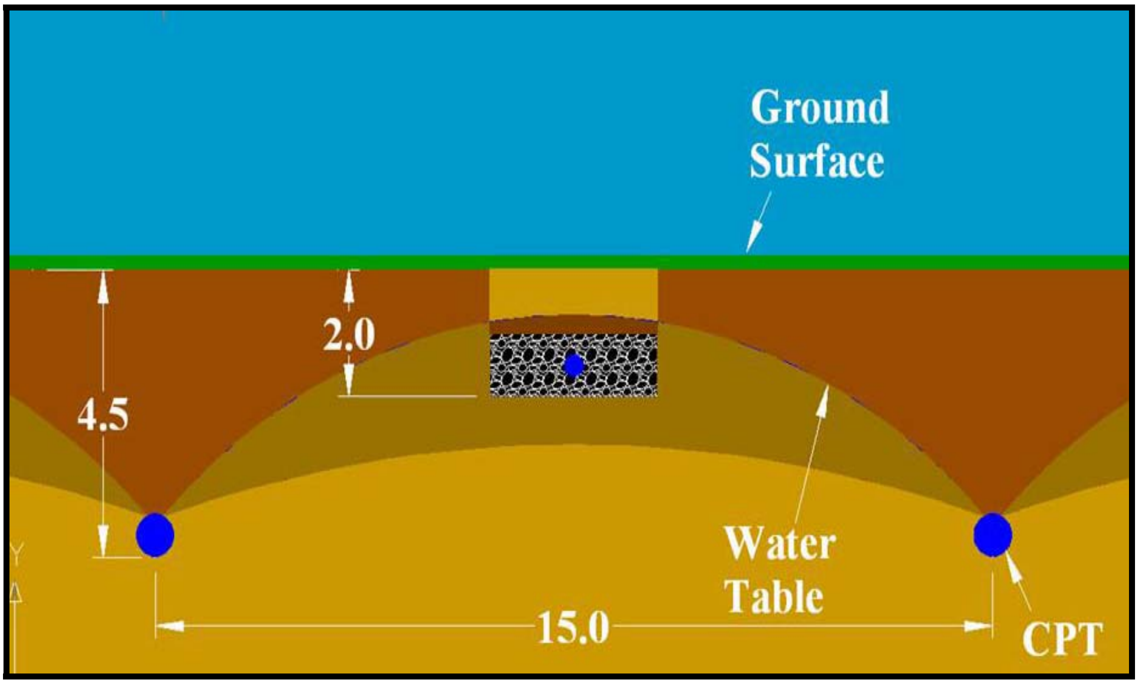
Modeling Water-Table Elevations for Curtain-Drain Applications with On-Site Wastewater Treatment Systems in Ohio



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Introduction and Executive Summary

Most On-Site Wastewater Treatment Systems (OSWTS) in Ohio's small and rural communities are subsurface soil absorption systems. However, Ohio's precipitation, soil and geologic characteristics limit the proper operation of these systems on some sites because of saturated soil conditions during parts of the year. Curtain drains are frequently used in these cases to artificially lower the water table (see Figure 1), with the goal of eliminating saturation of any portion of the treatment trench by natural water table conditions. This technique is similar to the use of subsurface drainage pipes on poorly drained cropland. With subsurface drainage the water table will be lowest directly at the drain, and highest at the midpoint between the two parallel drains.

With on-site systems installed on poorly drained soils, the concern from a public health standpoint primarily is the potential for partially or untreated wastewater to discharge to surface water bodies. The goal of using curtain drains near on-site systems should be to minimize, if not eliminate, any interaction between untreated wastewater and the near-surface ground water, eliminate any discharge of untreated wastewater to surface waters, and enhance the proper operation of the on-site system.

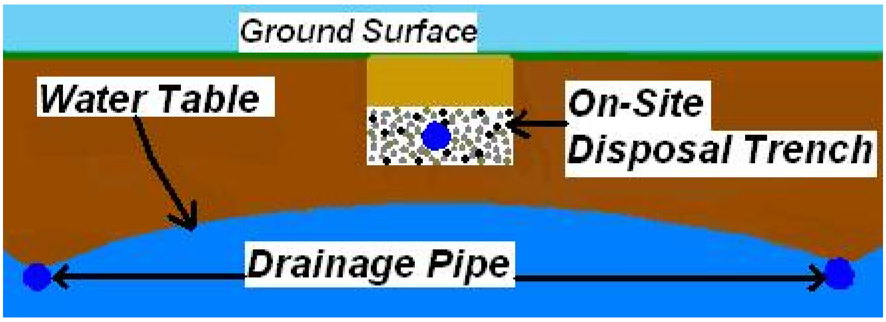

Figure 1. Example trench and curtain drain configuration for modeling the General Case.

