programs were developed using the Fortran language for a time-sharing computer system.

APPLICATIONS
The computer programs, developed to solve the Donnan drain spacing equation with Hooghoudt's correction for convergence, can be used to solve steady-state drainage problems on level and sloping land. The input variables that determine the drain spacing are: hydraulic conductivity of soil, \( P \); deep percolation recharge rate, \( R \); maximum height of water table that can be allowed between drains, \( H \); distance from drains to the impermeable barrier, \( D \); and radius of the gravel envelope, \( R_1 \).

INTRODUCTION
On sloping land that requires drainage, agricultural pipe drains are usually installed transverse to the slope along the land contours. Intuitively, it appears that the slope of the land affects the rate at which the deep percolation part of the irrigation water is drained away. Theoretical developments and Hele Shaw model studies have been made and approximate solutions given by various authors.

In the present study, a series of tests were made in a variable slope sand tank hydraulic model to demonstrate level and sloping land drainage problems. The studies were made to check theoretical drainage formulas for level land and to determine if the formulas could be applied to drainage on sloping land.

Data obtained from the model were used to check basic formulas developed for drains installed on level land. A computer program was developed to determine the drain spacing for pipe drains. The level land drainage formulas were applied to the data obtained from the model tests on sloping land. A computation to demonstrate the use of the computer program for determining drain spacings was made using typical data from a ground-water aquifer.

SAND TANK MODEL
The basic flume, Figures 1 and 2, used for the study was 60 ft (18.29 m) long, 2 ft (0.61 m) wide and 2-1/2 ft (0.76 m) deep with transparent plastic panels forming the right side looking downslope. For ease in tilting the flume, two 16WF36 continuous steel beams supported it. The steel beams were supported at two points. The downslope support was a pivot and the upslope beam support was the lifting point. The supports were located to minimize deflections. The spacing of supports was designed to give equal deflections at the ends and the center of the flume. Deflection was limited to one-fourth inch. Design load on the beams was 900 lb/ft (1,339.3 kg/m) (450 lb/ft (669.7 kg/m) on each beam) considering the weight of the flume, sand, water, beams, and persons standing on the walkway on the side of the flume.

Figure 2. Sketch of tilting flume. (Not to scale.)
Lifting one end of the flume to achieve the slope desired was done by two 8-ton (7.26-metric ton) motorized chain hoists. Templates were used to achieve the slope desired. After the slope was set, screwjacks were placed under the beams of the upslope lifting point for safety. Because of headroom limitations, the maximum slope that was obtainable with the flume was about 12 percent (about $6^\circ 50'$).

**Pipe Drains**

To simulate pipe drainage, eleven 5/8-inch (1.59-cm) od by 1/2-inch (1.27-cm) id plastic tubes were used. The plastic tubes were slotted with a bandsaw. The first drain was 4 inches (10.16 cm) from the downslope end of the flume. Drains were spaced 6 ft (1.83 m) apart, except for the last two at the upslope end which were 5 ft 4 inches (1.63 m) apart, making the last drain also 4 inches (10.16 cm) from the upslope end of the flume.

**Floor Drains**

Eleven floor drains were placed along the centerline of the flume. The first drain was 1 ft (30.48 cm) from the downslope end. The drains were spaced 6 ft (1.83 m) apart with the exception of the last two on the upslope end, which were 4 ft (1.22 m) apart, making the last drain also 1 ft (30.48 cm) from the upslope end of the flume. The floor drains were made from 1/2-inch (1.27-cm) galvanized pipe passing through the floor of the flume. A valve was in each drainline which led to a common 1-1/2-inch (3.81-cm) pipe manifold beside the flume floor and extending its full length. Each floor drain was covered by 100-mesh screen and a 1-inch (2.54-cm) thick layer of No. 16 coarse sand.

**Piezometer Wells**

Piezometer wells were placed in the sand along the centerline of the flume. They were made of 5/3-inch (1.54-cm) od by 1/2-inch (1.27-cm) id plastic tubes 7-1/2 inches (19.05 cm) long. The bottom ends of the tubes were plugged and the bottom 2 inches (5.08 cm) of the tubes were slotted in the same manner as the horizontal drains. A small cylinder of 100-mesh screen was used inside each piezometer to exclude sand. The piezometers were used to define the water table above the drains. The bottom of each piezometer well was one-half inch below the centerline of the horizontal drains.

**Hydraulic System**

The hydraulic system for the flume was a closed circuit flow system. The recharge water is pumped from a covered wood storage reservoir 7 by 7 by 4 ft (2.13 by 2.13 by 1.22 m) deep through a manifold piping system to plastic recharge modules. The water was in contact with only noncorrosive materials (plastic, painted wood, brass, and stainless steel) before entering the sand in the flume. The recharge water passed through a screen filter, and a 1-1/2-inch (3.81-cm) plastic pipe manifold to vertical 1/2-inch (1.27-cm) pipes. Each of the 10 pipes fed a separate recharge module.

**Recharge Modules**

Each recharge module consisted of two plastic tubes, 1/2-inch (1.27-cm) od by 3/8-inch (1.14-cm) id by 6 ft (1.83 m) long; the tubes were placed side by side 1 ft (0.3048 m) apart. These tubes were kept horizontal when the flume was tilted. The tubes were drilled with 12 holes, 0.020 inch (5.08 mm) in diameter, 1 ft (0.3048 m) apart on the upper side of the tubes. Each hole had an inverted cup over it. The water squirted up into the cup and then dripped onto the sand. By having the holes on top of the tubes, air could escape and the holes did not clog with foreign matter. The inverted cups eliminated spray as the water left the 1/2-inch (1.27-cm) tubes. The recharge system as described was for steady inflow tests. For intermittent inflow or transient recharge tests, a valve controlling recharge flow was turned on and off starting and stopping inflow almost instantaneously.

**Filling the Flume with Aquifer Sand**

With the exceptions described below, the flume was filled with a uniform rounded sand with a mean particle size of approximately 0.2 mm. A size analysis of the sand is shown in Figure 3. An envelope of No. 16 coarse sand, 0.2 ft (0.061 m) in diameter, was placed around each of the horizontal drains except the first and last drains which are the 1/2-ft (15.24-cm) thick vertical layers of coarse sand at each end of the flume. The vertical layer of No. 16 coarse sand was placed at the downslope end to simulate drainage into a ditch. The coarse sand at the upslope end was placed primarily to facilitate vertical distribution of inflow water for hydraulic conductivity tests. Hydraulic conductivity of the aquifer material could be determined by measuring the depths of uniform flow and discharge down the slope. The flume was filled to a depth of 2 ft 4 inches (0.71 m) with the uniform 0.2-mm sand. The sand was placed under water to eliminate bubbles forming in the sand aquifer. A 1-inch (2.54-cm) layer of No. 8 gravel was placed on top of the aquifer sand to spread the recharge water and prevent erosion of the fine aquifer sand.
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Mathematical Development

The mathematical development is based on steady conditions; i.e., constant recharge with constant discharge from the drains. The following concepts were used in setting up relationships to develop an equation to describe the steady-state condition:

1. The fundamental law pertaining to flow through saturated porous media is generally called Darcy's Law expressed in the following form

   \[ Q = P \frac{dy}{dx} A \]

   where \( P \) is the coefficient of hydraulic conductivity, \( \frac{dy}{dx} \) is the gradient, \( A \) is the cross-section area through which the water moves at a discharge of \( Q \) per unit time, Figure 4.

2. The Dupuit-Forchheimer assumptions are used which essentially state that flow is one dimensional. In more detail, the Dupuit-Forchheimer assumptions are (a) that all the streamlines are straight and parallel to the impermeable boundary, (b) that the velocity is constant throughout the depth of flow, and (c) that the velocity is
proportional to the slope (expressed as the tangent of the angle) of the water surface.

From Darcy’s Law and the definition sketch (Figure 4) we get

\[ Q = P \left( \frac{-dy}{dx} \right) A \]  

(1)

For a unit width, \( A = y \). Then

\[ q = Py \left( \frac{-dy}{-dx} \right) \]  

(2)

where \( q \) is the flow per unit width.

From continuity with a constant rate of deep percolation \( R \) per unit surface area

\[ q = R \left( \frac{S}{2} - x \right) \]  

(3)

where \( R \) is equal to deep percolation rate per unit area, and \( S \) is equal to the spacing between adjacent drains.

Equating Equations (1) and (3) gives

\[ Py \frac{dy}{dx} = R \left( \frac{S}{2} - x \right) \]  

(4)

\[ \frac{R}{P} \left( \frac{S}{2} - x \right) \frac{dx}{dy} = y \]  

(5)

Integrating this differential equation gives

\[ \frac{R}{P} \left[ \frac{S}{2} x - \frac{x^2}{2} \right] = \frac{y^2}{2} + C \]  

(6)

For the boundary conditions \( x = 0 \) when \( y = d \) the constant of integration is

\[ C = -\frac{d^2}{2} \]  

(7)

Thus, Equation (6) is

\[ \frac{R}{P} \left[ \frac{S}{2} x - \frac{x^2}{2} \right] = \frac{y^2}{2} - \frac{d^2}{2} \]  

(8)

At \( x = S/2 \) and \( y = b \), Equation (8) becomes

\[ \frac{R}{P} \left[ \left( \frac{S}{2} \right)^2 - \left( \frac{S}{2} \right)^2 \right] = \frac{b^2}{2} - \frac{d^2}{2} \]  

(9)

\[ \frac{1}{2P} \left[ \left( \frac{S}{2} \right)^2 \right] = \frac{b^2}{2} - \frac{d^2}{2} \]  

(10)

Solving for the drain spacing \( S^2 \) gives

\[ S^2 = \frac{4P(b^2 - d^2)}{R} \]  

(11)

(12)

which is the equation derived by Donnan. S. B. Hooghoudt developed an equation in 1940 to determine the water table when it was in equilibrium with constant rainfall or irrigation (steady-state condition). His equation is for drainage into parallel ditches, Figure 5. His development used the Dupuit-Forchheimer assumptions and was very similar to that described above. Hooghoudt’s equation is

\[ S^2 = \frac{4P(h^2 - h^2 + 2dh - 2dh)}{R} \]  

(13)

If we assume the ditch is empty (Figure 5), then \( h \) is equal to 0 and \( d + H = b \) in Equation (13). If the substitution is made, Equation 13 becomes

\[ S^2 = \frac{4P(b^2 - d^2)}{R} \]  

(14)

which is identical with Equation (12).

