WI 650.1905 Scope and Effect Equations

(a) Applicable situations for use

(1) Basic Drainage Concepts

Agricultural drainage is defined as the removal of "excess" (gravitational) water from agricultural lands, primarily for crop production purposes. Agricultural drainage is generally divided into two categories, surface drainage and subsurface drainage.

Surface drainage removes water from the soil surface by promoting gravitational flow overland and through channels for collection and conveyance to an outlet. Surface drainage can either directly remove water from an area, or it can divert water away from an area. Surface drainage includes land grading, ditching, tile surface inlets, and diversion by ditches, dikes, and floodways. Surface drainage systems use elevation differences and hydraulic gradients to cause water to flow from one location to an outlet at a lower elevation.

Subsurface drainage removes water from below the soil surface to a gravity (e.g. ditch) or a pumped outlet. Subsurface drainage can either directly remove water from an area (relief drainage), or it can intercept and divert water away from an area (interceptor drainage). Subsurface drainage includes tiling or ditching to convey excess soil water to an outlet. In some cases a water table that is "perched" above a restrictive or "impermeable" layer may be drained downward by drilling a vertical drain (or well) through the restrictive layer. Subsurface drainage is accomplished by installing a drain (ditch or tile) with a flowline below the surface of the water table such that the hydraulic head in the drain is less than the hydraulic head of the water table in the surrounding soil. Hydraulic gradients are formed towards the drain, which acts as a "sink". This causes the soil gravitational water to flow to the drain. The sink is maintained by continuing to remove the water from the drain by gravity or pumping. Figures 1 and 2 represent typical water table gradients towards a drainage tile and a drainage ditch, respectively.
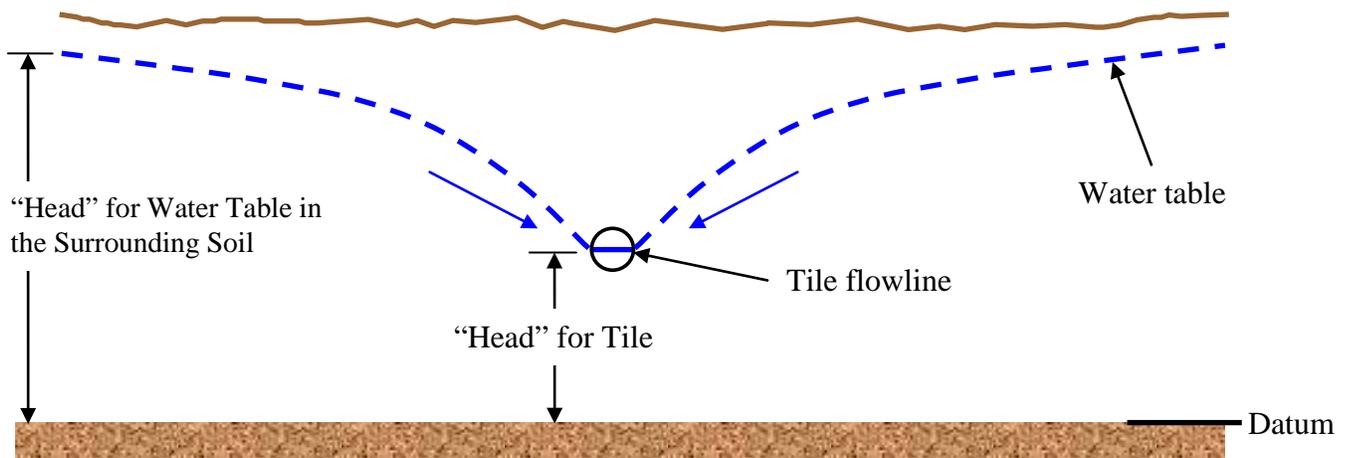

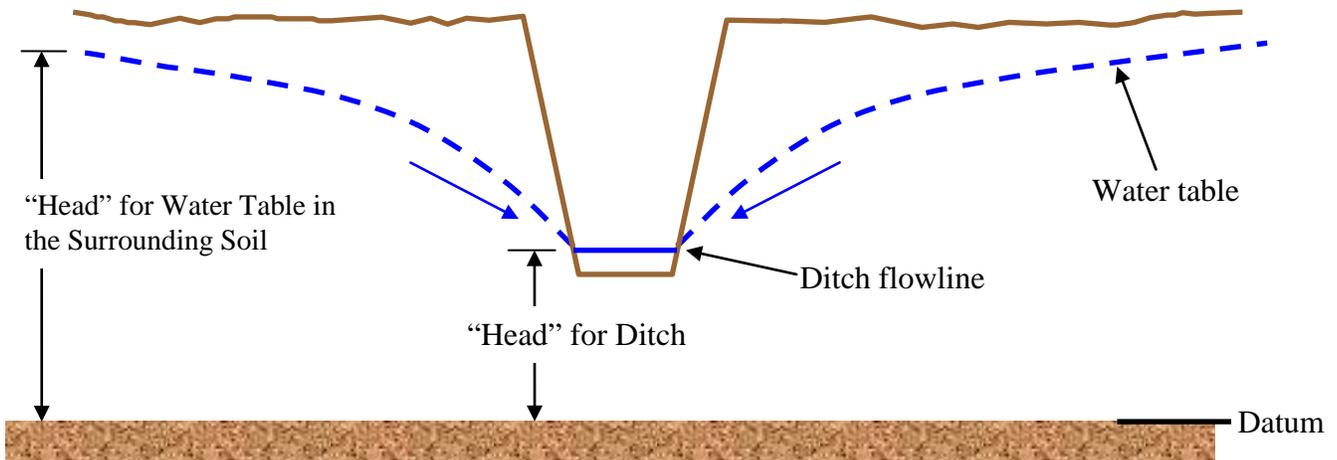**Figure 1. Typical water table gradients towards a drainage tile.**

Figure 2. Typical water table gradients towards a drainage ditch.

Subsurface drainage theory is based on Darcy's Law, a fundamental equation describing the flow of water through porous material, where the velocity of flow is proportional to the product of the soil hydraulic conductivity and the hydraulic gradient. Darcy's Law is the foundation for the development of scope and effect equations. Expressing Darcy's Law in terms of discharge:

$$Q = K \, i \, A$$

Where:
- Q = discharge
- K = hydraulic conductivity
- i = the hydraulic gradient
- A = aquifer cross sectional area intersected below the water table

Drainage practice applies drainage theories to the design and construction of surface and subsurface drainage systems. A basic knowledge of drainage systems and functions is a necessary prerequisite to evaluating the scope and effect of drainage practices. To apply this "Scope and Effect Equations" hydrology tool, one must use drainage principles to effectively investigate, analyze, and document the effect of a drainage system on wetland hydrology. Several basic concepts related to drainage systems are discussed in the following sections.

(i) Drainage maintenance

Ditches are often dug deeper than needed at the time of construction to allow for additional capacity for future planned or potential drainage needs, and/or for expected future sediment deposition to increase the ditch cleanout interval. Soil borings taken in the bottom of an existing ditch can assist in determining the location of the original ditch bottom, with the in-place layered soil below it, and the depth of the overlying sediment.