While curtain drains may help lower the water table for some conditions, there is minimal if any information about how frequently on-site systems may be inundated by the natural water table, and even less published information on how curtain drains affect near-surface ground water near on-site systems. An option is to use hydrologic models to estimate the effect of curtain drains on water tables. With this type of information, public health officials can better assess the risks of any potential interaction between untreated, or partially treated, wastewater and ground water, the potential for on-site system failure, and the potential for polluting surface waters with wastewater from on-site systems.

This report contains the results of modeling studies that evaluated the performance of subsurface drains to remove excess soil water from the soil profile with application to OSWTS. We evaluated water table levels in selected soil series where curtain drains may be installed near on-site wastewater treatment trenches. Fifty-eight representative soil series were analyzed using the agricultural water management computer model DRAINMOD (Skaggs, 1980a). This computer model was developed to use long-term climatic data and soil property information to predict water table levels for various combinations of drain depth and drain spacing on cropland, and has been validated on conditions in Ohio as well as five other states. DRAINMOD can also be used to estimate the average daily water table depth midway between two parallel drain pipes on soils where curtain drains may be used with on-site systems; and to assess the effect of daily wastewater application in addition to precipitation; the effect of land slope; the use of a shallower curtain drain depth; and the use of a gravel envelope to increase the effective radius of the curtain drain. DRAINMOD uses input and conducts calculations in metric units.

For the 58 soil series selected for this project, DRAINMOD was used to predict the number of days (NOD) each year that the water table depth would meet each of three criteria: water table depth less than or equal to ~1' (30 cm); water table depth less than or equal to ~2' (~60 cm); and water table depth less than or equal to ~3' (90 cm). The analysis for these 58 soils at these three criteria, were for a drain depth of ~4.5' (140 cm) or less if the soils series typically had a shallow profile, and for the drain spacings of 5 m (~16'), 10 m (~33'), and 15 m (~50'). To model the case where there was no subsurface drain, we used a drain spacing of 1000 m (~3,281') for about one-half of these soils series. These simulations and their analyses are termed the General Case.

As an example, curtain drains were simulated as installed at 4.5' below the soil surface, and at a spacing of 15'. For the example trench in Figure 1, a curtain drain would be approximately 6.5' to each side of the 2'-wide treatment trench (7.5' from center line of treatment trench). If the depth of the treatment trench is two feet, then the curtain drains are effectively 2.5' below the bottom of the treatment trench. This kind of configuration may be typical of the closest curtain drain spacing installed in Ohio soils, and obviously there are wider spacings installed as well.

For the above configuration, the average number of days per year with the water table predicted to rise to within two feet of the soil surface, with and without curtain drains, is presented in Table 1 for selected soil series. Table 1 also contains the soil series name, the number of years of climatic record used in the modeling for that soil series, the average annual precipitation. Note that if curtain drains were not installed on these soil series, the number of days with interaction between the water table and the trench bottom exceeds 100 days. Thus, there is potential for near-surface ground water pollution at some level, and potential for the on-site system to not operate properly, and possibly to fail. With a curtain drain installed at the stated drain spacing and depth, the presence of the curtain drain did not eliminate the potential for the water table to interact with the treatment trench for all but three soil series. For these situations, there is risk of near-surface ground water and surface water pollution, and again potential for the on-site system to fail.

For many of the soils evaluated, water table levels with the modeled curtain drain depths frequently met or exceeded the criteria each year of the simulation. Thus, the water table depth was frequently within 36 inches of the soil surface. The modeling results also show that given the same drain depth, a wider drain spacing increases the number of days with a shallow water table. Therefore, for the soil series listed in Table 1, if the curtain drains were to be installed at a wider spacing than 15' and/or a drain depth shallower than 4.5', the potential number of days of interaction increases. Of course, if the drains were placed deeper than 4.5' and at a drain spacing closer than 15', the number of days should decrease. Placing the drains deeper may not be an option for a number of Ohio soil series because of subsoil and bedrock limitations. Alternative on-site systems, such as mound systems and possibly others, have the potential to effectively increase the distance between the bottom of the treatment system and the curtain drain, thus decreasing the potential for water table related problems.