The distance from the water table to the impermeable layer, \( b \), is an important factor in Hooghoudt’s or Donnan’s equations. As this distance gets very large, so does the drain spacing, \( S \). This is because the Dupuit-Forchheimer assumptions do not account for radial flow into the drain. Hooghoudt recognized this difficulty and made a separate analysis for flow in the
vicinity of the drain. He assumed that the flow is radial in character. He then equated the flow obtained with the radial flow assumptions with the flow obtained with the horizontal flow equations. To be able to equate the flows, Hooghoudt developed a method of determining an equivalent depth that could be substituted for the depth, \( d \), between the drains and the impermeable barrier.

His equation for equivalent depth, \( d' \), can be written as

\[
d' = \frac{S}{B + C}
\]  

where

\[
B = \frac{1}{\pi} \left[ \ln \frac{\sqrt{2} d}{2r} + \sum_{n=1}^{\infty} \ln \left( 1 - \frac{1}{2} \left( \frac{d}{S} \right)^2 \right) \right] + \frac{1}{2} \sum_{n=-\infty}^{\infty} \ln \left( \frac{2nS - \sqrt{2} d}{2nS} + 16 \frac{d^2}{2nS^2 + 16d^2} \right)
\]  

and

\[
C = \frac{(S - \sqrt{2} d)^2}{8dS}
\]

In the above equations
\( d \) = depth of impermeable barrier below the drain \( Q \)
\( d' \) = Hooghoudt’s equivalent depth to the impermeable barrier
\( S \) = spacing between \( Q \) of drains
\( r \) = radius of drain plus thickness of gravel envelope
\( B, C \) = parameters defined by above equations
\( \ln \) = natural logarithm

With some rearrangement, W. T. Moody\(^3\) put Equation (15) in the dimensionless form

\[
d' = \frac{1}{1 + \frac{d}{S} \left[ \frac{8}{\pi} \ln \frac{d}{r} - \alpha \left( \frac{d}{S} \right) \right]}
\]

where

\[
\alpha \left( \frac{d}{S} \right) = 2\sqrt{2} + \frac{8}{\pi} \ln \frac{4}{3} - 2 \left( \frac{d}{S} \right) - \frac{4}{\pi} \ln \left( \sum_{n=1}^{\infty} \frac{(1 - 0.5y)^2 (1 + 7y + 20.25y^2)}{(1 + 4y)^2} \right)
\]

and

\[
y = \left( \frac{d}{nL} \right)^2
\]

Moody suggested the following two relationships, Equations (21) and (23), would be sufficiently accurate for most uses

\[
d' = \frac{1}{1 + \frac{d}{S} \left[ \frac{8}{\pi} \ln \frac{d}{r} - \alpha \left( \frac{d}{S} \right) \right]} \text{ for } 0 < \frac{d}{S} < 0.312
\]

where \( \alpha \) is a function of \( d/S \) and its value varies from \( \alpha = 3.561 \) for \( d/S = 0.0 \) to \( \alpha = 3.234 \) for \( d/S = 0.312 \). A close approximation to \( \alpha \) is given by the second degree relationship

\[
\alpha = 3.55 - 1.5(\frac{d}{S})^2
\]

and

\[
\frac{d'}{S} = \frac{1}{\frac{8}{\pi} \ln \frac{S}{r} - 1.15} \text{ for } 0.312 < \frac{d}{S}
\]

Figure 6 shows a typical example, the relationship of \( P/R \) (hydraulic conductivity over recharge rate) and drain spacing \( S \) for the range \( 0 < d/S < 0.312 \) and \( d/S > 0.312 \). The curves join together very well showing that Equations (21) and (23) are continuous at \( d/S = 0.312 \).
The use of Equations (21) and (23) to correct for convergence of flow near the drains have given excellent results when used with Donnan's or Hooghoudt's formulas for design of agricultural pipe drains, for steady-state conditions, and with Dumm's \(^5\) method for transient flow conditions.

**DRAINS ON BARRIER—STEADY RECHARGE**

For the case of a shallow aquifer where the drains can be placed on the barrier, the conditions are shown by the definition sketch, Figure 7. The depth, \(d\), drain to barrier, is zero and consequently there is no requirement to correct this depth for convergence of flow to a drain.

Then from Darcy's Law and using the Dupuit-Forchheimer assumptions

\[
Q = P \left( \frac{-dy}{dx} \right) A \tag{24}
\]

where the terms are the same as described before.

For a unit width \(A = y\)
\[ q = py \left( \frac{-dy}{-dx} \right) \]  

(25)  

With a constant recharge \( R \) per unit surface area, the equation of continuity is

\[ q = R \left( \frac{S}{2} - x \right) \]  

(26)  

Equating (25) and (26) gives

\[ py \left( \frac{dy}{dx} \right) = R \left( \frac{S}{2} - x \right) \]  

(27)  

or

\[ \frac{R}{p} \left( \frac{S}{2} - x \right) dx = ydy \]  

(28)  

Integrating the differential equation gives

\[ \frac{R}{p} \left[ \frac{Sx}{2} - \frac{x^2}{2} \right] = \frac{y^2}{2} + C \]  

(29)  

For the boundary conditions \( x = 0 \) when \( y = 0 \) the constant of integration \( C = 0 \).

At \( x = \frac{S}{2} \) and \( y = h \)

Equation (29) becomes

\[ \frac{R}{p} \left[ \frac{S^2}{4} - \frac{S^2}{8} \right] = \frac{h^2}{2} \]  

(30)  

Solving for \( S^2 \) results in

\[ S^2 = \frac{8P}{2R} h^2 = \frac{4P}{R} h^2 \]  

(31)  

or

\[ S = 2h \left( \frac{P}{R} \right)^{1/2} \]  

(32)

Equation (32) can be used to compute the drain spacing when drains are placed on the barrier for steady recharge conditions.

**MODEL VERIFICATION**

The height of the water table at the centerline between drains was measured on steady-state model tests for both a 6-ft (1.83-m) and a 12-ft (3.66-m) drain spacing. The measured water table heights were compared with predicted values using the Donnan equation and Moody’s equations for computing an equivalent depth. The equivalent depth, \( d' \), was used in the Donnan equation to replace \( d \). The Donnan equation rearranged is

\[ S^2 = \frac{4P(b')^2 - (d')^2}{R} \]  

(33)

where

- \( S \) = drain spacing
- \( P \) = hydraulic conductivity of the aquifer
- \( b' = d' + H = \) equivalent depth, \( d' \), below the drains plus water table height, \( H \), above drains
- \( R \) = recharge rate for the steady conditions

Substituting for \( b' \) in the above equation results in

\[ S^2 = 4P(2d'H + H^2) \]  

(34)

or

\[ pH^2 + 2pd'H - \frac{S^2}{4} R = 0 \]  

(35)

This is a quadratic equation in \( H \) and the formula for its solution is

\[ H = -2pd' \pm \sqrt{(2pd')^2 + PS^2R} \]  

(36)

or by rearranging terms

\[ H = -d' \pm \sqrt{(d')^2 + \frac{S^2}{4R}} \]  

(37)

Because \( H \) must always be positive and \( d' \) has a negative value in the equation, the positive root of the radical must always be used.
Substituting for $d'$, Equation (37) gives

$$H = \left[ \frac{d}{1 + 2.55\frac{d}{S} \ln \frac{d}{r} - 3.55\frac{d}{S} + 1.6\frac{d^2}{S^2} - 2.0\frac{d^3}{S^3}} \right]$$

$$+ \sqrt{\left( \frac{1 + 2.55\frac{d}{S} \ln \frac{d}{r} - 3.55\frac{d}{S} + 1.6\frac{d^2}{S^2} - 2.0\frac{d^3}{S^3}}{1 + 2.55\frac{d}{S} \ln \frac{d}{r} - 3.55\frac{d}{S} + 1.6\frac{d^2}{S^2} - 2.0\frac{d^3}{S^3}} \right)^2 + \frac{S^4}{4P}}$$  \hspace{1cm} (38)

for $0 < \frac{d}{S} < 0.312$

For the case $0.312 < \frac{d}{S}$

$$H = \left[ \frac{S}{8\pi \ln \frac{S}{r} - 1.15} \right]$$

$$+ \sqrt{\left( \frac{8\pi \ln \frac{S}{r} - 1.15}{8\pi \ln \frac{S}{r} - 1.15} \right)^2 + \frac{S^4}{4P}}$$  \hspace{1cm} (39)

A computer program combining Equations (38) and (39) to solve for $H$ for the full range of $d/S$ was prepared, Appendix 1. Values of $H$ for the sand tank tests were computed.

Using Equations (38) and (39) the computed water table elevations, $H$, were compared with measured water table elevations above the centerline of drains, Table 1 and Figure 8.

Agreement between measured and computed values is very good. The excellent agreement shows that for steady-state conditions the formulas based on the Dupuit-Forchheimer assumptions and corrected for convergence of flow lines can be used to compute the water table height at the centers of pipe drains.

**DRAINAGE FROM SLOPING LAND**

There is a general feeling among drainage engineers that the Donnan (Hooghoudt) drain spacing formula for steady flow and corrected for convergence at the drains should also be applicable for determining drain spacing on sloping land. A major purpose of the variable slope sand tank model studies was to determine if drainage formulas developed for level land could be applied to sloping land. Therefore, the equations were compared with tests made in the 60-ft (18.29-m) long flume using 6- and 12-ft (1.83- and 3.66-m) drain spacings at four slopes (2-1/2, 5, 7-1/2, and 10 percent). Plots were made to find if there was any trend with increasing slope. The height of the water table was taken as perpendicular to a line connecting the adjacent tile centerlines, Figure 9. The measured values of the water table height varied a small amount for the different slopes but the variation does not seem to have a definite trend. These variations can be attributed to nonuniformities in the density of sand aquifer, the aquifer material and gravel pack material around each drain, construction of drains, and infiltration recharge measurements. The data points are for mid-slope drains and do not include the end drains of the model.

