Chapter 7 — Scope and Effect Equations

notes

Objectives

Upon completion of this training, you will be able to:

- Explain the background behind drainage systems, especially as they relate to wetlands.
- Describe hydraulic conductivity, as it relates to drainage.
- Describe four equations used for determining the affect of water management on a wetland, covering data requirements, limitations, and factors affecting accuracy
- Adjust L_e for a wetland at the base of a slope.

Scope and Effect Web Site

http://msa.ars.usda.gov/ms/oxford/nsl/java/tools_java.html

Equations are preprogrammed and used on the web directly, no downloading.

Introduction

notes

Several equations, which were originally developed to evaluate the effect of artificial drainage systems on soil moisture, can help determine the effect of water management measures such as ditches, tile, and diversions on a wetland. Each equation must be carefully applied, respecting the limitations. The equations covered here are the ellipse, Hooghoudt, van Schilfgaarde, and Kirkham.

In this lesson, we will cover background, hydraulic conductivity, 4 procedures for evaluating the effect of water management systems on wetlands, how to adjust L_e for a wetland, and the usefulness of state drainage guides for evaluating wetlands.

Background

Tile is most efficient in the first 5 – 10 years after it's installed. A large storm, or a series of smaller storms, may cause a layer of sediment to build up in the tile, reducing its effectiveness. If a section of tile becomes completely plugged, water pressure builds up, and a blowout may result. If the tile outlet is submerged, the system is not free-flowing, and hence may cause water to back up into low-lying areas until the water level in the outlet drops to allow the water to move. The deterioration of a system can be seen in FSA crop history slides or other aerial photos over a period of years. The site will appear wetter and wetter in normal years, through increased size, apparently deeper water, or more severely stressed crops.

It is not unusual for a ditch system to be dug deeper than it needs to be when it is first constructed to allow additional capacity, anticipating future drainage needs, or to allow for sediment deposition and thereby increase the time between ditch cleanings. The amount of sediment deposited in a ditch can be determined from soil borings which show the difference between the natural layered soil and the overlying sediment. Tile systems which empty into a ditch are often planned such that the outlet of the tile is at least 1 foot above the bottom of the ditch into which it drains, to reduce the chance that the outlet will be blocked by sediment and to maximize the chance that the outlet will be free flowing even if the system experiences a large rainfall or snowmelt event.

Figure1

If a tile or ditch completely encircles a wetland, it can cut off the subsurface water that keeps a wetland wet, similar to a diversion above ground diverting surface water away from a wetland. Such a practice is an alteration to the hydrology that is not allowed under NFSAM rules. It is commonly known as encirclement (see Figure 1).

Encirclement is not an issue with wetlands where the groundwater component of the water budget is zero or negligible.

This illustrates the need to know the primary source of water for the wetland in question.

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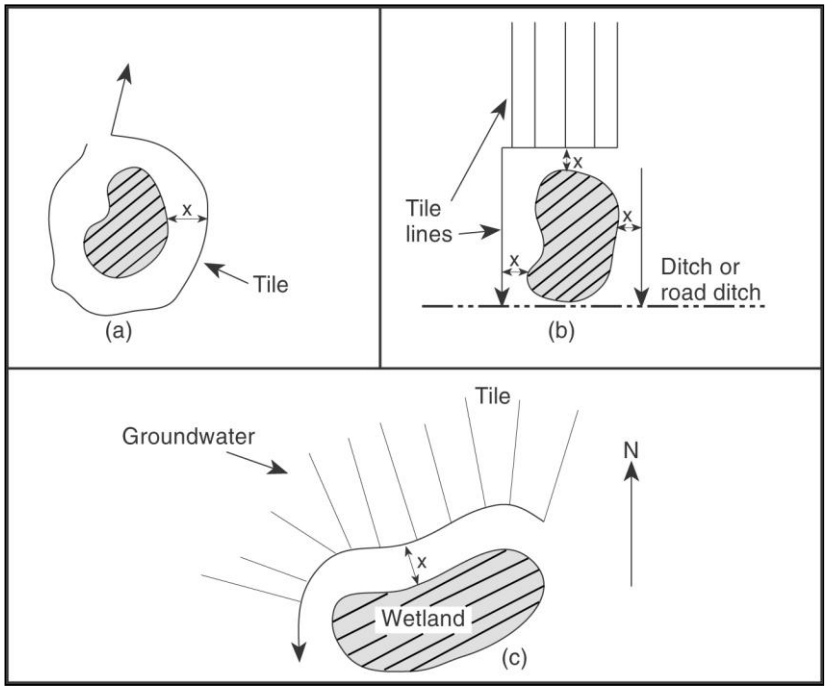

Figure 1. Examples of Encirclement of a Wetland

(a) Most obvious case of encirclement; tile forms ring entirely around wetland (hatched area) at a distance very close to that calculated for lateral effect ($x=L_e$).

(b) Tile cuts off water on three sides and ditch removes water on fourth side; cuts off groundwater even though tile is distance away from wetland that lateral effect equations say it should be.

(c) Tile is only placed on north and west sides of wetland but this is the direction that the groundwater comes from to reach the wetland. The primary water source for the wetland hydrology is groundwater and hence the tile acts as a diversion. Tile is distance from wetland that was calculated by lateral effect equations.

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Rule of Thumb

Tile must be at least 3 times L_e distance from the wetland on the side where groundwater is likely to enter the wetland if the wetland even gives the appearance of being encircled, or where the tile may act as a diversion.

Hydraulic Conductivity

Hydraulic Conductivity

Hydraulic conductivity, as referred to here, is the saturated horizontal hydraulic conductivity, as the flow to the drains is generally horizontal. In soils that have strata of differing textures and structures, the difference between horizontal and vertical hydraulic saturated conductivities can be significant. The horizontal K needs to be equal to or larger than the vertical K to apply the ellipse or Hooghoudt equations.

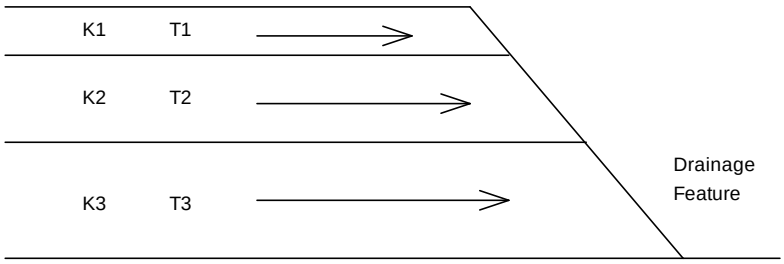
For layered soils, equivalent K may be computed by the following equation, which demonstrates the calculation of equivalent k for a soil with 3 layers:

$$\text{Equivalent } K = \frac{K_1T_1 + K_2T_2 + K_3T_3}{T_1 + T_2 + T_3}$$

Where: K and T are the hydraulic conductivity and thickness of each layer, respectively.