			With Curtain Drain	No Curtain Drain
Soil	Years of Record	Average Annual Precipitation (In)	Average Number of Days per Year WT <2'	Average Number of Days per Year WT <2'
Blount	47	37.6	9	202
Centerburg	47	37.6	3	185
Crosby	44	37.0	3	200
Genessee	47	37.6	1	179
Haskins	26	37.8	16	248
Hoytville	40	37.0	13	200
Kokomo	47	37.6	2	187
Lewisburg	34	37.0	10	207
Mahoning	46	37.0	44	218
Mermill	40	32.4	13	205
Miamian	45	37.0	13	203
Millgrove	26	29.2	0	161
Millsdale	40	32.4	2	268
Nappanee	26	29.2	13	186
Pewamo	26	29.2	7	171
Rittman	26	37.8	7	246
Sebring	26	37.8	7	228
Sleeth	47	37.6	0	352
Switzerland	34	40.4	4	288
Tedrow	40	32.4	0	355
Toledo	40	32.4	16	205
Wadsworth	26	37.8	3	235
Wauseon	40	32.4	8	199

Table 1. Average number of days per year with the water table within two feet of the soil surface, with and without a curtain drain (days rounded to nearest whole number).

Each of the soil series modeled had a distribution of the number of days for the three scenarios. A recurrence interval, based on the modeling results, was calculated for each soil series for each scenario. A series of tables and graphs were generated for all 58 soils (discussed further in the body of the report; presented in total in the Appendices on CD).

In addition to the General Case modeling and analyses, four soil series (Blount, Crosby, Hoytville, and Mahoning) were further modeled and analyzed for a set of four Case Studies: the effect of daily wastewater application in addition to precipitation; the effect of land slope; the use of a shallower curtain drain depth; and the use of a gravel envelope to increase the effective radius of the curtain drain. For the wastewater application case, two different application depths were chosen: 1.25 cm/day (~0.5 in/day) and 0.33 cm/day (0.13 in/day). For the slope analysis case, land slopes of 3% and 6% were evaluated. The shallow drain depth analysis focused on 60 cm (~24 in) and 90 cm (~36 in). For the gravel envelope case, an effective radius of 6 cm (2.36 in) was evaluated. For all of the results of these Case Studies, the results were compared and plotted against the values obtained for the 140-cm (~55 in) drain depth cases.

The results of the Case Studies are presented in the body of the report. The references include publications cited in the report, as well as peer-reviewed journal articles and papers on applications of DRAINMOD, and several publications related to agricultural drainage research in Ohio and elsewhere.

Notes on Use of These Results

The results presented in this report were produced using DRAINMOD, a water balance computer simulation model that has wide application for making decisions in agricultural water management. The soil physical property information need as input for DRAINMOD is typical for the soil series modeled, are not site specific, nor specific to one county in Ohio. These results are very reasonable estimates of the behavior of the water table in the modeled soil series as affected by the presence of subsurface drains. Of course, improved site-specific predictions are possible with highly site-specific soil physics data and on-site long-term climatic data. When site-specific water table observations (5-10 years) are available, the results in this report may be useful as supporting information for decision making.

These results can be used to assess the risk of any potential interaction between untreated, or partially treated, domestic wastewater and near-surface ground water under on-site systems, the potential for on-site system inundation and/or failure, and the potential for untreated, or partially treated, domestic wastewater from on-site systems to be discharged to surface waters. These results do not predict specific levels of pollution, exact failure of an on-site system, concentrations of pollutants potentially being discharged. However, I believe these results could be very helpful to engineers, scientists, public health specialists in determining a ranking of seasonally high water table soil series in terms of high to moderate risk of undesirable interaction between the near-surface ground water and on-site systems using curtain drains, compared to on-site systems on the same soil series without curtain drains.

Acknowledgements

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The analysis and compilation of model output was performed by Katherine M. Skalak (Former Research Engineer; now Union SWCD), Ahmed M. AlZoheiry (Former PhD Graduate Associate; now Alexandria University, Egypt), Yun Wang (Former MS Graduate Associate; now Wayne State University), and Dr. Larry C. Brown. The Appendices contain seven sections of archival information and modeling results for the 58 Ohio soils analyzed for this project (available on CD), and summaries are included in the body of the report. Errata: In the Appendices, all references to Crosby "fine sandy loam" should be Crosby "silt loam." A full errata sheet will be issued at a later date. For further information, please contact Dr. Brown at brown.59@osu.edu or 614.292.3826.