Tile systems that outlet into a ditch are often installed such that the tile outlet invert is a minimum of 1 ft above the bottom of the ditch. This reduces the potential for blocking of the tile outlet with sediment, and reduces the flooding of the tile outlet during large precipitation events.

Subsurface drains are most efficient in the first 5 to 10 years after installation. A large storm or a series of smaller storms can cause sediment to build up in the tile, reducing its effectiveness. A hole or cave in above a tile line may indicate that the tile line is damaged and needing repair. Tile can be damaged by rodents, tree roots or high water pressure (a "blowout"). When the pressure in the tile is reduced after a "blowout", the saturated soil can flow back into the broken tile line, causing a hole in the soil above the tile line. In addition, if a tile outlet is submerged, the system is not free-flowing, which may cause water to

back up into low-lying areas until the outlet water level drops allowing the tile to flow again. This can happen with increasing frequency if the outlet ditch is poorly maintained and filling with sediment. Such deterioration of a system can often be seen in crop history slides or other aerial photographs over a period of years. The site will appear wetter and wetter in normal precipitation years, through the increased size, apparent increased depth of ponding, and more severely stressed crops.

(ii) Encirclement

Encirclement occurs when the groundwater inflow or surface water runoff, that is a major part of the total water supply (inflow) to a wetland, is intercepted and diverted away from the wetland. Encirclement can occur when a ditch or tile diverts groundwater inflow away from a wetland. Ditches, diversions or tile surface inlets can also divert surface water away from a wetland. The ditch or tile does not have to completely surround the wetland for encirclement to occur. If groundwater or surface water inflows on one side of a wetland, a ditch or tile installed on that side of the wetland could divert away a significant percentage of the total inflow to the wetland. This would also be encirclement. Encirclement can significantly reduce groundwater and/or surface water inflow to the extent that the wetland hydrology is severely impacted or eliminated. Some examples of encirclement are illustrated and described in Figure 3.
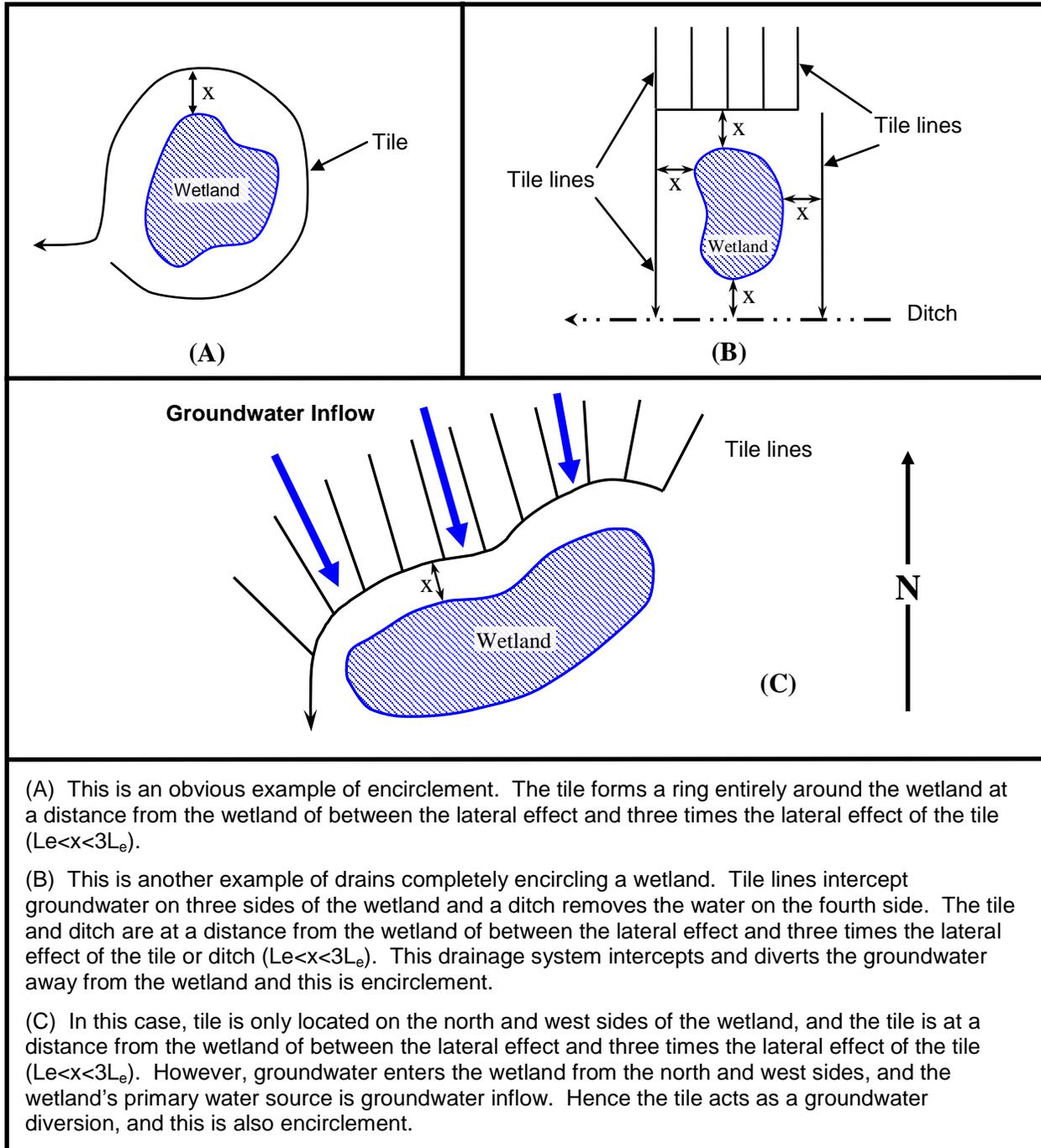
(A)

(B)

(C)

(A) This is an obvious example of encirclement. The tile forms a ring entirely around the wetland at a distance from the wetland of between the lateral effect and three times the lateral effect of the tile ($Le<x<3L_e$).

(B) This is another example of drains completely encircling a wetland. Tile lines intercept groundwater on three sides of the wetland and a ditch removes the water on the fourth side. The tile and ditch are at a distance from the wetland of between the lateral effect and three times the lateral effect of the tile or ditch ($Le<x<3L_e$). This drainage system intercepts and diverts the groundwater away from the wetland and this is encirclement.

(C) In this case, tile is only located on the north and west sides of the wetland, and the tile is at a distance from the wetland of between the lateral effect and three times the lateral effect of the tile ($Le<x<3L_e$). However, groundwater enters the wetland from the north and west sides, and the wetland's primary water source is groundwater inflow. Hence the tile acts as a groundwater diversion, and this is also encirclement.