Remember: flow is horizontal only

Use most restrictive profile between wetland and drainage feature in horizontal direction.



Specific measurements of K should be made when possible. Numerous methods have been developed to measure saturated K in the field. The method most commonly used is the auger hole method described in the Engineering Field Handbook (EFH) Chapter 14. This method requires a high water table, so is most frequently done during late winter through early spring.

In the absence of on-site or laboratory measurements, the hydraulic conductivity may be approximated using soil texture and appropriate algorithms (MUUF, ROSETTA, SOIL WATER CHARACTERISTIC). Values from ROSETTA for soil class average values are shown in Table 1

The permeability information on the Soils 5 pages should not be used directly. The soil scientists in NRCS classify permeability in seven general classes. The permeability range is converted to an average permeability. This is a compromise, as the resultant computations can be used to determine the effect of drainage on a wetland, or how far a drainage system must stay away from a wetland to avoid impacting it. Using the average value is an attempt to be fair to both circumstances where the results are applied.

The *Field Book for Describing and Sampling Soils, Version 2.0* (NRCS, 2002) states that "... permeability and permeability classes are not K_{sat}".

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ROSETTA
http://www.ussl.ars.usda.gov/models/rosetta/rosetta.htm

MUUF and SOIL WATER CHARACTERISTIC (from SPAW)

http://www.wcc.nrcs.usda.gov/wetdrain/wetdrain-tools.html

Table 1. Class Average Estimated values from ROSETTA.

	Drained	f	Ksat
Class	Vol@30 cm	0-30 cm	(cm/hr)
Clay	0.43691192	0.014564	0.562327
C Loam	0.32096906	0.010699	0.284963
loam	0.21100235	0.007033	0.430218
L sand	1.10831324	0.036944	4.908952
Sand	0.90042608	0.030014	13.50793
S Clay	0.49726929	0.016576	0.686576
S C L	0.5599364	0.018665	0.507795
S Loam	0.78517155	0.026172	1.390557
Silt	0.12233517	0.004078	1.499646
Si Clay	0.33395535	0.011132	0.625589
Si C L	0.18730478	0.006243	0.508497
Si Loam	0.05897512	0.001966	0.822032

Effective Radius

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Table 2

In several drainage equations, a parameter known as the effective radius, *re*, is used. Table 2 is the table taken from Skagg's work (7, page 5-38) and converted to inches and feet. Effective radius is considerably smaller than the actual drain tube radius to account for the resistance to inflow due to a finite number of openings in an otherwise impervious wall. An envelope around a drain tile increases the effective size of the drain by allowing free movement of water to drain openings. The actual value of re used in the equation ultimately changes the L_e value by only 1- 5 feet, which in most cases is a negligible difference.

Tile Diameter	re, inches	re, feet
4"	0.20	0.0167
5"	0.41	0.034
6"	0.58	0.048
8"	0.96	0.080 (extrapolated)
10"	1.33	0.111 (extrapolated)
12" and larger	1.70	0.142 (extrapolated & limit set)
Ditch, any size	12	1.0 (chosen by practical experience)
Drain tube*	1.177n	1.177n

*surrounded by a gravel envelope with a square cross section of length 2n on each side

Table 2. Effective radius of tile.

notes

Equations for Determining the Effect of Water Management on Wetlands

Effect Equations

We will cover four equations for determining the affect of water management on wetlands. They are:

- Ellipse
- Hooghoudt
- Van Schilfgaarde
- Kirkham (ponded conditions only)

Ellipse Equation

History

This equation has long been used to design drainage and water supply systems across the United States.

It is a steady state equation; that is, it assumes that the system steadily removes the rain that falls at a constant rate.

This equation is used to determine approximate economical spacings and depths of agricultural crops using the requirement that the water table should be lowered below the root zone within 24 to 48 hours after saturation. This equation has been used to determine if the hydrology of a wetland has been modified by drainage measures.

Data Requirements

Assumptions

When this equation was developed, a number of assumptions were made which need to be recognized by the user.

- The soil is homogenous and has a hydraulic conductivity, K.
- The drains are evenly spaced a distance of “S” apart.
- An impermeable layer underlies the drain at a depth, a, but the equation is not valid for large values of “a”. (a<=2d<=10')
- Rain is falling or irrigation water is applied at a rate, q. (Applies to humid areas)

Limitations

- The ellipse equation does not apply in situations where the vertical hydraulic conductivity exceeds the horizontal hydraulic conductivity.
- The ellipse equation assumes homogenous soils. If site conditions do not meet these limitations, another drainage equation should not be used.
- The equation itself does not have a factor for time, and as such, one must then adjust parameters to account for a time difference if a time is desired other than the 24 to 48 hours normally assumed.

notes

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- This equation assumes that the surface water has been removed and does not have to go through the subsurface drainage system.
- Assumes the tile is in a good state of repair and has an adequate outlet.

Factors Affecting Accuracy

- The value assumed for the drainage coefficient, q, has a significant effect on the results of the equation.
- Minor variability in the hydraulic conductivity, K, does not change the resultant spacing much.
- The depth to the impermeable layer affects the resultant spacing most significantly when the hydraulic conductivity is high, such as with sandy soils.

Procedure

Ellipse Equation

The procedure is largely selecting the parameters for the Ellipse equation and then completing the computations.

The ellipse equation is

$$S = \{ (4K) (m^2 + 2\ am) / q \}^{1/2},$$

Where:

S = parallel drain spacing, feet

K = weighted hydraulic conductivity above the restrictive layer, inches per hour

m = vertical distance after drawdown of the water table above the drain and at the midpoint between drains, feet (m = d – c)

a = depth to the impermeable layer or barrier below drains, feet

q =drainage rate, inches per hour

d = depth to drain from ground surface, feet

c = depth to water table drawdown after the evaluation period, feet

Note: K and q must be in the same units.

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The drainage coefficient (q) can also be obtained by using field trials combined with mathematical model such as DRAINMOD (see Chapter 8). An important limitation to be aware of with this equation is that it assumes that the surface water has been removed and does not have to go through the subsurface drainage system. This is often accomplished through a land slope that removes the water, through a ditch that removes surface water, or through surface intakes to the tile system. In addition, the outlet for the system must be of adequate size and grade for the system above it and be adequately maintained.

The depth of water drained (v) at various water table depths can be measured directly from large soil cores. However, it is not usually practical to collect large soil cores in many soils. The drainage volume is often derived from the soil moisture retention data. The DMSOILS or MUUF computer program, often used with DRAINMOD, can provide an estimate of this parameter. It also may be estimated using the soil's drainable porosity (f).