**NONDIMENSIONAL PLOT**

Substituting Moody's approximate formulas for Hooghoudt's equivalent depth in Formula (34) and rearranging the terms to obtain nondimensional parameters we get the following

$$\frac{S^2R}{H^2P} = \frac{8}{1 + \frac{d}{S} \left( \frac{8\pi \ln \frac{d}{r} - 3.4}{\ln \frac{S}{r}} \right)} + 4$$  \hspace{1cm} (40)

for $0 < \frac{d}{S} < 0.312$

and

$$\frac{S^2R}{H^2P} = \frac{\pi \frac{S}{H}}{\ln \frac{S}{r} - 1.15} + 4$$  \hspace{1cm} (41)

for $0.312 < \frac{d}{S}$

The terms are all defined previously.

A computer program was prepared and values of the parameters were computed using values of individual terms obtained from the flume tests. The results were plotted on log-log paper and are shown on Figures 10.
Table 1
RESULTS OF DRAINAGE TESTS—60-FOOT-LONG FLUME
ZERO SLOPE

Hydraulic conductivity \( K = 5.66 \times 10^{-4} \) ft/sec (48.902 ft/day),
Depth \( d = 2.0 \) ft

6-foot Drain Spacing

Hooghoudt's corrected depth \( d' = 0.8002 \) ft

<table>
<thead>
<tr>
<th>Deep percolation ( i )</th>
<th>Ft/sec ( x 10^{-5} )</th>
<th>Ft/day</th>
<th>Measured ft</th>
<th>Computed ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>ML/sec per panel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>0.7357</td>
<td>0.6356</td>
<td>0.0772</td>
<td>0.0700</td>
</tr>
<tr>
<td>5.0</td>
<td>1.4715</td>
<td>1.2714</td>
<td>0.1402</td>
<td>0.1348</td>
</tr>
<tr>
<td>7.5</td>
<td>2.2072</td>
<td>1.9070</td>
<td>0.1982</td>
<td>0.1954</td>
</tr>
<tr>
<td>10.0</td>
<td>2.9429</td>
<td>2.5427</td>
<td>0.2610</td>
<td>0.2525</td>
</tr>
</tbody>
</table>

12-foot Drain Spacing

Hooghoudt's corrected depth \( d' = 1.1559 \) ft

| 2.5 | 0.7357 | 0.63564 | 0.1767 | 0.1858 |
| 3.0 | 0.8829 | 0.76283 | 0.2067 | 0.2200 |
| 4.0 | 1.1772 | 1.0171  | 0.2787 | 0.2859 |
| 5.0 | 1.4715 | 1.2714  | 0.3413 | 0.3490 |
Computations to Determine Drain Spacing

General

Whenever a correction for convergence to determine drain spacing is used with the Donnan formula, it involves a trial-and-error process or the solution of a complicated quadratic equation. It also involves the

\[
\frac{D^2}{B} = \frac{B^2}{D} \quad \text{(for level land)}
\]

and

\[
\frac{D^2}{B} = \frac{B^2}{D} + \frac{R}{K} \quad \text{(for sloping land)}
\]

The scatter of data points is comparatively small.

It is believed that the scatter of data points is due to inherent error in the model tests.

Figure 8. Height of water table above drains versus recharge rate—Comparison of measured values with values computed with Donnan's formula using Hooghoudt's correction for convergence for level land.

Figure 9. Height of water table above drains versus recharge rate—Comparison of measured and computed values on level land with measured values on sloping land.

Figure 10. Nondimensional plot of hydraulic model data—6-ft drain spacing.

Figure 11. Nondimensional plot of hydraulic model data—12-ft drain spacing.
determination of whether the ratio, d/S, depth of drains to barrier, divided by the drain spacing falls within 0 < d/S < 0.312, or within 0.312 < d/S. A different value of the Hooghoudt corrected depth for convergence near the drain is applicable for each case. Publications describing methods for computing drain spacing (References 3, 4, 5, and 6) have suggested the use of graphs to assist in the computations. The graphs are helpful; however, in most cases, they must be prepared before computations can begin, and trial-and-error methods must be used even with the graphs.

A computer program using the Newton-Raphson recursive method was written which can determine the drain spacing quickly without the need for tables or graphs, Appendix 2. The program includes the cases for 0 < d/S < 0.312 and also for 0.312 < d/S. The values of permeability of the porous media and the recharge or deep percolation rate can be combined into a ratio, P/R.

With this program, the drain spacing can be computed by inserting the following values which are basic data and always known or estimated in solving a drainage problem:

Hydraulic conductivity, P—feet per day
Recharge rate, R—feet per day
Water table height above centerline of drains, H—feet
Radius of drain plus gravel pack, r—feet
Depth between centerline of drains and the impermeable barrier, d—feet
Estimated drain spacing, S1—feet

The estimated drain spacing, S1, is computed in the program using Donnan’s formula without convergence, and this estimated S1 is used with the Newton-Raphson method to solve for drain spacing, S, considering Hooghoudt’s correction for convergence. The Newton-Raphson recursive method of determining the solution within the accuracy desired can be done quickly with a digital computer.

Example

An example, Appendix 2, is given to determine the drain spacing using the computer program. This is done to show how much simpler and how the accurate drain spacing can be obtained in much less time and effort than using graphs and tables.

Basic Equations

To solve for drain spacing directly, Equations (38) and (39) are rearranged as shown below

\[ s^2 = \frac{8PHd}{R + \frac{8Rd}{S} \ln \frac{d}{r} - \frac{3.4Rd}{S}} + \frac{4H^2p}{R} \]  

for 0 < \( \frac{d}{S} \) < 0.312

and

\[ s^2 = \frac{nPHS}{R \ln \frac{S}{r} - 1.15R} + \frac{4H^2p}{R} \]

for 0.312 < \( \frac{d}{S} \)

Because the drain spacing dependent variable is nonlinear, iterative methods are necessary for solution. In this method there are four basic parts required in the iterative process to reach a solution or a root of the initial function. They are: initializing, computing, testing, and modifying. The last three components are repeated in a closed loop until the desired accuracy is achieved. Because there are two equations, each of which defines the function in a different range of d/S, it is necessary to make an initial test to determine which equation to use before proceeding to the successive approximation procedure of converging on the desired root. The process is one of computing and testing until an answer is obtained within the specified limits of accuracy. The initial values are modified using a modification of the "Newton" method called the "Newton-Raphson" method. This method, the derivative \( F'(x) \), is used to provide information which results in rapid convergence.

As shown previously, two formulas are used depending on whether d/S is greater or less than 0.312. The value of d/S is first computed from the estimated S and then corrected if necessary.

For the range 0 < d/S < 0.312

\[ F(S) = \frac{8PHd}{R + \frac{8Rd}{S} \ln \frac{d}{r} - \frac{3.4Rd}{S}} + \frac{4H^2p}{R} - S^2 \]

(44)

If we let the ratio P, the hydraulic conductivity of the aquifer, divided by R, the recharge rate, be replaced by the value T or
then the function becomes

\[ F(S) = \frac{8TdH}{S + \frac{8d}{\pi} \ln \frac{d}{r} - 3.4d} + 4T^2 - S^2 \]  \hspace{1cm} (45)

and the derivative

\[ F'(S) = \frac{8TdH}{\left[ S + \frac{8d}{\pi} \ln \frac{d}{r} - 3.4d \right]^2} - 2S \]  \hspace{1cm} (46)

and using the Newton-Raphson method for finding the solution

\[ S_{i+1} = S_i - \frac{F(S_i)}{F'(S_i)} = \frac{8TdHS_i}{\left[ S_i + \frac{8d}{\pi} \ln \frac{d}{r} - 3.4d \right]^2} + 4T^2 - S_i^2 \]  \hspace{1cm} (47)

for 0 < d/S \leq 0.312.

This relationship is designated Formula A in the computer program.

For the range 0.312 < d/S, the function in terms of drain spacing is

\[ F(S) = \frac{\pi TSH}{\ln \frac{S}{r} - 1.15} + 4T^2 - S^2 \]  \hspace{1cm} (48)

again \[ \frac{P}{R} = T \]

The derivative of the function is

\[ F'(S) = \frac{\pi TH}{\ln \frac{S}{r} - 1.15} - \frac{\pi TH}{\left[ \ln \frac{S}{r} - 1.15 \right]^2} - 2S \]  \hspace{1cm} (49)

Setting the equations up for using the Newton-Raphson method for finding a solution, we have

\[ S_{i+1} = S_i - \frac{F(S_i)}{F'(S_i)} = S_i - \frac{\pi TSH}{\ln \frac{S_i}{r} - 1.15} + 4T^2 - S_i^2 \]

\[ \frac{\pi TSH}{\ln \frac{S_i}{r} - 1.15} - \frac{\pi TH}{\left[ \ln \frac{S_i}{r} - 1.15 \right]^2} - 2S_i \]

for 0.312 < d/S

This relationship is designated Formula B in the computer program.

For each case it is necessary to estimate a value of S before using the Newton-Raphson method. Even if an estimate of S is not very close to the final solution, only a few successive approximation steps will be required. The first estimate for S is determined by solving the Donnan-Hooghoudt formula for S

\[ S_i^2 = 4P(b^2 - d^2) \frac{R}{T} \]  \hspace{1cm} (51)

Setting P/R = T

\[ S_i = 2(T(b^2 - d^2))^{1/2} \]  \hspace{1cm} (52)

In the above development, the terms are defined as:

- \( S \) = drain spacing, ft
- \( P \) = hydraulic conductivity of aquifer, ft/day
- \( R \) = recharge (deep percolation) rate, ft/day
- \( T \) = \( \frac{P}{R} \), dimensionless
- \( d \) = distance, impermeable barrier to \( Q \), of pipe drains, ft
- \( b \) = distance, impermeable barrier to water table at \( Q \), between tile drains, ft
The cost of installing an extensive drainage system is proportional to the amount of drain pipe with its installation costs. Therefore, anything that can be done to reduce the amount of drain pipe required by increasing the drain spacing would be helpful in reducing overall costs. In the formulas developed for computing maximum water table elevations or for computing drain spacing, the drain radius plus the gravel envelope is a factor. The gravel envelope is considered highly permeable and therefore it offers very little resistance to flow.