Figure 3. Examples of encirclement of a wetland with groundwater inflow as the primary source for hydrology

The potential for encirclement of a wetland can be minimized by keeping a drainage ditch or tile a minimum of 3 times the lateral effect distance ($3 \times L_e$) away from the edge of the wetland on any side where groundwater is likely to enter. This $3 \times L_e$ distance is applicable in areas of **reasonably level topography** where groundwater is the primary source of hydrology to the wetland, and where an impermeable layer is not near (within approximately 1 foot of) the drain invert. However, in areas of sloping topography, this $3 \times L_e$ distance may **not** be adequate to prevent a significant interception of groundwater inflow. In areas of sloping topography, a tile or ditch placed on top of, or just into a restrictive layer can intercept the majority of the groundwater flow from an overlying porous soil layer. In these situations, it is possible to intercept the majority of the groundwater flow and divert it away from a down slope wetland area, even if the tile or ditch is at a distance greater than three times the L_e distance away from the wetland edge. This is another example of encirclement. Figure 4 illustrates this situation.
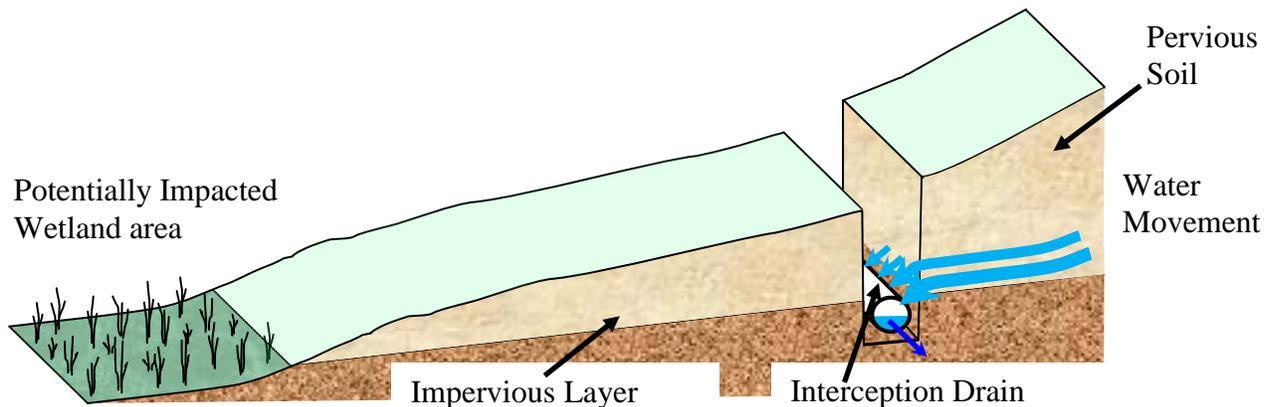

Figure 4. Example of interception and diversion of groundwater away from a wetland area (figure adapted from a Purdue University illustration)

When analyzing the effect of a **surface water** diversion on the hydrology of a wetland, a water budget computer program is the best tool. However, these water budget computer programs are relatively complex and data intensive. The percentage of the total 2 year frequency surface runoff to a wetland that is diverted away from the wetland can be used to **approximate** the effect of this diversion on the overall wetland hydrology. As a general rule, in order to minimize the impact on the hydrology of the wetland, any surface drainage system or combination of systems should not intercept greater than 9 percent of the total 2 year frequency surface runoff (in inches) to a wetland which has surface water as its primary source of hydrology.

(b) Data Required

(1) Hydraulic conductivity

Hydraulic conductivity (K), in this reference, is the saturated horizontal hydraulic conductivity, since the flow to the drains is generally horizontal. Hydraulic conductivity is also known as the value, or numerical expression, of soil permeability. Other applicable details related to hydraulic conductivity, including an equation for equivalent K, are found in NEH-650-19, Part 650.1905(d).

Soil scientists in NRCS classify soil permeability in seven general classes. For use in the scope and effect equations, the permeability range may be converted to an average permeability. Table 1 lists soil permeability classes, the permeability range and the average permeability value for each class. A soil scientist may be able to provide site specific soil permeability data from an on-site investigation. This is preferable, whenever possible. Soil scientists may use on-site investigations, sampling and testing, experience and professional judgment to determine the soil permeability data used for a specific site.

Table 1. Soil Permeability Classes

Permeability Range (Inches/Hour)	Permeability Class	Average Permeability Rate (Inches/Hour)
< 0.06	Very Slow	0.03
0.06 – 0.2	Slow	0.13
0.2 – 0.6	Moderately Slow	0.4
0.6 – 2.0	Moderate	1.3
2.0 – 6.0	Moderately Rapid	4.0
6.0 – 20.0	Rapid	13.0
> 20.0	Very Rapid	20.0

(2) Impermeable Layer

An impermeable layer is a soil layer through which the vertical movement of water is restricted. Water may still move through this "impermeable layer", but at a slower rate. A soil layer that has a saturated hydraulic conductivity of 1/10th or less of the saturated hydraulic conductivity in soil layer above it is widely accepted to be an impermeable layer. The depth from the soil surface to the impermeable layer is used in lateral effect equations to determine the lower boundary for the calculations.   Immediately above this boundary the flow lines can be assumed to be nearly horizontal.

If an impermeable layer is not encountered during an onsite investigation, one can be assumed to be present at a depth equal to twice the drain depth, or 10 feet, whichever is less. With increased soil depth, there generally is increased compaction due to the weight of the overlying soil, along with a significant reduction in root channels and earthworm activity. These all can result in significantly reduced soil permeability.

Under certain conditions it may be more reasonable to assume that the impermeable layer is at or near the bottom of the drain. This is true for clay soils (White 2006), soils with clay subsoils, or other similar soils. In these soils, structure can develop in the more frequently drained zone, above the ditch or tile invert, which may be due in part to repeated swelling and shrinking of the soil from cycles of wetting and drying from precipitation and drainage. In addition, the increased action of plant roots and worms within the more frequently drained zone above the drain invert facilitates movement of water within that portion of the soil. In these soils, the soil structure would be less developed in the more frequently saturated zone below the drain invert, and the movement of water in this zone would be significantly restricted. Several unique impermeable layer situations are discussed in greater detail in the van Schilfgaarde Equation section (e)(2) and the Hooghoudt Equation section (e)(3).

(3) Effective radius

In several drainage scope and effect equations, a parameter known as the effective radius, r_e, is used. The effective radius is considerably smaller than the actual drain tube radius to account for the resistance to inflow due to a limited number of openings in the otherwise solid tile. A gravel envelope around a drain tile increases the effective radius of the drain by allowing free movement of water to the drain openings. The effective radius values given in Table 2 were taken from the DRAINMOD Reference Report (Skaggs, 1980), with extrapolated values for corrugated drain tube diameters in excess of 8 inches (USDA – NRCS, 2005). A value of 12 inches is recommended for ditches.