Relationships between q, v, f:

q = drainage rate, in/hr

v = depth of water drained at various water table depths, cm^3

f = drainable porosity is v divided by volume of soil drained at given water table depth, dimensionless

q = (f* WTD) / t = v / t

Therefore, v = f*WTD

notes

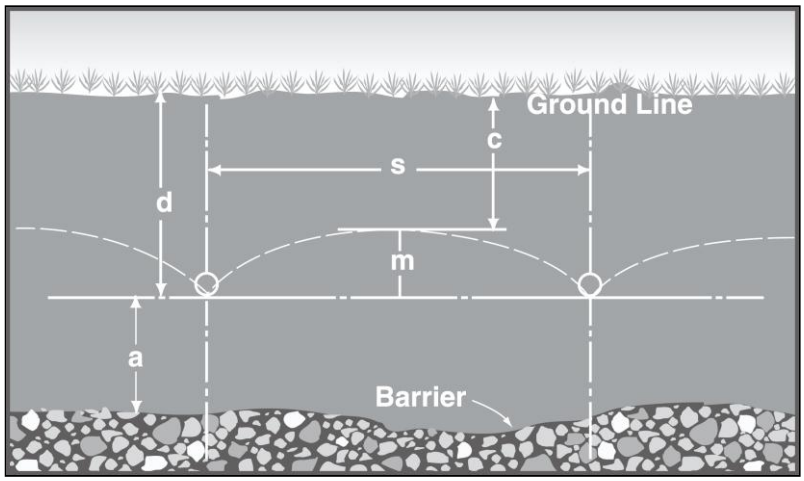
Example using the Ellipse equation

Assumptions:

- The saturation is to be removed in 14 days to a midpoint drawdown depth of 12 inches.
- The soil has a drainable porosity of 0.05 ft/ft.
- The tile is installed at a depth of 4.0 feet.
- An impermeable layer is located at 8 feet.
- K=1.14 inches/hr.

See Figure 2 and refer to the definitions under "Procedure" above for the parameters in the ellipse equation.

Figure 2



- m = d – c = 4' – 1' = 3 ft.
- K = 1.14 inches / hr x 24 hr / day = 27.36 inches / day

- a = 8’ – 4’ = 4ft
- v = drainable porosity x depth of drawdown at the midpoint; v = 0.05 ft / ft x 1’ = 0.05 ft
- v= 0.05 ft x 12 inches / foot = 0.60 inches
- q = v/t = 0.6 inches / 14 days = 0.043 inches/day
- S = { (4K) (m2 + 2am) / q } 1/2
- S = { (4 x 27.36 inches/day) (3’ x 3’ + 2 x 4’ x 3’) /0.043 inches / day } 1/2
- S = 290 feet

With the values used in this example, the water table midway between drains would be lowered by 1.0 feet from the soil surface during a 14 day period if the drains were spaced at 290 feet. If the drains were spaced at or closer than 290 feet, the entire strip of land between the drains is effectively drained, and potentially has the wetland hydrology removed. On the other hand, if the drains were spaced farther apart, there would be a strip between the drains bounded together by a line at 145 feet from each drain that would still have wetland hydrology. If only one drain exists, areas outside a line 145 feet from the drain would still have wetland hydrology present. This assumes that the outlet is adequate and the system has been maintained. This also assumes that the surface water has been removed so that ponded water does not have to be removed through the subsurface system.

notes

Review Results

notes

Here are 4 important points to consider in evaluating whether this equation has been applied correctly:

- Is the time for the situation to be removed an important point?
- Is the assumption of steady state conditions valid?
- Can a reasonable drainage coefficient be calculated or assumed?
- Was an equivalent hydraulic conductivity value, K calculated if multiple soil layers are involved?

Hooghoudt Equation

notes

History

This equation, and its next of kin, the ellipse equation, have long been used to design drainage and water supply systems across the United States. It is a steady state equation; that is, it assumes that the system steadily removes the rain that falls at a constant rate. This equation is used to determine approximate economical spacings and depths of agricultural drain tubing and ditches for agricultural crops using the requirement that the water table should be lowered below root zone within 24 to 48 hours after saturation. This equation has been used to determine if hydrology of a wetland has been modified by drainage measures.

The Hooghoudt equation is quite similar to the ellipse equation except that the hydraulic conductivity can be calculated separately for the layers above and below the drainage feature. The depth from the drain to the impermeable barrier is modified to be effective depth, $d_{e,}$ and replaces “a” in the equation.

notes

Data Requirements

When this equation was developed, a number of assumptions were made which need to be recognized by the user:

- The soil is homogeneous and has a hydraulic conductivity "K".
- The drains are evenly spaced a distance of "S" apart.
- An impermeable layer underlies the drain at a depth "a", but the equation is not valid for large values of "a".
- Rain is falling or irrigation water is applied at a rate "v".

Limitations

- The Hooghoudt equation does not apply in situations where the vertical hydraulic conductivity exceeds the horizontal hydraulic conductivity.
- The actual depth to the impermeable layer cannot be more than twice the depth of the drain, and it is not to exceed ten feet.
- The Hooghoudt equation assumes homogeneous soils. If site conditions do not meet these limitations, another drainage equation should be used.
- Assumes the tile is in a good state of repair and has an adequate outlet.
- The equation itself does not have a factor for time, and as such, one must then adjust parameters to account for a time difference if a time is desired other that the 24 to 48 hours normally assumed.

notes

Factors Affecting Accuracy

- The value assumed for the drainage coefficient, q, has a significant effect on the results of the equation.
- Minor variability in the hydraulic conductivity, K, does not change the resultant spacing much.
- The depth to the impermeable layer affects the resultant spacing most significantly when the hydraulic conductivity id high, such as with sandy soils.

Procedure

notes

The procedure involves selecting appropriate parameters for the equation and then completing the computations. One first determines an estimated spacing which allows the parameter, "a", to be changed to equivalent depth, d_e, for the final computations.

$$S' = \{ (8K_2 am + 4K_1m^2) /q \}^{1/2},$$

Where:

S' = estimated parallel drain spacing, feet

K_1 = weighted horizontal hydraulic conductivity above the drainage feature, inches per hour

K_2 = weighted horizontal hydraulic conductivity below the drainage feature, inches per hour

Note: K_1 and K_2 can be equal

m = vertical distance after drawdown of the water table above the drain and at the midpoint between drains, feet (= d –c, with d and c as defined below)

a = depth to the impermeable layer or barrier below drains, feet

q = drainage rate, inches per hour

d = depth to drain from ground surface, feet

c = depth to water table drawdown after the evaluation period, feet

π = 3.1416

r_e = effective radius of the drain, feet (see Table 2)

After an initial spacing S' is determined, d_e is calculated using one of the two following equations.

notes

$$d_e = \frac{a}{1 + \frac{a}{S'}\left[\frac{8}{\pi}\ln\frac{a}{r_e} - 3.4\right]}$$;for a/S' < 0.3

$$d_e = \frac{S'\pi}{8\left[\ln\frac{S'}{r_e} - 1.15\right]}$$; for a/S' > 0.3

Using the equivalent depth, d_e, the final spacing can be calculated with the Hooghoudt equation. The lateral effect distance (L_e) is half of the spacing distance (S).