To determine the effect of increasing the drain radius plus gravel envelope on the maximum height of water table between drains, computations were made with the computer program developed to compute water table height. Observing flow lines toward the end drains in the sand tank model with the gravel envelope extending from the elevation of the drains to the bottom of the tank (radius of drain + envelope = depth to barrier) showed that the water table between drains at the ends of the tank was considerably lower than that between the middle drains where the gravel envelope was only around the drains to a thickness or radius of one-tenth of a foot. Another report will show the water table profile between all drains for all tests. The average difference between the height of water table between the drains numbered 1-2 and 10-11, and the drains numbered 2-3 and 9-10 are shown in the following table. The difference is graphically illustrated in Figure 12.

AVERAGE DIFFERENCE IN MAXIMUM WATER TABLE BETWEEN DRAINS NO. 1-2 AND 10-11 AND DRAINS NO. 2-3 AND 9-10

<table>
<thead>
<tr>
<th>Recharge rate (ml/sec)</th>
<th>Maximum water table between Drains No. 1-2 and 10-11 (avg), ft</th>
<th>Maximum water table between Drains No. 2-3 and 9-10 (avg), ft</th>
<th>Difference between maximum water tables (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>2.059</td>
<td>2.079</td>
<td>0.020</td>
</tr>
<tr>
<td>5.0</td>
<td>2.102</td>
<td>2.138</td>
<td>0.036</td>
</tr>
<tr>
<td>7.5</td>
<td>2.146</td>
<td>2.193</td>
<td>0.047</td>
</tr>
<tr>
<td>10.0</td>
<td>2.190</td>
<td>2.252</td>
<td>0.062</td>
</tr>
</tbody>
</table>

In the fine sand aquifer, the water flowed almost horizontally until it reached the gravel envelope at the end drains with a much greater hydraulic conductivity, where it flowed vertically upward to the pipe drain. This flow net has the effect of reducing the headloss due to convergence of the streamlines flowing toward the drain.

Hooghoudt’s method of correcting for convergence assumed radial flow toward the drain from a radial distance out from the drain equal to the depth between the drain and the barrier. Figures 13 and 14 show the reduction in water table height above the drains in the sand tank model with increased drain radius plus gravel pack. The curves are based on Equations (38) and (39). Values of the ratios P/R and the data points for a radius of drain plus gravel envelope equal to 0.1 foot were the same values as were tested in the sand tank model. For given values of P/R and drain spacings, the height of water table drops rapidly as the drain radius plus gravel envelope is increased.

EFFECT OF DRAIN RADIUS ON DRAIN SPACING

If increasing the radius of the drain plus gravel envelope causes a reduction in maximum water table height between drains, it follows that increasing the drain plus gravel envelope radius would allow an increased drain spacing and thereby the total cost of a drainage installation could possibly be reduced. A feasible method might be developed to accomplish this end. It seems feasible to install highly permeable material in a narrow trench below the drain—possibly using inorganic highly porous material made from plastic would be practical. Additional studies should be made to determine just what effect using an envelope in a trench below the pipe drain would have compared to the full radius used in the computations in this report.
To determine approximately how much the drain spacing could be increased by increasing the drain and gravel envelope radius, computations were made using the computer program, Appendix 1, to solve the Donnan equation with Hooghoudt's correction. A typical field condition with the following values was used: water table above drains at the centerline \( H = 4.0 \text{ ft} (1.22 \text{ m}) \); hydraulic conductivity of aquifer \( P = 1.5 \text{ ft} (0.457 \text{ m}) \) per day; deep percolation rate \( R = 0.00417 \text{ ft} (0.00127 \text{ m}) \) per day using the ratio \( P/R = 359.97 \); depths—drains to barrier, \( D = 31.5 \text{ ft} (9.60 \text{ m}) \). For a radius of drain plus gravel pack equal to 0.7 ft (0.2134 m) the computer program gives an answer for drain spacing of 537 ft (163.7 m). This answer is based on steady-state conditions in which the deep percolation rate is taken as the average deep percolation rate during the peak irrigation season (17 days between irrigations). This example uses the same data as L. D. Dumm used in Table 4 of his paper. (Reference 6) Dumm computed a drain spacing of 490 ft for what he describes as dynamic equilibrium in which water buildup is considered for each irrigation. With a value of \( R = 0.0049 \text{ ft} (0.00149 \text{ m}) \) per day for average deep percolation rate, which would represent an average time between irrigations of 14.5 days, a drain spacing of 489 ft (149.05 m) was computed using the computer program.

Values of the radius of drain plus gravel envelope were increased in steps and computations made to show how much the drain spacing could be increased. Doubling the radius from 0.7 ft (0.213 m) to 1.4 ft (0.426 m) resulted in an increase in drain spacing from 489 ft (149.05 m) to 511 ft (155.75 m), or 4-1/2 percent. Table 2. Increasing the radius of drain plus envelope to 8 ft (2.44 m) resulted in a drain spacing of 572 ft (174.35 m), or an increase of 17 percent over the spacing of 489 ft (149.05 m) with a 0.7-ft (0.213-m) radius, Table 2 and Figure 15. Additional values of drain spacing were computed for a range of values for the ratio of \( P/R \), hydraulic conductivity divided by the deep percolation. They are included in Figure 15 and Table 3.
REFERENCES


4. Dumm, Lee D., Drain Spacing Formula, Agricultural Engineering, October 1954


NOTATION

The following symbols are used in the report.

Dimensioned variables are indicated by giving their dimensions in units of length (L) and time (T) in parentheses after their definitions.

\[
\begin{align*}
A &= \text{cross section area (L}^2) \\
\alpha, \beta, \gamma &= \text{parameters described in text} \\
b &= \text{height of water table above impermeable barrier (L)} \\
b' &= \text{Hooghoudt's equivalent height of water table above impermeable barrier (L)} \\
d &= \text{depth, centerline of drains to impermeable barrier (L)} \\
d' &= \text{D in computer programs} \\
\frac{dy}{dx} &= \text{Hooghoudt's equivalent depth (L)} \\
H &= \text{hydraulic gradient (dimensionless)} \\
h &= \text{height of water table above centerline of drains (L)} \\
in &= \text{depth of water in an open ditch drain (L)} \\
\ln &= \text{natural logarithm} \\
P &= \text{coefficient of hydraulic conductivity (L/T)} \\
Q &= \text{discharge (L}^3/T) \\
q &= \text{discharge per unit area (L/T)} \\
r &= \text{radius of drain plus thickness of gravel envelope (L)} \\
R &= \text{R in computer programs} \\
R' &= \text{recharge or deep percolation rate (L/T)} \\
S &= \text{spacing between centerlines of drains (L)} \\
S_i &= \text{estimated drain spacing (L)} \\
T &= \text{dimensionless ratio (P/R)} \\
x, y &= \text{rectangular coordinates (L)}
\end{align*}
\]
TABLE 2
COMPUTER PRINTOUT - P/R = 306.12

COMPUTATIONS FOR DRAIN SPACING - STEADY RECHARGE
DONNAN'S FORMULA WITH HOGHOUDT'S CORR FOR CONVERGENCE
FOR 0 < D/S <= .312 OR .312 < D/S,
WATER TABLE ABOVE DRAINS AT CENTER LINE, H - FT 4.00
RADIUS OF DRAIN + GRAVEL PACK, R1 - FT 0.70
DEPTH - DRAINS TO BARRIER, D - FT 31.5

<table>
<thead>
<tr>
<th>PERMEABILITY</th>
<th>AVG RECHARGE</th>
<th>DRAIN SPACING</th>
</tr>
</thead>
<tbody>
<tr>
<td>FT/DAY P(K)/R(I) FT/DAY</td>
<td>FT</td>
<td></td>
</tr>
<tr>
<td>1.500</td>
<td>306.12</td>
<td>0.00490</td>
</tr>
</tbody>
</table>

COMPUTATIONS FOR DRAIN SPACING - STEADY RECHARGE
DONNAN'S FORMULA WITH HOGHOUDT'S CORR FOR CONVERGENCE
FOR 0 < D/S <= .312 OR .312 < D/S,
WATER TABLE ABOVE DRAINS AT CENTER LINE, H - FT 4.00
RADIUS OF DRAIN + GRAVEL PACK, R1 - FT 1.40
DEPTH - DRAINS TO BARRIER, D - FT 31.5

<table>
<thead>
<tr>
<th>PERMEABILITY</th>
<th>AVG RECHARGE</th>
<th>DRAIN SPACING</th>
</tr>
</thead>
<tbody>
<tr>
<td>FT/DAY P(K)/R(I) FT/DAY</td>
<td>FT</td>
<td></td>
</tr>
<tr>
<td>1.500</td>
<td>306.12</td>
<td>0.00490</td>
</tr>
</tbody>
</table>

COMPUTATIONS FOR DRAIN SPACING - STEADY RECHARGE
DONNAN'S FORMULA WITH HOGHOUDT'S CORR FOR CONVERGENCE
FOR 0 < D/S <= .312 OR .312 < D/S,
WATER TABLE ABOVE DRAINS AT CENTER LINE, H - FT 4.00
RADIUS OF DRAIN + GRAVEL PACK, R1 - FT 2.80
DEPTH - DRAINS TO BARRIER, D - FT 31.5

<table>
<thead>
<tr>
<th>PERMEABILITY</th>
<th>AVG RECHARGE</th>
<th>DRAIN SPACING</th>
</tr>
</thead>
<tbody>
<tr>
<td>FT/DAY P(K)/R(I) FT/DAY</td>
<td>FT</td>
<td></td>
</tr>
<tr>
<td>1.500</td>
<td>306.12</td>
<td>0.00490</td>
</tr>
</tbody>
</table>
### TABLE 2 (CONT.)