Table 2. Effective Radius of Drainage Tile or Ditch

Drain Type and Size	Effective Radius, r_e	
	In Inches	In Feet
Corrugated Drain Tube Diameter:		
3"	0.14	0.0115
4"	0.20	0.0167
5"	0.41	0.034
6"	0.58	0.048
8"	0.96	0.080
10"	1.33	0.111
12" or larger	1.70	0.142
Clay Tile Diameter:		
4" (1/16" space between tiles)	0.12	0.0098
4" (1/8" space between tiles)	0.19	0.0157
Ditch (any size)	12.00*	1.00
Drain tube surrounded by a gravel envelope**	0.5885L	0.5885L

*Chosen by practical experience
**Gravel envelope with a square cross section of length L on each side

(4) Drainable Porosity

Drainable porosity is the volume of water that will be released per unit volume of saturated soil by lowering the water table. For drainage design or analysis, drainable porosity is used to represent the fraction of the total soil volume that is water that can be drained by a subsurface drain.   Drainable porosity is a dimensionless value (cm^3/cm^3 or cm/cm), and is often represented as "f". The drainable porosity of a soil can be evaluated in a laboratory by measuring the amount of water released when the water table is lowered a certain amount. The drainable porosity for a given soil can also be approximated by the MUUF computer program. The MUUF computer program was developed by Baumer et al. (1987) to estimate soil hydraulic properties (including drainable porosity) for use in the computer program DRAINMOD (Rodrigue, approximate date 2000). A list of the drainable porosities is available for many soils mapped in Wisconsin, and is included (on a separate sheet) in the Wisconsin Lateral Effect Spreadsheet.

(e) Methodology

(1) Scope and Effect Equations Background Information

"Scope and effect", as related to drainage, describes the physical extent, or dimensions, of the drainage system itself (scope) and the surface and/or subsurface drainage impact, or influence (effect) of the system. Therefore, the "scope" of a ditch or tile system would be the lengths, locations and extent of the system itself. The "effect" of the drainage system refers to the extent of the removal of surface water ponding or soil saturation by the system.

"Scope and Effect" or "lateral effect" (L_e) equations were developed to determine the effect of drainage systems on water table drawdown. These equations can be used to evaluate the effect of existing or proposed drainage systems, and determine whether a drainage system removes the wetland hydrology from a site. According to Phillips, Skaggs and Chescheir (2010), the "lateral effect of a drainage ditch or other drain or similar structure may be defined as the width of a strip of land adjacent to the ditch which is drained such that it no longer satisfies the wetland hydrologic criteria." Note that this definition is applicable to tile as well as ditches. The L_e can also be described as the distance from one (or potentially both) side(s) of a ditch or tile that is drained to a specified depth below the ground surface within a set period of time. Lateral effect equations applicable to Wisconsin conditions are described in this section.

The ellipse equation, originally developed to approximate economical spacings and depths of drain tile or tubing and ditches for agricultural crops, is not recommended for Wisconsin drainage scope and effect evaluations. While it has a history of wide applications in drainage work and is relatively simple to use, several limitations of the ellipse equation resulted in discontinuing its use for scope and effect evaluations in Wisconsin.

One limitation of the ellipse equation is that it is a steady state equation. It is based on the assumption that the drain steadily removes the rain that falls at a constant rate. However, Wisconsin rainfall events are typically sporadic, and not continuous for the length of time that a drain is functioning. In addition, the equation does not have a factor for time. Other parameters in the equation must be artificially adjusted in order to specify a drainage time other than the 24 to 48 hours normally assumed for crop production. Furthermore, the ellipse equation does not consider the convergence of flow near the drain. Therefore, it does not accurately represent flow lines near the drain.

Three lateral effect equations are recommended for use in evaluating the impacts of drainage systems on the hydrology of Wisconsin wetland sites. The three equations that are recommended for use in Wisconsin are the van Schilfgaarde, Hooghoudt, and Kirkham equations. Each of these equations has limitations and is only recommended for certain site conditions. Therefore, it is important to understand the limitations of the equations and to select an equation that is applicable to the given site conditions.

(2) van Schilfgaarde Equation

(i) Applicable situations for use

The van Schilfgaarde equation may be used where the soil saturation is the result of a high water table and the hydrology has been altered with ditch or tile drainage. It is a non-steady state equation. This equation is appropriate for Wisconsin where the rainfall is sporadic.

Although the van Schilfgaarde equation should **not** be used when a drain invert is at or near an impermeable layer (see "limitations" section, below), when a ditch or tile is installed **through** an impermeable layer and into a layer of higher permeability, the van Schilfgaarde equation can be used for the analysis. The ditch or tile in this case can act as a vertical drain, especially if the lower soil layer is fairly rapidly permeable. For this situation, the entire depth from the ground surface to the free water surface in the drain (ditch or tile) should be used for d, which is described below. The "upper" restrictive layer should not be modeled as the "impermeable layer" in this case, since this restrictive layer should *not* be considered the lower boundary of the calculations. This restrictive layer should be included as a layer

in the calculation of the equivalent hydraulic conductivity. Another, deeper, impermeable layer should be used for the lower boundary of the calculations.

(ii) Data required

The following parameters are required for the van Schilfgaarde equation (see Figures 5 and 6 for illustrations of many of these parameters):

- Equivalent saturated hydraulic conductivity, K
- Initial height of the water table above the drain, m_o, which is often equal to d
- Height of the water table above the drain at the midpoint between the drains (or the lateral effect distance) after a specified drawdown time period t, m
- Depth from the ground surface to the water table at the midpoint between the drains (or L_e distance) after drawdown, c
- Depth from the ground surface to the free water surface in the drain, d
- Time for the water table to drop from the initial height to the drained height, t
- Depth from the free water surface in the drain to the impermeable layer below the drain, a
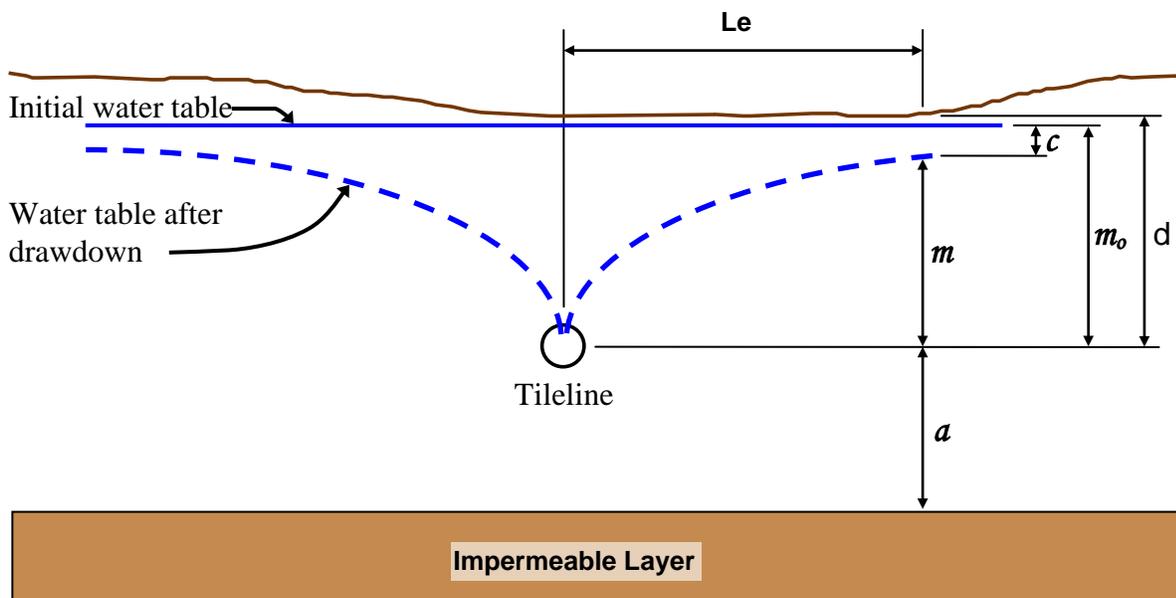- Drainable porosity
- Effective radius of the drain