$S = \{ (8K_2 d_e m + 4K_1 m^2) / q \}^{½}$,

Where:

S = parallel drain spacing, feet

K_1 = weighted horizontal hydraulic conductivity above the drainage feature, inches per hour

K_2 = weighted horizontal hydraulic conductivity below the drainage feature, inches per hour

m = vertical distance after drawdown of the water table above the drain and at the midpoint between drains, feet (= d – c, with d and c as defined below)

d_e = equivalent depth to the impermeable layer or barrier below drains, feet

q = drainage rate, inches per hour

d = depth to drain from ground surface, feet

c = depth to water table drawdown after the evaluation period, feet

π = 3.1416

Example

notes

Assumptions:

- Assume the saturation is to be removed in 14 days to a midpoint drawdown depth of 12 inches.
- Assume the soil has a drainable porosity of 0.05 ft/ft, per lineal foot.
- The tile is installed at a depth of 4.0 feet.
- An impermeable layer is assumed at 8 feet.
- Assume the tile is installed at the point where the soil changes.
- The K value above the drain is 2.0 inches/ hour and K below the drain is 1.14 inches/hour.
- Assume the tile is a 5”corrugated plastic drain tile.

See Figure 1 and refer to the definitions above for the parameters in the Hoodghoudt equation.

- **M** = d – c = 4’- 1’= 3ft.
- $\mathbf{K_1}$ = 2.0 inches / hr x 24 hr/day = 48 inches/day
- $\mathbf{K_2}$ = 1.14 inches / hr x 24hr / day= 27.36 inches/ day
- **v** = drainable porosity x depth of drawdown at the midpoint;
- **v** = 0.05 ft/ft x 1’= 0.05 ft
- **v** = 0.05 ft x 12 inches/foot = 0.60 inches
- **t** = time to remove saturation in days = 14 days
- **q** = v/t = 0.6 inches/14 days = 0.043 inches/day

notes

- a = 8’- 4’ = 4 ft
- S’ = {(8K2 am + 4K1m2)/q}1/2
- S’ = { (8 x 27.36 inches/day x 4’x 3’) + (4 x 48 in/day x (3 ft)2)/ 0.043 inches/day}1/2
- S’ = 318 feet
- a/S = 4’/318’ = 0.0126, which is less than 0.3, so the first equation for converting a to d, will be used.
- De = a/ {1+[(a/S’)[(8/ π)ln(a/re) – 3.4]]} = 4’/{1 + [(4’/318’)[8/3.1416)ln(4’/0.34’)-3.4]]}=3.60 ft.
- S = {(8K2dem + 4K1m2)/q}1/2
- S = {8 x 27.36 inches/day x 3.6’ x 3’) + (4 x 48 in/day x (3 ft)2)/ 0.043 inches/day}1/2
- S = 308 feet
- Check: 308’ is within 10% of 318’ so no need to correct de for a different spacing; the result will be essentially the same.
- Le = 1/2S = ½ x 308’ = 154 feet.

Note that the results of this example produce spacing that is 18’ longer than the results with the ellipse equation example. One would expect this, since the hydraulic conductivity in the top 4 feet is higher in this example than it was in the example with the ellipse equation, and the effective depth is less than the depth from the drain to the impermeable barrier.

The Hooghoudt equation is often executed in a spreadsheet to minimize computational errors.

Review Results

Important points to consider to evaluate whether this equation has been applied correctly are listed here.

- Is the time for the saturation to be removed an important point?
- Is the assumption of steady state conditions valid?
- Can a reasonable drainage coefficient be calculated or assumed?
- Was an equivalent hydraulic conductivity value (K) calculated that considered all the soil layers involved?
- Was equivalent depth used?
- Was final spacing within 10% of estimated spacing used to determine d_e?

notes

van Schilfgaarde Equation

notes

Data Requirements

- This equation requires information on hydraulic conductivity which is described under Section I. Applications in the beginning of this module.
- A drainable porosity value is needed, and can be determined most readily by an application of the MUUF soils program, which is used with the DRAINMOD computer program (see Chapter 8).
- The time to remove the saturation and the height of the water table after drainage are specified in NFSAM and COE criteria.

Limitations

This is a non-steady state equation. The assumptions of this equation are appropriate for many parts of the United States where the rainfall is sporadic rather than constant (semi-arid condition, e.g. ND, SD).

- The equation does not yield a reasonable solution when the drain rests on the impermeable layer; that is, when a = 0.
- The equation must use equivalent depth instead of actual depth to give the best results.
- Surface water must be removed from a site in order to apply this equation correctly. The surface water may be removed by a ditch, natural ground slope, or the surface intake for a tile.

notes

- The equations for d_e below allow one to convert actual depth to the impermeable layer to equivalent depth.

$$d_e = \frac{a}{1 + \frac{a}{S'}\left[\frac{8}{\pi}\ln\frac{a}{r_e} - 3.4\right]} \text{;for a/S' < 0.3}$$

$$d_e = \frac{S'\pi}{8\left[\ln\frac{S'}{r_e} - 1.15\right]} \text{; for a/S' > 0.3}$$

Factors Affecting Accuracy

The van Schilfgaarde equation does include a parameter for time, so it can be used to compare how much water is removed in 7 days vs. removal in 14 days.

The time period selected does affect the results noticeably.

The drainable porosity (f) affects the results of the equation but f values that are similar in magnitude, such as 0.02 and 0.026, result in minor differences in the resultant spacing calculated. Peat and much soils have “f” values such as 0.238 and 0.28; these result in much shorter spacings than do those in clay/silt/loam soils that have an “f” value in the range of 0.02 to 0.07.

Procedure

The procedure involves selecting appropriate parameters for the same equation and then completing the computations.

- Use the van Schilfgaarde equation with the known depth, a, in place of d_e to determine an estimated spacing, S'.
- Use the estimated spacing S' in the appropriate equation (see Limitations, above) to determine the equivalent depth, d_e, which replaces in the van Schilfgaarde equation for the final computations.
- Use d_e to determine the spacing, S, in the van Schilfgaarde equation.
- Compare the estimated S' to S; if they are within 10% of each other, the difference can be assumed to be negligible. If the difference is more than 10%, us the calculated S value as S', repeat steps 2 through 4 until the S' and S values are within 10%.

notes

The van Schilfgaarde equation is:

$$S = \left[\frac{9Ktd_e}{f'[\ln m_o(2d_e + m) - \ln m(2d_e + m_o)]} \right]^{1/2}$$

S = drain spacing, feet

K = hydraulic conductivity in feet per day

d_e = equivalent depth, feet, from drainage feature to impermeable layer

m = height of water table above the enter of the drain at midplane after time t, feet

m_o = initial height of water table above the center of the drain, feet

t = time in days for water table to drop from m_o to m

f = drainable porosity for the given water table change

a = depth from free water surface in drainage feature to impermeable layer, feet

f' = drainable porosity adjusted for surface roughness, = f + {(s/12)/(m_o – m)}
(12 is conversion for inches to feet)
(f' modification by Tom Keep, NRCS)

s = water trapped on the surface by soil roughness, inches

Note: use zero if unsure

S' = estimated drain spacing, feet

The lateral effect distance is ½ the calculated spacing, of L_e = 1/2S.