**COMPUTATIONS FOR DRAIN SPACING - STEADY RECHARGE**  
**DONNAN’S FORMULA WITH HOGHOUDT’S CORR FOR CONVERGENCE**  
**FOR 0 < D/S <= .312 OR .312 < D/S,**  
**WATER TABLE ABOVE DRAINS AT CENTER LINE, H - FT 4.00**  
**RADIUS OF DRAIN + GRAVEL PACK, R1 - FT 5.60**  
**DEPTH OF DRAINS TO BARRIER, D - FT 31.5**

<table>
<thead>
<tr>
<th>PERMEABILITY FT/DAY</th>
<th>AVG RECHARGE P(K)/R(I) FT/DAY</th>
<th>DRAIN SPACING FT D/S</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.500</td>
<td>306.12</td>
<td>0.00490 558.31 0.0564</td>
</tr>
</tbody>
</table>

**COMPUTATIONS FOR DRAIN SPACING - STEADY RECHARGE**  
**DONNAN’S FORMULA WITH HOGHOUDT’S CORR FOR CONVERGENCE**  
**FOR 0 < D/S <= .312 OR .312 < D/S,**  
**WATER TABLE ABOVE DRAINS AT CENTER LINE, H - FT 4.00**  
**RADIUS OF DRAIN + GRAVEL PACK, R1 - FT 8.00**  
**DEPTH OF DRAINS TO BARRIER, D - FT 31.5**

<table>
<thead>
<tr>
<th>PERMEABILITY FT/DAY</th>
<th>AVG RECHARGE P(K)/R(I) FT/DAY</th>
<th>DRAIN SPACING FT D/S</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.500</td>
<td>306.12</td>
<td>0.00490 571.52 0.0551</td>
</tr>
</tbody>
</table>
### TABLE 3

**Computer Printout - P/R = Variable**

**Computations for Drain Spacing - Steady Recharge**

Donnan's Formula with Hooghoudt's Corr for Convergence

*For 0 < D/S <= .312 or .312 < D/S,*

Water Table Above Drains at Center Line, H = FT 4.00

Radius of Drain + Gravel Pack, R1 = FT 0.60

Depth = Drains to Barrier, D = FT 31.5

<table>
<thead>
<tr>
<th>Permeability (FT/Day)</th>
<th>Avg Recharge (P(K)/R(I))</th>
<th>Drain Spacing (FT)</th>
<th>D/S</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.500</td>
<td>1500.00</td>
<td>0.00100</td>
<td>1173.88</td>
</tr>
<tr>
<td>1.500</td>
<td>750.00</td>
<td>0.00200</td>
<td>804.45</td>
</tr>
<tr>
<td>1.500</td>
<td>75.00</td>
<td>0.02000</td>
<td>205.20</td>
</tr>
<tr>
<td>1.500</td>
<td>0.75</td>
<td>2.00000</td>
<td>10.26</td>
</tr>
</tbody>
</table>

**Computations for Drain Spacing - Steady Recharge**

Donnan's Formula with Hooghoudt's Corr for Convergence

*For 0 < D/S <= .312 or .312 < D/S,*

Water Table Above Drains at Center Line, H = FT 4.00

Radius of Drain + Gravel Pack, R1 = FT 1.20

Depth = Drains to Barrier, D = FT 31.5

<table>
<thead>
<tr>
<th>Permeability (FT/Day)</th>
<th>Avg Recharge (P(K)/R(I))</th>
<th>Drain Spacing (FT)</th>
<th>D/S</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.500</td>
<td>1500.00</td>
<td>0.00100</td>
<td>1197.81</td>
</tr>
<tr>
<td>1.500</td>
<td>750.00</td>
<td>0.00200</td>
<td>827.48</td>
</tr>
<tr>
<td>1.500</td>
<td>75.00</td>
<td>0.02000</td>
<td>222.09</td>
</tr>
<tr>
<td>1.500</td>
<td>0.75</td>
<td>2.00000</td>
<td>12.09</td>
</tr>
</tbody>
</table>

**Computations for Drain Spacing - Steady Recharge**

Donnan's Formula with Hooghoudt's Corr for Convergence

*For 0 < D/S <= .312 or .312 < D/S,*

Water Table Above Drains at Center Line, H = FT 4.00

Radius of Drain + Gravel Pack, R1 = FT 2.40

Depth = Drains to Barrier, D = FT 31.5

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### TABLE 3 (CONT.)

**COMPUTATIONS FOR DRAIN SPACING - STEADY RECHARGE**

DONNAN'S FORMULA WITH HOGHOUDI'S CORR FOR CONVERGENCE  
FOR $0 < \frac{D}{S} \leq \cdot312$ OR $\cdot312 < \frac{D}{S}$,
WATER TABLE ABOVE DRAINS AT CENTER LINE, $H$ - FT 4.00
RADIUS OF DRAIN + GRAVEL PACK, $R_1$ - FT 4.80
DEPTH - DRAINS TO BARRIER, $D$ - FT 31.5

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**COMPUTATIONS FOR DRAIN SPACING - STEADY RECHARGE**

DONNAN'S FORMULA WITH HOGHOUDI'S CORR FOR CONVERGENCE  
FOR $0 < \frac{D}{S} \leq \cdot312$ OR $\cdot312 < \frac{D}{S}$,
WATER TABLE ABOVE DRAINS AT CENTER LINE, $H$ - FT 4.00
RADIUS OF DRAIN + GRAVEL PACK, $R_1$ - FT 6.00
DEPTH - DRAINS TO BARRIER, $D$ - FT 31.5

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Appendix 1

DOCUMENTATION OF COMPUTER PROGRAM PRO 1532-DRHWT

1. BRECS Program Description PRO 1532-DRHWT.
2. BRECS Users Manual PRO 1532-DRHWT.
3. FORTRAN Listing EJC16 for PRO 1532-DRHWT with two example computations.
BUREAU OF RECLAMATION ENGINEERING COMPUTER SYSTEM

HYDRAULICS PROBLEM AREA

UPFC PROGRAM DESCRIPTION-PFG 1532-REFAX

BY

E. J. CARLSON

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF RECLAMATION

DIVISION OF GENERAL RESEARCH

HYDRAULICS BRANCH

ENGINEERING AND RESEARCH CENTER

DENVER, COLORADO 68/74/74
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CHAPTER 1. PROGRAM TITLE

CHAPTER 2. PURPOSE

CHAPTER 3. METHOD

CHAPTER 4. INPUT-OUTPUT

CHAPTER 5. LIMITATIONS

(A)
PROGRAM TITLE

WATER TABLE HEIGHT ABOVE PIPE DRAINS-STABLE RECHARGE

PURPOSE

TO COMPUTE MAXIMUM HEIGHT OF WATER TABLE ABOVE
AGRICULTURAL PIPE DRAINS AT THE CENTERLINE BETWEEN
LINES OF DRAINS.

METHOD

THE PROGRAM COMPUTES MAXIMUM WATER TABLE
HEIGHT USING MOHAN'S FORMULA CORRECTED FOR
COVERAGE OF FLOW TO DRAINS BY HOGHOUAIRS
METHOD.

INPUT-OUTPUT

THE INPUT WILL CONSIST OF:
VALUES OF AQUIFER HYDRAULIC CONDUCTIVITY,
DEEP PERCOLATION RATE, DRAIN SPACING, DISTANCE-CENTER
OF DRAINS TO AQUIFER, RADIUS OF DRAIN PLUS
THICKNESS OF GRAVEL PACK

THE OUTPUT WILL CONSIST OF:
HYDRAULIC CONDUCTIVITY OF AQUIFER, AVERAGE RECHARGE,
RATIO P/R, MAXIMUM WATER TABLE, RATIO D/S.

LIMITATIONS

PROGRAM CAN BE USED FOR LABORATORY OR FIELD
TYPE COMPUTATIONS. THERE ARE NO GENERAL LIMITATIONS.
BUREAU OF RECLAMATION ENGINEERING COMPUTER SYSTEM

---

HYDRAULICS PROBLEM AREA

PRESOS USERS MANUAL - RUS 1522-DWMT

BY

E.J. CARLSON

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF RECLAMATION

DIVISION OF GENERAL RESEARCH

HYDRAULICS BRANCH

ENGINEERING AND RESEARCH CENTER

DENVER, COLORADO 08/24/71

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(A)
PROGRAM TITLE

WATER TABLE HEIGHT ABOVE PIPE DRAINS-STEADY RECHARGE

OUTPUT


GENERAL DESCRIPTION

THE TIME SHARING FORTRAN COMPUTER PROGRAM COMPUTES THE MAXIMUM HEIGHT OF WATER TABLE BETWEEN ADJACENT PIPE DRAINS. THE THEORETICAL FORMULA FOR COMPUTING DRAIN SPACING IS REARRANGED SO THAT INSTEAD OF SOLVING FOR DRAIN SPACING, THE MAXIMUM HEIGHT OF WATER TABLE IS THE RESULTANT VALUE WITH DRAIN SPACING BEING AN INDEPENDENT VARIABLE. THE PROGRAM DETERMINES THE VALUE OF THE RATIO U/S, (DISTANCE OF DRAINS TO BARRIER/URAIN SPACING) AND THE PROGRAM THEN SELETS WHICH FORMULA TO USE TO COMPUTE MAXIMUM HEIGHT OF WATER TABLE BETWEEN DRAINS. A DIRECT SOLUTION OF A QUADRATIC FORMULA IS THEN MADE FOR MAXIMUM WATER TABLE HEIGHT.

THE PROGRAM IS AVAILABLE ON PUNCH PAPER TAPE AND IT IS ALSO CURRENTLY STORED IN THE TIME SHADING SYSTEM IN USE AT THE E AND R CENTER.