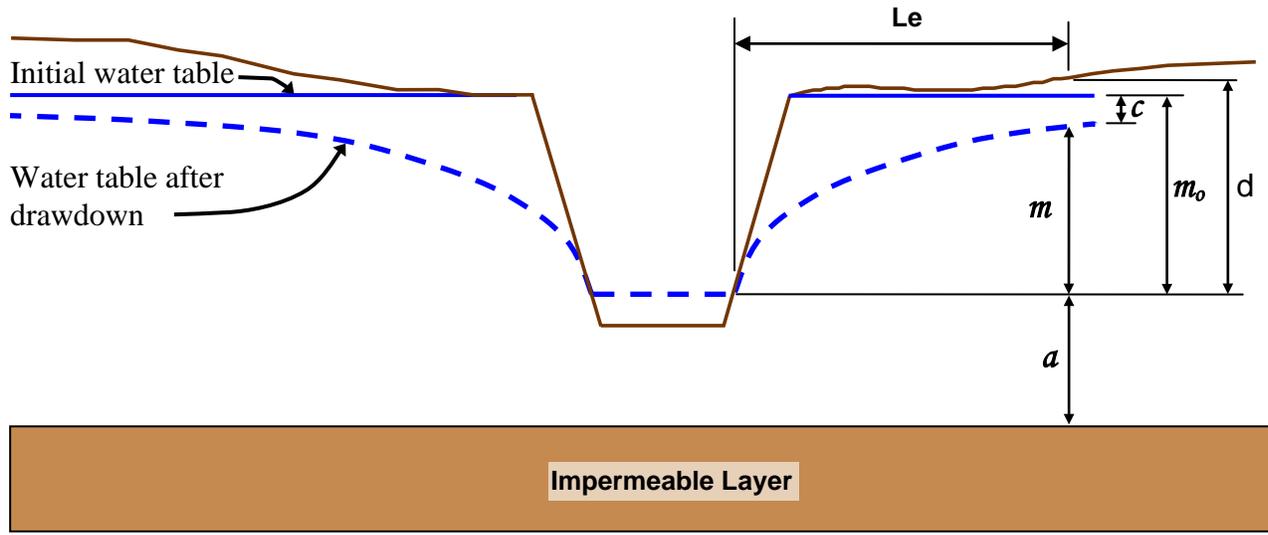**Figure 5: Variables for van Schilfgaarde Equation for Tile Drainage System**

Figure 6: Variables for van Schilfgaarde Equation for Ditch Drainage System

(iii) Limitations

- This equation **does not** yield a reasonable solution when the drain rests on an impermeable layer. If the bottom of the drain is at or near (e.g., within one foot of) an impermeable layer, the Hooghoudt Equation should be used.
- The equation must use the equivalent depth to the impermeable layer instead of the actual depth to give the best results. Additional equations are used to convert from actual depth to the impermeable layer to equivalent depth.
- The van Schilfgaarde equation evaluates water table drawdown. It does not analyze the removal of surface water from a site. If surface water is present, it must be removed with a ditch, the natural ground slope or a tile inlet, in order for the van Schilfgaarde equation to be applicable to the site, and the evaluation of this surface water removal must be done using another method.
- Drains are assumed to be in good, operating condition with adequate outlets.

(iv) Factors affecting the accuracy of the results

The van Schilfgaarde equation includes a parameter for time, and it can be used to compare the water table drawdown that occurs over different time periods. The calculated spacing (and L_e) distance is significantly affected by the assumed time period. The calculated spacing is also affected by the selected drainable porosity value. However, drainable porosity values of similar magnitude, such as 0.120 and 0.126, result in minor changes in the calculated spacing.

(v) Sources of data

Some soils data are described in section (b), along with information related to determining (or estimating) the depth to the impermeable layer. Values for the effective radius of the drain are given in Table 2, of section (b)(3). Additional information, including the procedure to compute the equivalent saturated hydraulic conductivity, is given in NEH-650-19, Part 650.1905(d).

(vi) _Methodology_

The van Schilfgaarde equation is:

$$S = \left[\frac{9Ktd_e}{f'\left[\ell n(m_o(2d_e + m)) - \ell n(m(2d_e + m_o))\right]} \right]^{0.5}$$

$$L_e = \frac{S}{2}$$

Where: L_e = Lateral effect distance, ft

   S = drain spacing, ft

   d_e = equivalent depth from the drain to the impermeable layer, ft

   K = equivalent hydraulic conductivity, ft/day

   t = time for water table to drop from m_o to m, days (14, per the National Food Security Act Manual (NFSAM))

   f   = drainable porosity of the water conducting soil expressed as a fraction (voids drained at 60 cm tension), ft/ft, cm^3/cm^3, or cm/cm

   f '   = drainable porosity adjusted for surface roughness = (f + s/12)

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

   m_o = initial height of water table (m) above centerline of tile (or water surface in ditch), ft

   m   = height of water table at the midpoint between the drains (or L_e distance) above the centerline of tile (or water surface in ditch), after time t, ft

        = [(ground surface elevation at the Le distance) – (centerline or flowline elevation of drain) – 1.0 ft drawdown], per NFSAM

The procedure for using the van Schilfgaarde equation involves an iterative approach as described below.

Step 1 – use the van Schilfgaarde equation with the known depth, a, in place of the equivalent depth, d_e, to determine an estimated spacing, S'. Where, "a" is the depth from free water surface in drain to impermeable layer (ft), as indicated in Figures 5 and 6.

$$S' = \left[\frac{9Kta}{f'\left[\ell n(m_o(2a + m)) - \ell n(m(2a + m_o))\right]} \right]^{0.5}$$

Step 2 – Use the estimated spacing, S', in the appropriate equation to determine the equivalent depth, d_e, which replaces "a " in the van Schilfgaarde equation for the final computations. Note that r_e is the effective radius of the drain in feet.

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

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

Step 3 – Use d_e in the van Schilfgaarde equation to calculate the spacing, S.

$$S = \left[\frac{9Ktd_e}{f'\left[ln\left(m_o\left(2d_e + m\right)\right) - ln\left(m\left(2d_e + m_o\right)\right)\right]} \right]^{0.5}$$

Step 4 – Compare the estimated S' to S; if they are within 10 percent of each other, the difference can be assumed to be negligible. If the difference is more than 10 percent, use the calculated S value as S', repeating Steps 2 through 4 until the S' and S values are within 10 percent.

(3) Hooghoudt Equation

(i) Applicable situations for use

The Hooghoudt equation, a modification of the ellipse equation, has a long history of use in designing drainage systems across the United States. One limitation of the Hooghoudt equation is that it is a steady state equation. It is based on the assumption that the drain steadily removes the rain that falls at a constant rate. This equation has been used to determine economical spacings and depths of agricultural drain tile and ditches for 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 can also be used to determine whether the hydrology of a wetland has been modified by drainage.