Example—Exhibit 1

notes

Use a Glencoe soil (see soils 5 data sheet).

Assumptions:

- Assume a 5” tile will be installed at a 4’ depth.
- The impermeable layer is at 10 feet.
- The drainable porosity for Glencoe is 0.026 ft/ft.
- The saturation is to be removed in 14 days to a 12” depth.
- The equivalent hydraulic conductivity is calculated for this soil. It is assumed that the permeablity below the 60” depth (the limit of the soils 5 information) is one drainage class lower than what is experienced at the 60” depth, due to compaction and lack of root channels and worm holes. (See Table 1)

$$K=\frac{1.1\text{in/hr}(48")+1.3\text{in/hr}(12")+0.4\text{in/hr}(60")}{120\ \text{inches}}=0.77\text{in/hr}$$

- Note: The equation of the previous page uses K in feet per day. The calculated here is in inches/hour. 1 inch/hr = 2 ft/day
- A 5” tile has an effective radius of 0.41” = 0.034 feet. (See Table 2)
- At time = 0, the soil is saturated to the surface so mo = 4’ (the depth of the drain). At the end of 14 days, the saturation is desired to be 12” (or 1 foot) below the surface, so m = 4’ –1’ = 3 feet.

notes

- The impermeable layer is at 10'. The drain is 4' below the surface. Hence the depth from the drain to the impermeable layer is the difference, or 10' – 4' = 6 ft. Therefore, a = 6 feet.
- The water trapped by surface roughness is .1 inches.
- Calculate the adjusted drainable porosity,
- f' = f + (s/12)/(mo – m)
  = 0.026 + (.1/12)/(1) = 0.034
- Calculate the estimated spacing, S' using the van Schilfgaarde equation.

$$S' = \left[\frac{9(Kx2)(t)(a)}{f[\ln m_o(2a+m) - \ln m(2a+m_o)]} \right]^{1/2}$$

Note: 2 is conversion from in/hr to ft/day for K

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- Use the estimated spacing to calculate de. Finding the ratio a/S' will indicate which of the two equations from Limitations above should be used. a/S = 6'/390' = 0.015. This is less than 0.3 so the first equation will be used.

$$d_e = \frac{a}{1+(a/S')\{\{(8/\pi)\times\ln(a/r_e)\}-3.4\}} =$$

$$\frac{6'}{1+(6'/390')\{\{8/3.1416)\times\ln(6'/0.034')\}-3.4\}} = 5.23'$$

- Use the van Schilfgaarde equation to determine spacing.

$$S = \left[\frac{9(K \text{ x } 2)\,(t)\,(d_e)}{f'\{\ln m_o(2d_e + m) - \ln m(2d_e + m_o)\}} \right]^{1/2} =$$

$$S = \left[\frac{9(0.77\text{in/hr x } 2)\,(14\,\text{days})(5.23')}{(0.034)\,\{\ln 4'(2\text{x}5.23'+3') - \ln 3'(2\text{x}5.23'+4)\}} \right]^{1/2} = 370 \text{ feet}$$

- Check that the estimated and actual spacings are within 10% of each other.

$$\frac{390'-370'}{370'} = \frac{20'}{370'} = 5.4\% \quad \text{OK}$$

- A 5” tile installed 4’ deep in Glencoe soil needs a spacing of 370’ to remove the saturation from the top 12” of soil in 14 days. Its lateral effect under these circumstances is 185 feet, since Le = 1/2S.

notes

Review Results

notes

Important points to consider to evaluate whether this equation has been applied correctly are listed here.

- Was the depth to the barrier converted to equivalent depth?
- Was equivalent hydraulic conductivity calculated if multiple soil layers are involved?
- Is the time parameter consistent with what is required by the rules?
- Does the spacing seem reasonable?
- Is the m value correct for the soil type (sandy or non-sandy) and the rules (NFSAM or COE)?
- Was the drainable porosity selected for the correct soil and the correct phase of the soil in the county?
- Is the tile installed at the impermeable barrier? (Result is invalid)?

Kirkham's Equation

notes

Data Requirements

Under conditions where ponded water exists, the drainage rate can be calculated by equations developed by Kirkham (1945). These equations require more input data than the other drainage equations.

Typically, one must have a good contour map of the site to determine available storage. The site can be surveyed to determine storage also.

Calculations need to be done to determine the volume of runoff from a 2 year (50% chance) precipitation event.

Information is needed about what tile is installed in the basin. Soils information is needed for the hydraulic conductivity and drainable porosity.

In the case where a single tile line under a wetland is being evaluated, a spacing for the tile is not readily known. A suggested procedure is to determine the area of the wetland and the length of tile under the wetland. Divide the area by the length and use that as an approximate spacing.

Limitations

This equation must be used in conjunction with the Ellipse equation, Hooghoudt equation, or the van Schilfgaarde equation to determine the total amount of time to remove water from the site.

notes

Kirkham's equation only handles the removal of ponded water through a subsurface tile system with no surface intakes.

Factors Affecting Accuracy

The equation is quite sensitive to the depth of ponded water to be removed. Thus, careful calculations are needed to determine the volume of water that runs off the watershed.

In many cases it will be critical to consider evapotranspiration.

Definition of Terms—Figure 3

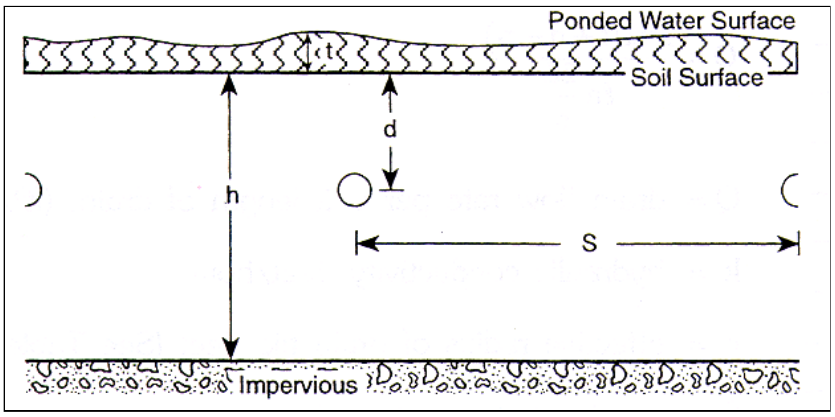


Figure 3. Definition of terms for Kirkham's equation.