INPUT DATA

INPUT DATA ARE ADDED TO THE TIME SHARING FORTRAN PROGRAM WITH THE TELETYPING CONSOLE ON LINE. VALUES OF HYDRAULIC CONDUCTIVITY OF THE AQUIFER MATERIAL AND THE DEEP PERCOLATION RECHARGE RATE ARE ADDED IN THE DATA STATEMENTS. DIMENSION STATEMENTS DETERMINE THE NUMBER OF DATA VALUES THAT CAN BE USED. DIMENSION AND DATA STATEMENTS CAN BE CHANGED TO PROVIDE FOR AS MANY VALUES OF HYDRAULIC CONDUCTIVITY OF THE AQUIFER MATERIAL AND OF THE RECHARGE DUE TO DEEP PERCOLATION RATES AS ARE DESIRED. VALUES OF URAIN SPACING, RADIUS OF URAIN PLUS THICKNESS OF GRAVEL PACK AND DISTANCE OF DRAINS TO BARRIER ARE INPUT ON LINE IN ANSWER TO THE QUESTION "INPUT".

27
EJC16

100 C COMPUTATIONS FOR MAXIMUM WATER TABLE BETWEEN DRAINS - STEADY RECHARGE - DONNAN'S FORMULA WITH HOOQHOUDE'S CORRECTION FOR CONVERGENCE
110 C IF 0 < D/S <= .312 USE FORMULA A. IF .312 < D/S USE FORMULA B
120 C DIMENSION P(5)
130 C DIMENSION R(5)
140 C DATA P/
150 C DATA R/
160 C DATA S/
170 C DATA F/
180 C DATA G/
190 C DATA H/
200 C S = DRAIN SPACING - FT
210 C R = RADIUS OF DRAIN + GRAVEL PACK - FT
220 C D = DEPTH DRAINS TO BARRIER - FT
230 C READ 1,S,R,D
240 1 FORMAT (3F5.2)
250 PRINT 3,S,R,D
260 3 FORMAT (1H1,17X,

260 & 50H:COMPUTATIONS FOR MAX WATER TABLE - STEADY RECHARGE,

290 & 15X,54HDONNNAN'S FORMULA WITH HOOQHOUDE'S CORR FOR CONVERGENCE,

300 & 15X,33HFOR 0 < D/S <= .312 OR .312 < D/S,

310 & 15X,21HDRAIN SPACING, S - FT F6.1,

320 & 15X,38HRADIUS OF DRAIN + GRAVEL PACK, R1 - FT F5.2,

340 & 15X,33IDEPHT DRAINS TO BARRIER, D - FT F6.1,

350 & 15X,50HPERMEABILITY AVG RECHARGE MAX WATER TABLE,

360 & 15X,54H/DAY P(K)/R(I) FT/DAY FT D/S//,

360 & 5 FORMAT (4X,F7.3,2X,F8.2,2X,F8.4,9X,F10.4,8X,F8.4)

370 DO 10 K = 1,S

375 IF (P(K),EQ. 0.) GO TO 2

380 DO 20 I = 1,D

385 IF (R(I),EQ. 0.) GO TO 10

390 T = P(K)/R(I)

395 V = D/S

400 IF ( V GT. 0.312 ) GO TO 6

410 A = 1 + (2.546*D/S)*ALOG(R/D)

420 B = -3.55*(D/S) + 1.6*(D**2/S**2) - ((2*D**3)/(S**3))

430 C = D/(A*B)

440 E = SQRT(C**2 + (S**2*R(I))/(4.*P(K)))

450 H = -C + E

530 PRINT 5,P(K),T,R(I),H,V

540 5 FORMAT (4X,F7.3,2X,F8.2,2X,F8.4,9X,F10.4,8X,F8.4)

550 G0 TO 20

570 GO TO 10

572 C START FORMULA B (FOR .312< D/S)

580 6 A1 = 2.546*(ALOG(S/R1) - 1.15)

590 B1 = (S/A1)

600 C1 = SQRT(B1**2 + (S**2*R(I))/(4.*P(K)))

610 H = -B1 + C1

630 PRINT 6,P(K),T,R(I),H,V

690 8 FORMAT (4X,F7.3,2X,F8.2,2X,F8.4,9X,F10.4,8X,F8.4)
EJC16 CONTINUED

700 20 CONTINUE
710 PRINT, " "
720 10 CONTINUE
730 2 STOP
740 END
INPUT: 00240

? 0060000010000200

Computations for Max Water Table - Steady Recharge

Donnan's formula with Hooghoudt's Corr for Convergence
For 0 < D/S <= .312 or .312 < D/S
Drain spacing, S - ft 6.0
Radius of drain + gravel pack, R1 - ft 0.10
Depth - drains to barrier, D - ft 2.0

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Stop

Computer Units: 7.7

Ready
**Computations for Max Water Table - Steady Recharge**

- Donnan's formula with Hooghoudt's corr for convergence
- For $0 < D/S <= .312$ or $.312 < D/S$

**Drain Spacing, $S$ - ft**: 12.0

**Radius of Drain + Gravel Pack, $R_1$ - ft**: 0.10

**Depth - Drains to Barrier, $D$ - ft**: 2.0

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**Stop**

**Computer Units**: 4.0

**Ready**
Appendix 2

DOCUMENTATION OF COMPUTER PROGRAM PRO 1532-DRSP

1. BRECS Program Description PRO 1532-DRSP.
2. BRECS Users Manual PRO 1532-DRSP.
3. FORTRAN Listing EJC18 for PRO 1532-DRSP with an example computation.
HYDRAULICS PROBLEM AREA

BRECS PROGRAM DESCRIPTION-FPO 1532-DRSP

BY

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UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF RECLAMATION

DIVISION OF GENERAL RESEARCH

HYDRAULICS BRANCH

ENGINEERING AND RESEARCH CENTER

DENVER, COLORADO  UN/25/71
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CHAPTER 5. LIMITATIONS ................................................... 1

(A)
PROGRAM TITLE

DRAIN SPACING-STEADY RECHARGE

PURPOSE

TO COMPUTE DRAIN SPACING BETWEEN LINES OF AGRICULTURAL TYPE PIPE DRAINS.

METHOD

THE PROGRAM COMPUTES DRAIN SPACING USING RUMANS FORMULA CORRECTED FOR CONVERGENCE OF FLOW TO DRAINS BY HOOGHOUTS METHOD.

INPUT-OUTPUT

THE INPUT WILL CONSIST OF:
VALUES OF AQUIFER HYDRAULIC CONDUCTIVITY,
DEEP PERCOLATION RATE, MAXIMUM HEIGHT OF WATER TABLE ABOVE CENTER OF DRAINS AT CENTER LINE BETWEEN DRAINS, RADIUS OF DRAIN PLUS THICKNESS OF GRAVEL PACK, DISTANCE-CENTER OF DRAINS TO BARRIER.

THE OUTPUT WILL CONSIST OF:
HYDRAULIC CONDUCTIVITY OF AQUIFER, AVERAGE RECHARGE RATE, RATIO P/R, DRAIN SPACING, RATIO U/S.

LIMITATIONS

PROGRAM CAN BE USED FOR LABORATORY OR FILL TYPE COMPUTATIONS. THERE ARE NO GENERAL LIMITATIONS.
BUREAU OF RECLAMATION ENGINEERING COMPUTER SYSTEM

U.S. DEPARTMENT OF THE INTERIOR

ENGINEERING AND RESEARCH CENTER

DENVER, COLORADO 00/25/71
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<td>CHAPTER 4. INPUT DATA</td>
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(A)
DRAIN SPACING-STEADY RECHARGE

THE VALUES SHOWN ON THE OUTPUT LISTING ARE THE INPUT DATA AND THE COMPUTE
VALUES OF DRAIN SPACING AND COMPUTED VALUES OF THE RATIO P/R (HYDRAULIC
CONDUCTIVITY / DEEP PERCOLATION RECHARGE RATE) AND D/S (DISTANCE OF DRAINS
ABOVE THE BARRIER / DRAIN SPACING).

THE TIME SHARING FORTRAN COMPUTER PROGRAM COMPUTES THE DRAIN SPACING FOR
PLACING ADJACENT PIPE DRAINS. THE THEORETICAL FORMULA FOR STEADY STATE
DRAINAGE INCLUDES A CORRECTION FOR CONVERGENCE AS THE WATER APPROACHES THE
DRAIN. THE CORRECTION FOR CONVERGENCE DEPENDS ON THE VALUE OF THE RATIO D/S
(DISTANCE OF DRAINS ABOVE THE BARRIER / DRAIN SPACING). THE COMPUTER PROGRAM
COMPUTES A FIRST ESTIMATE FOR DRAIN SPACING USING AN UNCORRECTED FORMULA TO
DETERMINE WHICH RANGE THE RATIO D/S FALLS. THE PROGRAM THEN SELECTS THE
FORMULA TO BE USED WITH WHICH TO COMPUTE THE ACCURATE DRAIN SPACING. THE
NEWTON-RAPHSON METHOD OF CONVERGING ON A SOLUTION BY THE ITERATIVE METHOD
WITHIN THE ACCURACY DESIRED IS USED IN THE FINAL STEP FOR COMPUTING THE DRAIN
SPACING.