The Hooghoudt equation is similar to the ellipse equation, except that the hydraulic conductivity is calculated separately for the layers above and below the drain. In addition, the depth from the drain to the impermeable layer is modified to be equivalent depth. This calculation for equivalent depth accounts for the convergence of flow near the drain and therefore corrects a major shortcoming of the ellipse equation.

In Wisconsin the primary application of the Hooghoudt equation is for sites where the bottom of the drain is at, near (within about a foot of) or into, but **not** through or below, an impermeable layer. When a ditch or tile is installed into an impermeable layer, the Hooghoudt Equation should be used to analyze the lateral effect, with the drain depth set equal to the depth to the impermeable layer, which is the effective depth ($D_{effective}$) in this situation. Figures 7 and 8 illustrate examples of this situation.

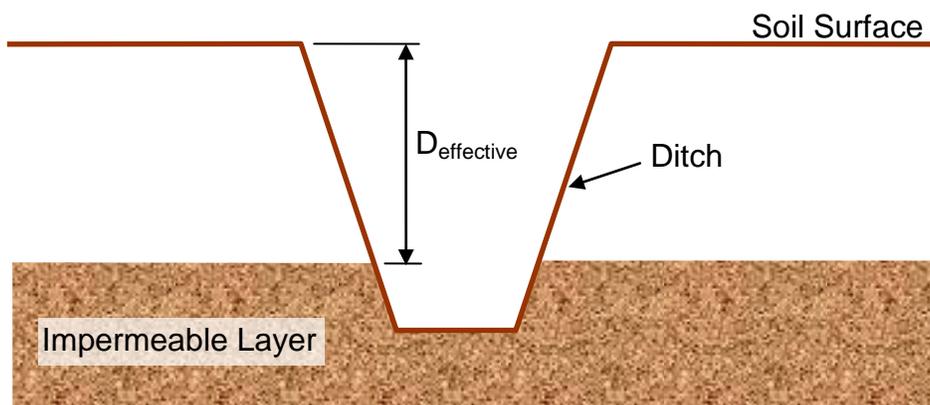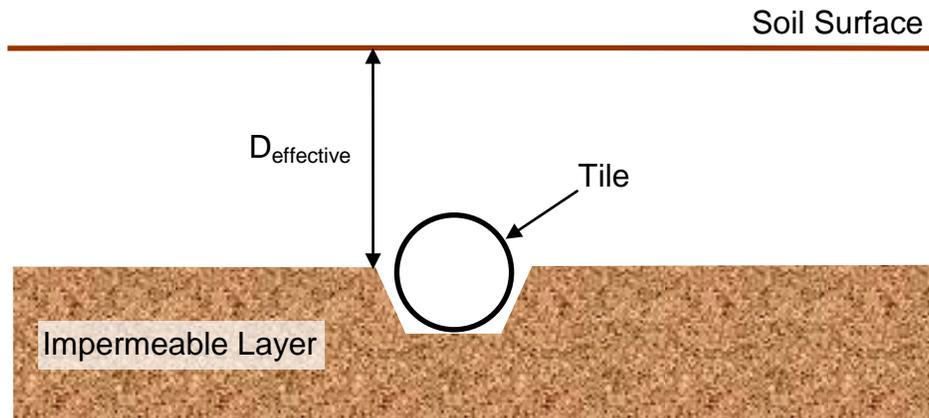**Figure 7: Ditch constructed into an impermeable Layer**

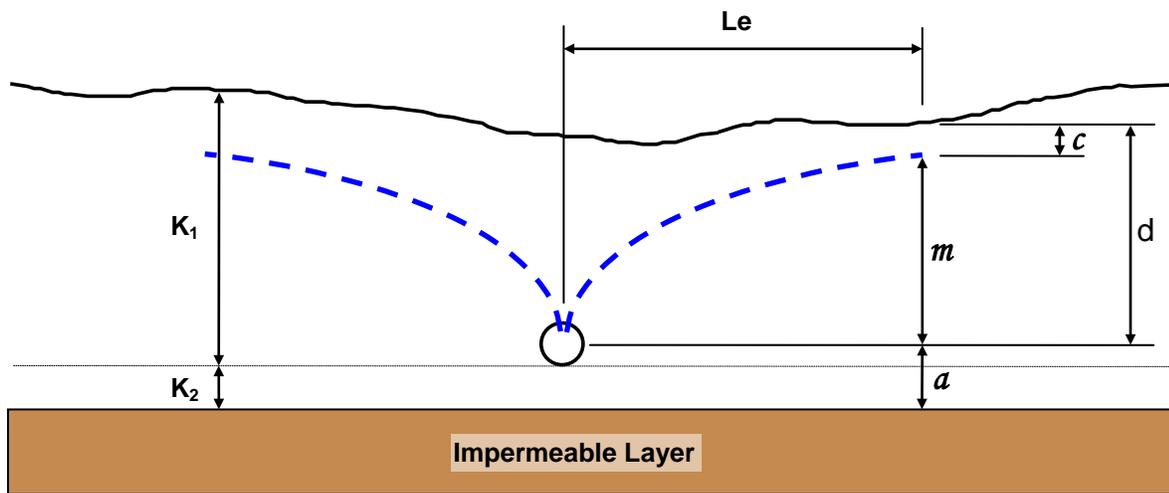**Figure 8: Tile installed into an impermeable Layer**

Figure 9: Variables for Hooghoudt Equation for Tile Drainage System

(ii) Data required

The following parameters are required for the Hooghoudt equation (see Figures 9 and 10 for illustrations of many of these parameters):
- Equivalent horizontal hydraulic conductivity above the drain (K_1)
- Equivalent horizontal hydraulic conductivity below the drain (K_2)
- Height of the water table above the drain at the midpoint between the drains (or the lateral effect distance) after a specified drawdown time period t (m)
- Depth from the ground surface to the water table at the midpoint between the drains (or L_e distance) after drawdown (c)
- Depth from the ground surface to the free water surface in the drain (d)
- Time for the water table to drop from the initial height to the drained height (t)
- Depth from the free water surface in the drain to the impermeable layer below the drain, a
- Drainable porosity
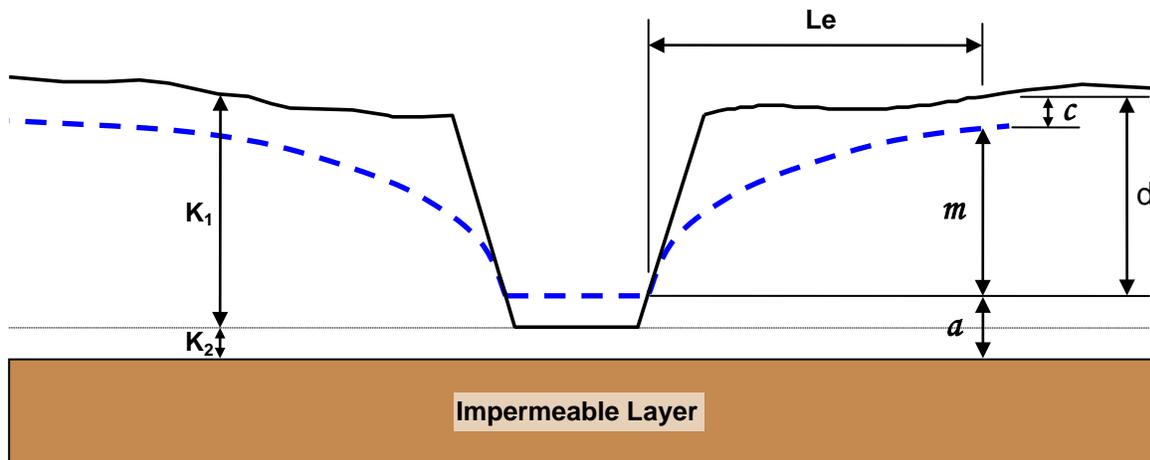- Effective radius of the drain