S = distance between drains, feet

d = distance from soil surface to centerline of drain, feet

r_e = effective radius of drain tile, feet (see Table 2)

h = distance from soil surface to impervious layer, feet

t = depth of ponded water, feet

notes

Procedure

The procedure involves selecting the parameters for the equation and completing the computations.

For parallel drains

$$Q = \frac{4\pi k(t + d - r_e)}{g}$$

$$g = 2\ln\left\{\frac{\sinh[\pi(2d - r_e)/S]}{\sinh(\pi r_e/S)}\right\} - 2\sum_{n=1}^{\infty} (-1)^n \ln\left\{\frac{\sinh^2(2\pi nh/S) - \sinh^2\frac{\pi r_e}{S}}{\sinh^2(2\pi nh/S) - \sinh^2\frac{\pi(2d - r_e)}{S}}\right\}$$

For a single drain

$$Q = \frac{2\pi k(t + d - r_e)}{\ln\frac{2d}{r_e}}$$

Q = drain flow rate per unit length of drain, (ft^3/hr/ft)

k = hydraulic conductivity, feet/hour

r_e = effective radius of drain tile, feet (See Table 2)

S = spacing between tiles, feet

d = depth from soil surface to centerline of tile, feet

t = depth of ponded water, feet

π = 3.1416

h = depth to impermeable layer, feet

n = the summation value (ie. n = 1, 2, 3, …)

notes

Example—Figure 4

The pothole shown in Figure 4, below, has an effective surface area of 1.6 acres. The tile installed under the basin has the following lengths:

S = 50’

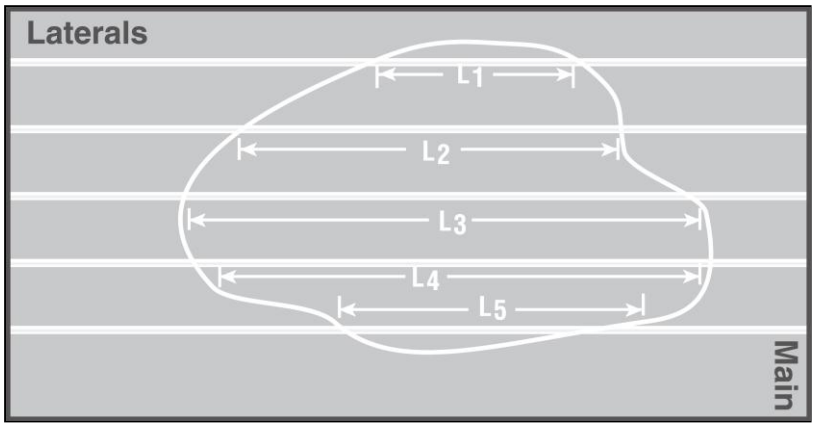
L_1 = 200’

L_2 = 350’

L_3 = 450’

L_4 = 400’

L_5 = 250’



The total length of tile under the basin is the sum of L1, L2, L3, L4, and L5 or 1650 feet. The drain tubing is 4” with an effective radius of 0.20 inch. The tubing is installed at a 3’ depth with an impermeable layer 8 feet below the soil surface. Water runs into the pothole from a 15 acre watershed. After a 2-year rainfall event, water is ponded in the pothole at a depth of 7.5 inches. How long is required for the surface ponding to be removed?

notes

The Soils 5 page identifies the soil as having a permeability of 0.6 to 3.4 inches/hour. An average K is then (0.6 + 3.4)/2 = 2.0 inches per hour. The drainable porosity, calculated by MUUF, is 0.04. Assume an ET rate of 0.10 inches per day.

The drainage rate is calculated using Kirkham's equation above for parallel drains. Substituting the parameters for this example into the equation, the following results occur:

The drainage rate is:

$$Q = \frac{4\pi 2\,\text{in/hr}\left(t + 3\,\text{ft} - \frac{0.2}{12}\,\text{ft}\right)}{g}$$

$$g = 2\ln\left(\frac{\sinh\left[\pi\left(2x3 - \frac{0.2}{12}\right)/50\right]}{\sinh\left[\pi\frac{0.2}{12}/50\right]}\right)$$

$$-2\left((-1)^1\ln\frac{\sinh^2(2\pi 8/50) - \sinh^2\left[\frac{\pi\frac{0.2}{12}}{50}\right]}{\sinh^2(2\pi 8/50) - \sinh^2\left[\frac{\pi\left(6-\frac{0.2}{12}\right)}{50}\right]} + (-1)^2\ln\frac{\sinh^2(2\pi 2x8/50) - \sinh^2\left[\frac{\pi\frac{0.2}{12}}{50}\right]}{\sinh^2(2\pi 2x8/50) - \sinh^2\left[\frac{\pi\left(6-\frac{0.2}{12}\right)}{50}\right]}\right)$$

= 11.809 – 2(-0.1118+0.011+…)

g = 12.01

notes

With a ponded depth of 7.5 inches (t), which is 0.625 feet, the flowrate for the tubing can be determined.

$$Q = \frac{4\pi\,(2\text{in/hr})\,\frac{1\text{ft}}{12\text{ inches}}\left(0.625+3-0.0167\right)\text{ft}}{12.01} = 0.629\text{ft}^3/\text{hr}$$

Or Q = 0.629 ft^3/hr per ft length of drain tubing

The total length of the drains under the pothole is $L_1 + L_2 + L_3 + L_4 + L_5$ = 1650 feet. With this information, the flowrate of the system can be determined.

Q = 0.629 ft^2/hr x 1650 ft = 1038 ft^3/hr

This represents the flowrate that would pass through the soil to the drain assuming the drain flows full with no back pressure. Whether the system would actually take this flowrate depends on the length, grade and size of the main.

The area of the pothole is 1.6 acres, as planimetered. Convert this to a volume to be removed.
Area x depth = volume

V = 1.6 acres x 43560 ft^2/acre x (7.5”/12in/ft – .1”/12in/ft) = 42,979 ft^3

The time to remove the ponded water through the soil is

42,979 ft^3 /1038ft^3/hr/24 hr/day = 1.73 days

Now the Hooghoudt or van Schilfgaarde equation would be used to determine the time needed to remove the saturation and the two times summed.

A spreadsheet is available in some states for Kirkham's equation. The spreadsheets also use the ellipse equation to determine the time to remove the subsurface saturation so the total time is determined by one effort. Compare the results of the spreadsheet (Exhibit 2) to the computations shown here.

notes

Review Results

Important points to consider to evaluate whether this equation has been applied correctly are listed here.