THE PROGRAM IS FOR STEADY STATE DRAINAGE CONDITIONS. THE PROGRAM CAN BE USED
AS A SUBPROGRAM FOR OTHER DRAINAGE PROBLEMS.
INPUT DATA

INPUT DATA ARE ADDED TO THE TIME SHARING FORTRAN PROGRAM WITH THE TELTYPE
CONSOLE ON LINE. VALUES OF HYDRAULIC CONDUCTIVITY OF THE AQUIFER MATERIAL AND
THE DEEP PERCOLATION RECHARGE RATE ARE INPUT IN THE DATA STATEMENTS. DIMENSION
STATEMENTS ARE USED TO DETERMINE THE NUMBER OF DATA VALUES TO BE USED.
DIMENSION AND DATA STATEMENTS CAN BE CHANGED TO PROVIDE FOR AS MANY VALUES OF
HYDRAULIC CONDUCTIVITY OF AQUIFER MATERIAL AND OF THE RECHARGE DUE TO DEEP
PERCOLATION RATES AS ARE DESIRED.
VALUES OF MAXIMUM WATER TABLE ABOVE THE CENTER OF DRAINS, RADIUS OF DRAIN +
THICKNESS OF GRAVEL PACK AND DISTANCE OF DRAINS TO BARRIER ARE INPUT WITH THE
CONSOLE ON LINE IN ANSWER TO THE QUESTION "INPUT". THE PROGRAM IS AVAILABLE ON
PUNCHED PAPER TAPE FOR THE TELTYPE CONSOLE. IT IS ALSO CURRENTLY STORED IN
THE TIME SHARING SYSTEM USED BY THE E AND R CENTER IN DENVER, COLORADO.
COMPUTATIONS FOR DRAIN SPACING - STEADY RECHARGE

USING DÖNNAN'S FORMULA WITH HØGHOUDT'S CORR FOR CONVERGENCE
IF 0 < D/S <= .312 USE FORMULA A. IF .312 < D/S USE FORMULA B

DIMENSION P(5)
DIMENSION R(5)
DATA P/
  51.0,2.0,5.0,10.0/
DATA R/
  .001,.002,.02,.2,.0/

INPUT VALUES

H = WATER TABLE CENTER LINE ABOVE DRAINS - FT
R1 = RADIUS OF DRAIN + GRAVEL PACK - FT
D = DEPTH - DRAINS TO BARRIER - FT

READ 1,H,R1,D

1 FORMAT (3F5.2)
PRINT 3,H,R1,D FOR H

FOR O < D/S <= .312 OR .312 < D/S,

H = WATER TABLE CENTER LINE ABOVE DRAINS AT CENTER LINE, H - FT F5.2,
D = DEPTH - DRAINS TO BARRIER, D - FT F5.2,

START FORMULA A (FOR O < D/S <= .312)

D0 10 K = 1.5
D0 20 I = 1.5
D0 30 J = 1.20
D0 40 A = 8.0*T*H*D*S1
D0 50 B = S1 + (8.0*D/3.1416)*ALO6(D/R1) - 3.4*D
D0 60 C = A/B + 4.0*T*H**2 - S1**2
D0 70 E = A/S1
D0 80 G = E/B - A/B**2 - 2.*S1
D0 90 S = S1 - C/G
D0 100 SAB = ABS(S-S1)
D0 110 V = D/S
D0 120 IF (V < G) G0 TO 6
D0 130 IF (SAB < S) G0 TO 4
D0 140 S1 = S

CONTINUE
D0 20 30 PRINT 5,P(K),T,R(I),S,V
D0 30 5 FORMAT (4X,F7.3,2X,F8.2,2X,F8.5,6X,F10.2,8X,F8.4)
D0 40 50 G0 TO 20
D0 50 570 G0 TO 10
CONTINUED

572C  START FORMULA B (FOR 312<D/S)

580  6 DO 40 J = 1,20

590  A1 = 3.1416*H*S1

600  B1 = ALOG(S1/R1) - 1.15

610  C1 = A1/B1 + 4.*T*H**2 - S1**2

620  E1 = A1/S1

630  G1 = E1/B1 - E1/B1**2 - 2.*S1

640  S = S1 - C1/G1

650  SAE = ABS(S-S1)

652  VL = D/S

660  IF (SAB .LT. 0.1) GO TO 7

662  S1 = S

670  40 CONTINUE

680  7 PRINT 8,P(K),T,F(I),S,VL

690  8 FORMAT (4X,F7.3,2X,F6.2,2X,F6.5,6X,F10.2,8X,F8.4)

691  20 CONTINUE

692  9 PRINT, " "

693  10 CONTINUE

710  2 STOP

720  END
### Computations for Drain Spacing - Steady Recharge

Donnan's formula with Hooghoudt's corr for convergence

For $0 < D/S < 0.312$ or $0.312 < D/S$

- Water table above drains at center line, $H = 4.00$
- Radius of drain + gravel pack, $R1 = 0.60$
- Depth - drains to barrier, $D = 31.5$

#### Permeability

<table>
<thead>
<tr>
<th>$P(k)/R1$</th>
<th>Avg Recharge</th>
<th>Drain Spacing</th>
<th>$D/S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FT/DAY</td>
<td>FT/DAY</td>
<td>FT</td>
<td></td>
</tr>
<tr>
<td>0.500</td>
<td>500.00</td>
<td>0.00100</td>
<td>641.42</td>
</tr>
<tr>
<td>0.500</td>
<td>250.00</td>
<td>0.00200</td>
<td>430.34</td>
</tr>
<tr>
<td>0.500</td>
<td>25.00</td>
<td>0.02000</td>
<td>96.51</td>
</tr>
<tr>
<td>0.500</td>
<td>2.50</td>
<td>0.20000</td>
<td>20.80</td>
</tr>
<tr>
<td>1.000</td>
<td>1000.00</td>
<td>0.00100</td>
<td>942.26</td>
</tr>
<tr>
<td>1.000</td>
<td>500.00</td>
<td>0.00200</td>
<td>641.42</td>
</tr>
<tr>
<td>1.000</td>
<td>50.00</td>
<td>0.02000</td>
<td>157.32</td>
</tr>
<tr>
<td>1.000</td>
<td>5.00</td>
<td>0.20000</td>
<td>32.15</td>
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<tr>
<td>2.000</td>
<td>2000.00</td>
<td>0.00100</td>
<td>1369.41</td>
</tr>
<tr>
<td>2.000</td>
<td>1000.00</td>
<td>0.00200</td>
<td>942.26</td>
</tr>
<tr>
<td>2.000</td>
<td>100.00</td>
<td>0.02000</td>
<td>246.49</td>
</tr>
<tr>
<td>2.000</td>
<td>10.00</td>
<td>0.20000</td>
<td>50.81</td>
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<td>5.000</td>
<td>5000.00</td>
<td>0.00100</td>
<td>2218.80</td>
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<tr>
<td>5.000</td>
<td>2500.00</td>
<td>0.00200</td>
<td>1541.80</td>
</tr>
<tr>
<td>5.000</td>
<td>250.00</td>
<td>0.02000</td>
<td>430.34</td>
</tr>
<tr>
<td>5.000</td>
<td>25.00</td>
<td>0.20000</td>
<td>96.51</td>
</tr>
<tr>
<td>10.000</td>
<td>10000.00</td>
<td>0.00100</td>
<td>3177.00</td>
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<td>0.00200</td>
<td>2218.80</td>
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<td>10.000</td>
<td>500.00</td>
<td>0.02000</td>
<td>641.42</td>
</tr>
<tr>
<td>10.000</td>
<td>50.00</td>
<td>0.20000</td>
<td>157.32</td>
</tr>
</tbody>
</table>

STOP

COMPUTER UNITS 4.9

READY
CONVERSION FACTORS—BRITISH TO METRIC UNITS OF MEASUREMENT

The following conversion factors adopted by the Bureau of Reclamation are those published by the American Society for Testing and Materials (ASTM Metric Practice Guide, E 380-68) except that additional factors (*) commonly used in the Bureau have been added. Further discussion of definitions of quantities and units is given in the ASTM Metric Practice Guide.

The metric units and conversion factors adopted by the ASTM are based on the "International System of Units" (designated SI for Systeme International d'Unités), fixed by the International Committee for Weights and Measures; this system is also known as the Giorgi or MKSA (meter-kilogram-second-ampere) system. This system has been adopted by the International Organization for Standardization in ISO Recommendation R-31.

The metric technical unit of force is the kilogram-force; this is the force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 9.80665 m/sec/sec, the standard acceleration of free fall toward the earth's center for sea level at 45 deg latitude. The metric unit of force in SI units is the newton (N), which is defined as that force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 1 m/sec/sec. These units must be distinguished from the (inconstant) local weight of a body having a mass of 1 kg, that is, the weight of a body is that force with which a body is attracted to the earth and is equal to the mass of a body multiplied by the acceleration due to gravity. However, because it is general practice to use "pound" rather than the technically correct term "pound-force," the term "kilogram" (or derived mass unit) has been used in this guide instead of "kilogram-force." In expressing the conversion factors for forces. The newton unit of force will find increasing use, and is essential in SI units.

Where approximate or nominal English units are used to express a value or range of values, the converted metric units are expressed as equally significant values.