Figure 10: Variables for Hooghoudt Equation for Ditch Drainage System

(iii) _Limitations_

- The Hooghoudt equation is limited to situations were the horizontal hydraulic conductivity equals or exceeds the vertical hydraulic conductivity.
- The Hooghoudt equation is limited to sites where an impermeable layer underlies the drain. The actual depth to the impermeable layer cannot be more than twice the depth of the drain, and the depth from the ground surface is not to exceed 10 feet.
- Homogeneous soils are assumed in applying the Hooghoudt equation. Where site conditions differ, another method of analysis should be used.
- The equation does not have a factor for time. Therefore, other parameters in the equation must be adjusted in order to assume a drainage (drawdown) time other than the 24 to 48 hours normally assumed for crop production.
- The equation must use the equivalent depth to the impermeable layer instead of the actual depth to give the best results. Additional equations are used to convert from actual depth to the impermeable layer to equivalent depth.
- The Hooghoudt equation evaluates water table drawdown. It does not analyze the removal of surface water from a site. If surface water is present, it must be removed with a ditch, the natural ground slope or a tile inlet, in order for the Hooghoudt equation to be applicable to the site, and the evaluation of this surface water removal must be done using another method.
- Drains are assumed to be in good condition, with adequate outlets, and are evenly spaced a given distance apart.

(iv) _Factors affecting the accuracy of the results_

The value used for the drainage coefficient, q, has a significant affect on the spacing (and L_e) distance calculated using the Hooghoudt equation. The depth to the impermeable layer affects the calculated spacing most significantly when the hydraulic conductivity is high, such as with sandy soils.

(v) _Sources of data_

Some soils data are described in section (b), along with information related to determining (or estimating) the depth to the impermeable layer. Values for the effective radius of the drain are given in Table 2, of section (b)(3). Additional information, including the procedure to compute the equivalent saturated hydraulic conductivity, are given in NEH-650-19, Part 650.1905(d).

(vi) Methodology

The Hooghoudt equation is:

$$S = \left[\frac{\left(8K_2 d_e m + 4K_1 m^2 \right)}{q} \right]^{0.5}$$

$$L_e = \frac{S}{2}$$

Where: L_e = Lateral effect distance, ft
   S = drain spacing, ft
   K_1 = equivalent horizontal hydraulic conductivity above the drain, in/hr
   K_2 = equivalent horizontal hydraulic conductivity below the drain, in/hr
   m = height, after drawdown, of water table above the drain at the midpoint between the drains, ft ($m = d - c$)
   d = depth to the free water surface in the drain from the ground surface, ft
   c = depth from the ground surface to the water table at the midpoint between the drains (or at L_e distance) after drawdown, ft
   q = drainage rate, in/hr ($q = v/(t \times 24\ \text{hrs/day})$), where v is given below
   v = volume per unit area of soil water removed (= f x c x 12 in/ft), in
   t = time to remove soil saturation (drawdown time), days
   f = drainable porosity of the water conducting soil expressed as a fraction (voids drained at 60 cm tension), ft/ft, cm^3/cm^3, or cm/cm
   d_e = equivalent depth from the drain to the impermeable layer, ft

The procedure for using the Hooghoudt equation involves an iterative approach as described below.

Step 1 – Use the Hooghoudt equation with the known depth, a, in place of the equivalent depth, d_e, to determine an estimated spacing, S'. Where, "a" is the depth from free water surface in drain to impermeable layer (ft), as indicated in Figures 9 and 10.

$$S' = \left[\frac{\left(8K_2 am + 4K_1 m^2 \right)}{q} \right]^{0.5}$$

Step 2 – Use the estimated spacing, S', in the appropriate equation to determine the equivalent depth, d_e, which replaces "a" in the Hooghoudt equation for the final computations. Note that "r_e" is the effective radius of the drain in feet.

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

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

Step 3 – Use d_e to determine the spacing, S, in the Hooghoudt equation.

$$S = \left[\frac{\left(8K_2 d_e m + 4K_1 m^2\right)}{q} \right]^{0.5}$$

Step 4 – Compare the estimated S' to S; if they are within 10 percent of each other, the difference can be assumed to be negligible. If the difference is more than 10 percent, use the calculated S value as S', repeating Steps 2 through 4 until the S' and S values are within 10 percent of each other.

(4) Kirkham Equation

(i) Applicable situations for use

Under conditions where ponded water exists, the drainage rate can be determined using equations developed by Kirkham. It is applicable only for calculating the removal of ponded water (and not the soil saturation) through a tile drainage system with no surface inlets. The tile line(s) need to be located directly under the ponded area in order to apply this equation correctly. Flow net analyses show that streamlines are much closer together immediately over the drain than at some distance from it. This means that water enters the soil over the drain more rapidly than midway between the drains. There are two versions of the Kirkham equation(s), one for parallel drains and another for a single drain.

(ii) Data required

The following parameters are required for the Kirkham equation:

- Saturated hydraulic conductivity
- Depth from the soil surface to the center of the tile
- Average depth of ponded water (based on hydrologic and topographic input)
- Depth from the ground surface to the impermeable layer
- Effective radius of the drain
- Spacing between the drain lines
- Total length of the drains under the depression
- Estimated evapo-transpiration

Typically, one must have a good topographic map of the site to determine available surface storage. A topographic survey will be required if maps are not available. Calculations must be performed to determine the volume of runoff from a 2-year (50 percent chance) rainfall event. Details of the subsurface drain system are needed.

(iii) Limitations

- The Kirkham equation is applicable to conditions where tile lines are located directly below the ponded area.
- This equation is only applicable to removing ponded water via a subsurface tile drainage system. Therefore, the removal of ponded water with surface inlets or any surface drains (ditches) must be evaluated using other means.
- The Kirkham equation must be used in conjunction with the van Schilfgaarde equation or the Hooghoudt equation to determine the total time needed to remove ponding **and** soil saturation from a site. The Kirkham equation determines the time needed to remove the ponded water, and another equation must be used to evaluate the effects of the tile on the soil saturation.
- Drains are assumed to be in good condition, with adequate outlets, and are evenly spaced a given distance apart.