- Is the runoff volume reasonable for the watershed involved?
- Does the length of tile measured under the wetland seem correct?
- Does the surface area seem reasonable?
- Is the depth of ponding reasonable for this type of site?
- Is the time parameter correct for the rules being used?
- Was the hydraulic conductivity adjusted if multiple soil layers are involved?
- Does the time to remove the water seem reasonable?

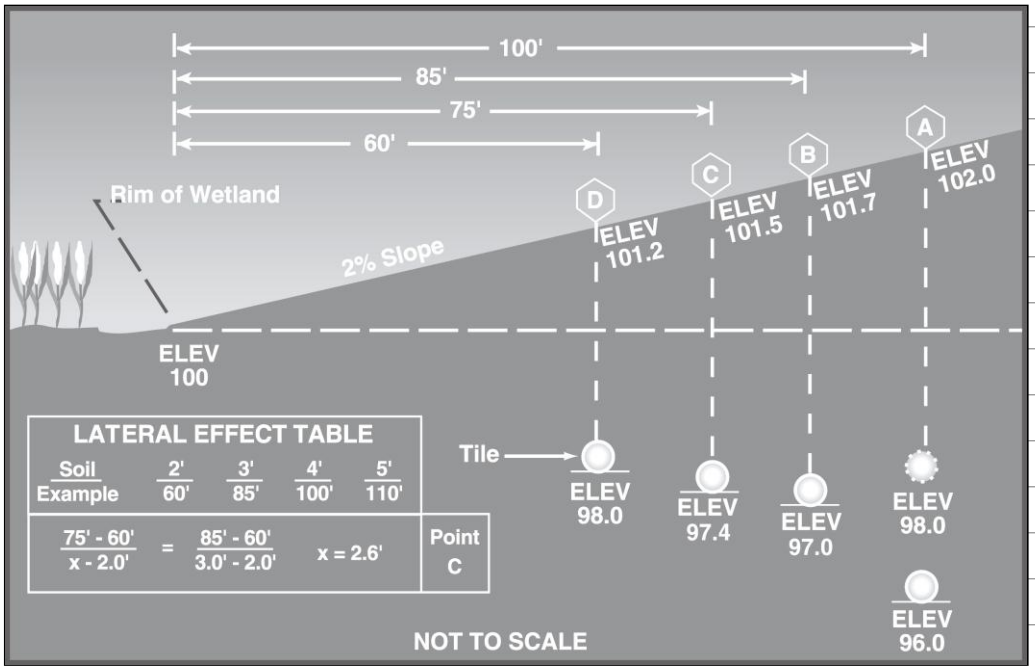
notes

notes

Adjusting L_e for a Wetland at the Base of a Slope

Figure 5

In accordance with the NFSAM, new tile must be installed far enough away from a wetland to avoid impacting the wetland hydrology. When tile is to be installed adjacent to a wetland, and the wetland is distinctly the low point in the topography, the engineer may choose to adjust the distance the tile is to be installed away from the wetland to account for the surrounding slop of the land. This is not a simple linear adjustment. This is best illustrated with an example. See Figure 5.



Assume the wetland rim is at elevation 100. If the wetland is expected to pond the 2 year precipitation event at an elevation above 100, the "rim" should be assumed to be at the anticipated elevation of ponding for the 2- year event. This is a key elevation to identify since the depth of the tile will be compared to this elevation.

In Figure 5, for the assumed soil, if the tile were installed 4' deep, 100 feet from the rim of the wetland (the calculated L_e), the tile would actually be only two feet below the rime of the wetland. Therefore, the lateral effect should be adjusted to allow the tile to be moved closer to the wetland. However, if the tile were moved to 60' from the wetland (the lateral effect for a tile at a 2' depth), the tile flowline would be at elevation 97.2, which is 2.8 feet below the rim of the wetland, when the lateral effect distance was calculated based on a two foot depth. This is not acceptable.

Straight-line interpolation is allowed for this situation to find lateral effect distances for depths between those given in the L_e table. Some trial and error calculations may be needed to determine the needed distance between the tile and the wetland to achieve the desired grade and layout.

The tiler and owner may choose to install the tile at a variety of distances from the wetland, provided the tile is installed at the corresponding depth for that distance. The option selected may well depend on the surrounding land and the system layout and grade that is desired for the tile system. In the example here, four choices are given; as many are available as there are depths at which the tile may be installed.

Soil Lateral Effect Distances for Depths Given

Name	2'	3'	4'	5'
Example	60'	85'	100'	110'

notes

Drainable Porosity

notes

This is the volume of water that will be released per unit volume of soil by lowering the water table. Wetland criteria currently uses 30 cm as the minimum water table depth in mineral soils, 15 cm for sand. Drainable porosity is a dimensionless value. It is often represented by the letter “f”. The drainable porosity for a given soil can be calculated by the computer programs DMSOILS or MUUF. Some NRCS state offices have a list of the drainable porosities for the soils that are mapped in that state.

Grade

This is the elevational change of the system in the direction of the outlet. It is expressed as a percentage, or as feet of fall per foot of channel length. Drainage systems are installed on a positive grade to allow the water to flow toward the outlet of the system.

Hydraulic Conductivity

This is the rate at which water moves through a porous medium-soil. It is abbreviated as “K”. This can be synonymous with saturated horizontal hydraulic conductivity, as the flow to the drains is generally horizontal. In soils that have strata of differing textures and structures, the difference between horizontal and vertical hydraulic saturated conductivities can be significant. The horizontal “K” is usually larger than the vertical “K”. For layered soils, an equivalent “K” is determined for use in the drainage equations.

Hydraulic Conductivity is not synonymous with "permeability".

notes

Impermeable Layer

This is the layer of soil where water movement becomes restricted such that vertical movement of water is limited.

Local rules of thumb exist about when to know if a layer is impermeable or not. Water may still move through the so-called impermeable layer. The concept of an impermeable layer is not necessarily the same for irrigation and drainage work as it is for wetland hydrology. *An impermeable layer can be defined as one that has a hydraulic conductivity that is less than the layer above it by at least a power of 10.*

Lateral Effect

A single line or ditch effectively drains the land a distance (x) on each side of the drainage feature. This distance (x) is called the lateral effect distance, or the distance over which the drainage feature affects the subsurface hydrology on one side of the drainage feature. The lateral effect is half of the width of the zone of influence.