Table I

<table>
<thead>
<tr>
<th>QUANTITIES AND UNITS OF SPACE</th>
<th>Multiply</th>
<th>By</th>
<th>To obtain</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LENGTH</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mill</td>
<td></td>
<td>25.4 (exactly)</td>
<td>Micron</td>
</tr>
<tr>
<td>Inches</td>
<td></td>
<td>25.4 (exactly)</td>
<td>Millimeters</td>
</tr>
<tr>
<td>Centimeters</td>
<td></td>
<td>0.0003048 (exactly)</td>
<td>Centimeters</td>
</tr>
<tr>
<td>Feet</td>
<td></td>
<td>0.3048 (exactly)</td>
<td>Centimeters</td>
</tr>
<tr>
<td>Feet</td>
<td></td>
<td>0.003048 (exactly)</td>
<td>Meters</td>
</tr>
<tr>
<td>Yards</td>
<td></td>
<td>0.9144 (exactly)</td>
<td>Meters</td>
</tr>
<tr>
<td>Miles ( statute)</td>
<td></td>
<td>1.609344 (exactly)</td>
<td>Miles</td>
</tr>
<tr>
<td>Miles</td>
<td></td>
<td>1.609344 (exactly)</td>
<td>Kilometers</td>
</tr>
<tr>
<td><strong>AREA</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Square inches</td>
<td></td>
<td>6.4516 (exactly)</td>
<td>Square centimeters</td>
</tr>
<tr>
<td>Square feet</td>
<td></td>
<td>*929.03</td>
<td>Square centimeters</td>
</tr>
<tr>
<td>Square feet</td>
<td></td>
<td>0.092903</td>
<td>Square meters</td>
</tr>
<tr>
<td>Square yards</td>
<td></td>
<td>0.836127</td>
<td>Square meters</td>
</tr>
<tr>
<td>Acres</td>
<td></td>
<td>*0.40469</td>
<td>Hectares</td>
</tr>
<tr>
<td>Acres</td>
<td></td>
<td>*4,046.9</td>
<td>Square meters</td>
</tr>
<tr>
<td>Acres</td>
<td></td>
<td>*0.0040469</td>
<td>Square kilometers</td>
</tr>
<tr>
<td>Square miles</td>
<td></td>
<td>2.59998</td>
<td>Square kilometers</td>
</tr>
<tr>
<td><strong>VOLUME</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Cubic inches</td>
<td></td>
<td>16.3871</td>
<td>Cubic centimeters</td>
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<tr>
<td>Cubic feet</td>
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<td>0.0293168</td>
<td>Cubic meters</td>
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<tr>
<td>Cubic yards</td>
<td></td>
<td>0.764555</td>
<td>Cubic meters</td>
</tr>
<tr>
<td><strong>CAPACITY</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluid ounces (U.S.)</td>
<td></td>
<td>29.5737</td>
<td>Cubic centimeters</td>
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<tr>
<td>Fluid ounces (U.S.)</td>
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<td>29.5728</td>
<td>Milliliters</td>
</tr>
<tr>
<td>Liquid pints (U.S.)</td>
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</tr>
<tr>
<td>Liquid pints (U.S.)</td>
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<td>0.473166</td>
<td>Liters</td>
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<tr>
<td>Quarts (U.S.)</td>
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<td>*946.38</td>
<td>Cubic centimeters</td>
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<tr>
<td>Quarts (U.S.)</td>
<td></td>
<td>*3,785.43</td>
<td>Cubic centimeters</td>
</tr>
<tr>
<td>Gallons (U.S.)</td>
<td></td>
<td>3.78543</td>
<td>Cubic decimeters</td>
</tr>
<tr>
<td>Gallons (U.S.)</td>
<td></td>
<td>3.78533</td>
<td>Liters</td>
</tr>
<tr>
<td>Gallons (U.S.)</td>
<td></td>
<td>*0.00378543</td>
<td>Cubic meters</td>
</tr>
<tr>
<td>Gallons (U.K.)</td>
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<td>4.54609</td>
<td>Cubic decimeters</td>
</tr>
<tr>
<td>Gallons (U.K.)</td>
<td></td>
<td>4.54606</td>
<td>Liters</td>
</tr>
<tr>
<td>Cubic feet</td>
<td></td>
<td>28.3160</td>
<td>Liters</td>
</tr>
<tr>
<td>Cubic yards</td>
<td></td>
<td>*794.55</td>
<td>Liters</td>
</tr>
<tr>
<td>Acre-feet</td>
<td></td>
<td>1,233.5</td>
<td>Cubic meters</td>
</tr>
<tr>
<td>Acre-feet</td>
<td></td>
<td>*1,233.500</td>
<td>Liters</td>
</tr>
</tbody>
</table>
### Table II

**QUANTITIES AND UNITS OF MECHANICS**

<table>
<thead>
<tr>
<th>Multiply</th>
<th>By</th>
<th>To obtain</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MASS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grains (1/7,000 lb)</td>
<td>64,798.91</td>
<td>Milligrams</td>
</tr>
<tr>
<td>Tons (long) (2,000 lb)</td>
<td>31,023</td>
<td>Ounces (avo)</td>
</tr>
<tr>
<td>Pounds (avdp)</td>
<td>45.35923 (exactly)</td>
<td>Kilograms</td>
</tr>
<tr>
<td>Short tons (2,000 lb)</td>
<td>907.185</td>
<td>Kilograms</td>
</tr>
<tr>
<td>Long tons (2,240 lb)</td>
<td>1,016.05</td>
<td>Kilograms</td>
</tr>
</tbody>
</table>

| **FORCE/AREA** | | |
| Pounds per square inch | 0.070307 | Kilograms per square centimeter |
| Pounds per square inch | 0.689476 | Newtons per square centimeter |
| Pounds per square foot | 4.88243 | Kilograms per square meter |
| Pounds per square foot | 47.8803 | Newtons per square meter |

| **MASS/VOLUME (VISCOSITY)** | | |
| Ounces per cubic inch | 1.72099 | Grams per cubic centimeter |
| Ounces per gallon (U.K.) | 10.0181 | Kilograms per cubic meter |
| Pounds per cubic foot | 0.0680185 | Grams per cubic centimeter |
| Feet (linear) per cubic yard | 1.38894 | Grams per cubic meter |

| **MASS/CAPACITY** | | |
| Ounces per gallon (U.S.) | 7.4893 | Grams per liter |
| Ounces per gallon (U.K.) | 8.322 | Grams per liter |
| Pounds per gallon (U.S.) | 119.829 | Grams per liter |
| Pounds per gallon (U.K.) | 116.276 | Grams per liter |

| **BENDING MOMENT OR TORQUE** | | |
| Inch-pounds | 0.01151 | Foot-kilograms |
| Inch-kilograms | 1.3558 x 10^3 | Foot-kilograms |
| Foot-pounds | 0.72258 | Foot-kilograms |
| Foot-kilograms | 1.3558 x 10^3 | Foot-kilograms |
| Foot-pounds per inch | 5.441 | Centimeter-kilograms per centimeter |
| Inch-inches | 72.030 | Gram-centimeters |

| **VELOCITY** | | |
| Feet per second | 0.3048 (exactly) | Centimeters per second |
| Feet per second | 0.3048 (exactly) | Centimeters per second |
| Feet per year | 9.6577 x 10^-6 | Centimeters per second |
| Miles per hour | 1.60934 | Kilometers per hour |
| Miles per hour | 1.60934 | Kilometers per hour |
| Feet per hour | 0.44704 (exactly) | Meters per second |

| **ACCELERATION** | | |
| Feet per second^2 | 0.0069 | Meters per second^2 |

| **FLOW** | | |
| Cubic feet per second | 0.028317 | Cubic meters per second |
| Cubic feet per minute | 0.4719 | Liters per second |
| Gallons (U.S.) per minute | 0.06309 | Liters per second |

| **FORCE** | | |
| Pounds | 0.453592 | Kilograms |
| Pounds | 0.453592 | Kilograms |

### Table II—Continued

**WORK AND ENERGY**

<table>
<thead>
<tr>
<th>Multiply</th>
<th>By</th>
<th>To obtain</th>
</tr>
</thead>
<tbody>
<tr>
<td>British thermal units (Btu)</td>
<td>0.252</td>
<td>Kilogram calories</td>
</tr>
<tr>
<td>British thermal units (Btu)</td>
<td>1,055.06</td>
<td>Joules</td>
</tr>
<tr>
<td>Foot pounds</td>
<td>1.35582</td>
<td>Joules</td>
</tr>
</tbody>
</table>

| **POWER** | | |
| Horsepower | 745.70 | Watts |
| Foot pounds per second | 0.745703 | Watts |

| **HEAT TRANSFER** | | |
| Btu in/ft^2 degree F in, thermal conductivity | 1.442 | Milliwatts/cm degree C |
| Btu in/ft^2 degree F in, thermal conductivity | 0.1240 | Kg calories/m^2 degree C |
| Btu/lb-deg F, thermal conductivity | 1.4883 | Kg calories/m^2 degree C |
| Btu/lb-deg F, thermal conductivity | 0.468 | Milliwatts/cm^2 degree C |
| Btu/lb-deg F, thermal conductivity | 4.85 | Kg calories/m^2 degree C |
| Degree F in/ft^2 (Btu/lb IR, thermal resistance) | 1.761 | Degree C/cm^2 milliwatt |
| Btu/lb-deg F, (c, heat capacity) | 4.1836 | J/g degree C |
| Btu/lb-deg F, (c, heat capacity) | 1.0488 | Cal/g degree C |
| Btu/lb-deg F, (c, heat capacity) | 0.9682 | Cal/g degree C |

| **WATER VAPOR TRANSMISSION** | | |
| Grains/ft^2 (water vapor) transmission | 16.7 | Grams/24 hr m^2 |
| Perms (permeance) | 0.669 | Metric perms |
| Perms/lamb (permeability) | 1.67 | Metric square centimeters |

### Table III

**OTHER QUANTITIES AND UNITS**

<table>
<thead>
<tr>
<th>Multiply</th>
<th>By</th>
<th>To obtain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cubic feet per square foot per day (seepage)</td>
<td>0.34848</td>
<td>Liters per square meter per day</td>
</tr>
<tr>
<td>Pound seconds per square foot (viscosity)</td>
<td>4.41844</td>
<td>Kilograms per square meter</td>
</tr>
<tr>
<td>Fahrenheit degrees change</td>
<td>5/9 exactly</td>
<td>Celsius or Kelvin degrees change</td>
</tr>
<tr>
<td>Volumetric ratio</td>
<td>0.03037</td>
<td>Kiloliters per million liter</td>
</tr>
<tr>
<td>Litre per square foot (foot-candle)</td>
<td>10.764</td>
<td>Lumens per square meter</td>
</tr>
<tr>
<td>Ohm-millimeters per foot</td>
<td>0.000966</td>
<td>Ohm-meter milimeters per meter</td>
</tr>
<tr>
<td>Millimeters per cubic meter</td>
<td>29.3147</td>
<td>Milimeters per cubic meter</td>
</tr>
<tr>
<td>Millimeters per square foot</td>
<td>10.763</td>
<td>Millimeters per square meter</td>
</tr>
<tr>
<td>Gallons per square yard</td>
<td>4.4482</td>
<td>Liters per square meter</td>
</tr>
</tbody>
</table>

**POWER**

<table>
<thead>
<tr>
<th>Multiply</th>
<th>By</th>
<th>To obtain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pound</td>
<td>0.453592</td>
<td>Kilograms</td>
</tr>
<tr>
<td>Pounds</td>
<td>0.453592</td>
<td>Kilograms</td>
</tr>
</tbody>
</table>

---

**NATIONAL WEIGHING AND MEASURING CORPORATION**

*GPO 831-189*
ABSTRACT
A sand tank model study of drainage by pipe drains on level and sloping land was made in a 60-ft long, 2-ft wide, and 2-1/2-ft deep flume. The flume could be tilted to a 12 percent slope. Theoretical equations developed for steady-state drainage conditions on level land were verified. The study showed that drain spacing formulas developed for level land can be used for spacing midslope drains on sloping land which has a shallow impermeable barrier. Computer programs using verified formulas to determine drain spacing and maximum water table height between drains were developed and checked with data obtained from the flume study. The time-sharing computer programs have been entered into the Bureau of Reclamation Engineering Computer System (BRECS).