(iv) _Factors affecting the accuracy of the results_

The equation is quite sensitive to the depth of ponded water to be removed. Thus, the topographic survey of the site and the hydrologic modeling of the runoff volume from the watershed are both very important. In many cases it will be critical to consider evaporation and transpiration by plants (evapo-transpiration).

(v) _Sources of data_

Data sources for the soil hydraulic conductivity and the effective drain radius are the same as those for the van Schilfgaarde and Hooghoudt equations.

The average monthly evaporation values for Wisconsin listed in Table 3 are from the Companion Document 313-5 of the Wisconsin Supplement WI-25 (January 2005) to the NRCS National Engineering Handbook, Part 651 Agricultural Waste Management Field Handbook. Evaporation and transpiration data is also available from other climatological data sources.

Table 3. Monthly Precipitation and Evaporation in Wisconsin

Month	Average Precipitation* (Inches)	Average Evaporation Open Water** (Inches)	Net Precipitation less Evaporation Open Water Condition (Inches)
January	1.1	0.3	0.8
February	0.9	0.3	0.6
March	1.8	0.7	1.1
April	2.7	1.5	1.2
May	3.8	2.3	1.5
June	4.4	3.6	0.8
July	3.8	5.0	-1.2
August	3.5	5.1	-1.6
September	3.7	4.0	-0.3
October	2.2	2.6	-0.4
November	1.9	1.5	0.4
December	1.3	0.5	0.8

*Source for Precipitation Data: "Climatological Data Annual Summary, 1976, NOAA". Average Values from several Stations.

**Source for Evaporation Data: "Mean Monthly Evaporation From Shallow Lakes and Reservoirs;" Standard Drawing ES-1016 (13 sheets). Material from deleted section of SCS National Engineering Handbook, Section 4.

(vi) _Methodology_

The Kirkham equation is:

For Parallel Drains:

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

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

For a Single Drain:

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

Where: Q = Drain flow rate per unit length of drain, ft³/hr/ft
k = hydraulic conductivity, ft/hr
r_e = effective radius of the tile, ft
S = spacing between the tile lines, ft
d = depth from the soil surface to the tile center line, ft
t = average depth of the ponded water, ft
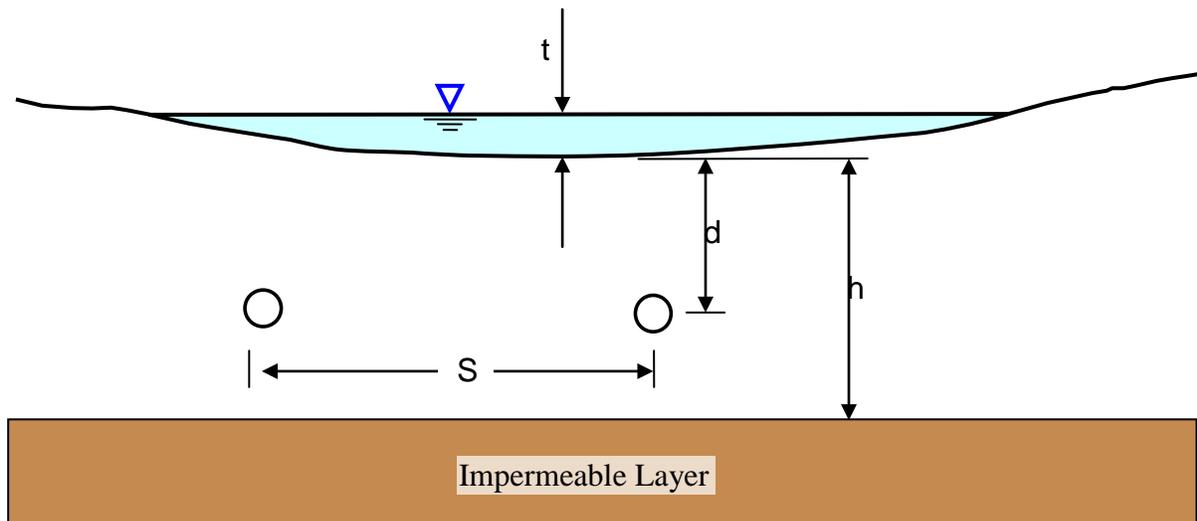h = depth to the impermeable layer, ft

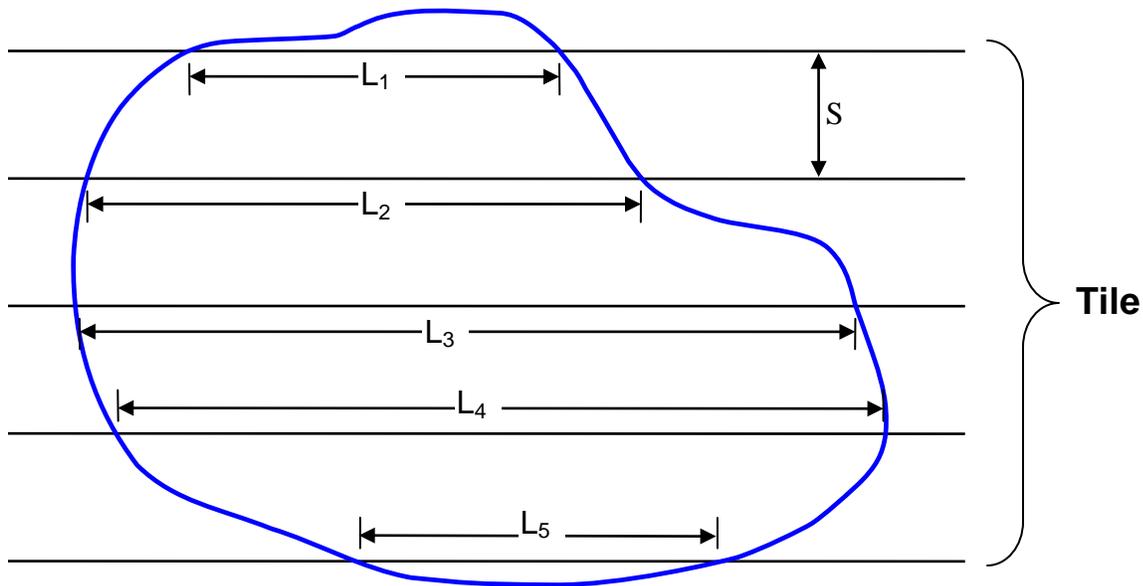**Figure 11: Variables for Kirkham Equation for Tile Drainage System**

Figure 12: Depressional Area with Tile Drainage System

Important points to consider to determine whether the Kirkham equation is being correctly applied include:

- Is the runoff volume reasonable for the watershed and the storm (e.g. 2-year 24-hour) analyzed?
- Is the depth of ponding reasonable for this type of site?
- Does the length of tile under the wetland seem reasonable/correct?
- Does the surface area seem reasonable?

(5) Lateral Effect Spreadsheet

An EXCEL Spreadsheet, developed in Wisconsin, is available to perform the computations for the van Schilfgaarde, Hooghout and Krikham equations. This Lateral Effect spreadsheet also gives guidance (on the "Intro" tab) as to which equation, or combination of equations, is recommended for use for a given situation.

(g) References

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