Scope & Effect

This term describes the process of determining what influence a drainage system has on surrounding land. The drainage system may be surface or subsurface, offsite or onsite.

notes

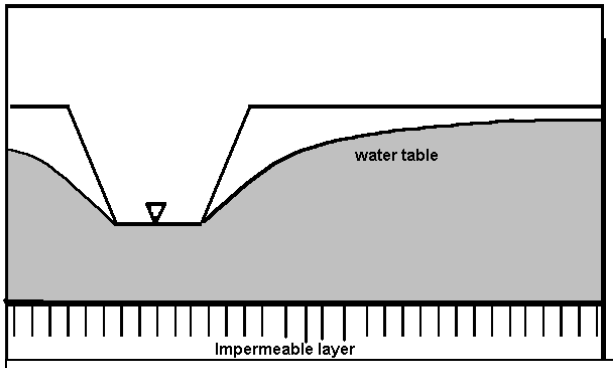
Spacing

This term, when applied to a tile or ditch system, refers to the distance between adjacent tile lines or ditches. Ideally, the individual tile or ditch line effectively drains a distance halfway between the two lines, so together the entire distance between the two lines is drained.

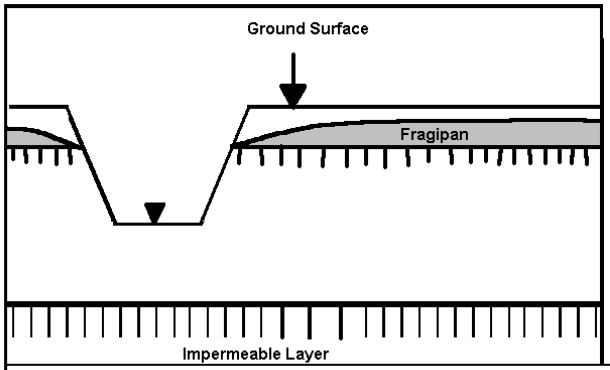
Zone of Influence

A single tile line or ditch effectively drains the land a distance (x) on the left side of the ditch or tile and a distance (y) on the right side of the ditch or tile. The corridor of land affected by this tile or ditch is the sum of x and y, and is also called the zone of influence.

Type of Saturation (Water Table)



Endosaturation -the soil is saturated with water in all layers from the upper boundary of saturation to a depth of 200 cm or more from the mineral soil surface.



Episaturation - the soil is saturated with water in one or more layers within 200 cm of the mineral soil surface and also has one or more unsaturated layers, with an upper boundary above a depth of 200 cm, below the saturated layer. A perched water table.

References

notes

1. Luthin, James, *Drainage Engineering*, John Wiley and Sons, New York, 1966.

2. Van Schilfgaarde, Jan, Editor, *Drainage for Agriculture*, American Society of Agronomy, Inc., 1974.

3. Soil Conservation Service, *National Engineering Handbook (NEH)*, Chapter 16, Agricultural Drainage, 1971.

4. Kirkham, D. 1945, *Seepage of steady rainfall through soil into drains*. Transaction of the American Geophysical Union, Volume 39, pages 892-908.

5. Soil Conservation Service, *National Food Security Act Manual*, 3rd Edition, March 1994.

6. Schwab, Glenn, Richard Frevert, Talcott Edminster, and Kenneth Barnes, *Soil & Water Conservation Engineering*, John Wiley and Sons, Inc. Second Printing, 1996, notably Chapter 17 on Subsurface Drainage.

7. Skaggs, R. Wayne and the Soil Conservation Service. DRAINMOD Reference Report, *Methods for Design and Evaluation of Drainage-Water Management Systems for Soils with High Water Tables*, 1980.

Module 7 – Exhibit 1

Client: _____ Date: _____
County: _____ Tract: _____ Wetland #: _____
Soil Series: Glencoe _____ By: _____ Ckd By: _____

CALCULATIONS FOR WEIGHTED PERMEABILITY
For Use in Lateral Effect Computations

Depth of Drainage (ft) : 4.00 or 48 inches

Layer Number	Avg Perm Rate In/hr	Depth in inches	
		Upper Limit	Lower Limit
1	1.1	0	10
2	1.1	10	35
3	1.1	35	48
4	1.3	48	60
5	0.4	60	120

Ka = 1.10 Kb = 0.55

DRAINAGE EVALUATION MODEL: Lateral Effect based on soil porosity

K1 =	1.1	in/hr	Hydraulic Conductivity of Layer above drain
K2 =	0.55	in/hr	Hydraulic Conductivity of Layer below drain
d =	4	feet	Depth to Free water surface--ditch or tile
h =	10	feet	Depth to Impermeable Layer
f =	0.026	ft/ft	Drainable Porosity
t =	14	days	Saturation removal time period
D =	12	inches	Depth of Water Table below surface
r =	0.41	inches	Effective Radius of drain
s =	0.1	inches	Surface roughness storage

*** ZONE OF INFLUENCE by Glover Eqn., modified by Van Schilfgaarde
Le = 185 ft, Lateral Effect of Drain

This worksheet is set up to use 5 layers. If less than five are used, fill the other permeabilities with zero and the other layer depths with a value greater than 120.

The lowest depth of real layer must be 120 inches, at whichever row it appears in the column labeled "Lower limit". An impermeable barrier is assumed at 10 feet (120 inches). The permeability rates entered in the second column should be an average of the range of rates given in the Soils 5 data. If only one value is given, use that.

Module 7 – Exhibit 12

State	MN	Project	Sample
By	SMMJ	05/01/96	Ckd by

Drainage Evaluation Models—Pothole subsurface drain scope & effect

Enter Data

K_1	=	2.00	in/hr	Hydraulic Conductivity of Layer Above Drain
K_2	=	2.00	in/hr	Hydraulic Conductivity of Layer Below Drain
d	=	3.00	feet	Depth to Centerline of Drain
h	=	8.00	feet	Depth to Impermeable Layer
S	=	50.00	feet	Drain Spacing
r	=	0.20	inches	Effective Radius of Drain <Tab Right>
L	=	1650	feet	Sum of Drain Tubing Length under Pothole
A	=	69,700	sq. ft.	Area of Ponded Area
t	=	0.63	feet	Depth of Water Ponded on Surface
f	=	0.040	ft/ft	Drainable Porosity
T	=	7	days	Ponding PC versus FW Criteria
Tt	=	14	days	Ponding and Saturation PC versus FW Criteria
D	=	12	inches	Depth of Water Table Below Surface
s	=	0.10	inches	Surface Roughness Storage
WA	=	15	acres	Contributing Watershed Area to Ponded Area
Q_o	=	0.141	cfs	Outlet Capacity

Time for Surface Water Removal by Kirkham Equation

T	**=**	**1.7**	days	Time to Drain Surface Water from Pothole
g_1	=	0.287	cfs	Outlet Capacity for Minimum Time

Outlet Capacity is Limiting

Time to Drain Ponded Area using Outlet Capacity = 3.5 days
Volume of Ponded Water = 0.79 in/watershed acre

Time to Drawdown Water Table by Van Schilfgaarde mod. Glover Eqn.

T	=	0.4	days	Time to Drawdown Water Table from the Surface to 12 inches.