METHODOLOGY

Among the approximate 475 recognized soil series in Ohio, 58 reference soil series (see Table 2) were selected as a representative sample of Ohio soil series. These soil series were originally selected by a team of state, federal, and university soil scientists and engineers (Atherton et al., 1998; Patterson et al., 1997; Tornes et al., 1998) for drainage modeling based on their characteristics to respond to subsurface drainage or not, and to what general degree. During 1996-1997, several thousand simulations were conducted over these 51 reference soil series, and some of the curtain drain analyses were an expansion from the earlier modeling and analysis on conventional subsurface drainage (Patterson et al., 1997; Prenger et al., 1997). In addition to the original 51 soil series, seven additional series were added to this group at the request of representatives from the Ohio Department of Health: Haskins, Lewisburg, Mahoning, Rittman, Sebring, Switzerland and Tedrow. All simulations were conducted using the agricultural water management model DRAINMOD (Skaggs, 1980a; http://www.bae.ncsu.edu/soil_water/drainmod/).

Soil Series	Soil Type	Soil Series	Soil Type
Adrian	MUCK	Mermill	SICL
Avonburg	SIL	Miamian	CL
Barkcamp	CL	Millgrove	L
Blount	SICL	Millsdale (100)	CL
Canfield	GR-SIL GR	Muskego	SP MUCK
Carlisle	MUCK	Nappanee	SIL
Centerburg	SIL	Omulga	C SIC
Clermont	SIL	Paulding	SIC C
Conneaut	SIL	Pewamo	SICL
Coshocton	SH-SIL CN	Rarden	SIC
Crosby	SL	Ravenna	SIC
Doles	SIL	Rittman	SIL
Eel	CL	Roselms	C SIC
Eldean	CL	Rossmoyne	SIL
Ellsworth	SIL	Sarahsville	CL
Fairpoint	SIL	Saranac	L SIL
Fitchville	SIL	Sebring	SIL
Frenchtown	SIL L	Shoals	SIC C
Genessee	FSL SL	Sleeth	SIC C
Glenford	SIL	Switzerland	SIL
Haney	FSL SL	Tedrow	S
Haskins	SL	Toledo	SIL
Hoytville	CL	Upshur	SICL
Kokomo	MK-SIL	Wadsworth	GR-SIL GR
Lewisburg	SIL	Wauseon	SIL
Loudonville (90)	L SIL	Wellston	MUCK
Luray	SIL	Wheeling	GR-SIL GR
Mahoning	SIL	Willette	SIL
Melvin	L FSL	Wooster	SICL

Table 2. Fifty-eight Ohio soil series evaluated in the curtain drain modeling study. The soil type designations are USDA soil textural classifications that can be found in any modern county soil survey publication.

DRAINMOD was developed to aid the design and evaluation of the performance of drainage and subirrigation systems, and their effects on water table level, soil-water content, relative crop yield, etc., based on long-term climatological records (Skaggs, 1980a). DRAINMOD ver. 5.1 requires inputs for soil characteristics, drainage system parameters (depth, spacing, etc.), climatic records (hourly precipitation; max/min daily temp), crop information, and field trafficability patterns (NCCI, 1986; Skaggs, 1980a; Workman et al., 1986; 1990). The USDA Soil Interpretation Record (SIR) database and the Map Unit Use File (MUUF) (http://www.wcc.nrcs.usda.gov/wetdrain/wetdrain-tools.html) were used to obtain all soils information and to develop the soils input format files. The soil data include soil-water retention data, drainage volume, upward flux, Green-Ampt infiltration parameters, and lateral saturated hydraulic conductivity. The methodologies and algorithms used in MUUF to derive soils parameter values for DRAINMOD are described by Baumer (1989) and Baumer and Rice (1988).

DRAINMOD has been applied to a number of Ohio soils and situations (Atherton et al., 1998; Desmond et al., 1995; Nolte et al., 18982a; 1982b; 1983; Ozkan et al., 1990; 1991; Oztekin et al., 1999; 2001; 2002a; 2002b; Patterson et al., 1997; Prenger et al., 1997; Skaggs et al., 1981; Workman and Fausey, 1995; Workman and Skaggs, 1989; 1994). Applications specific to land application of wastewater are Oztekin et al. (1991) in Ohio and in North Carolina, Skaggs and Nassehzadeh-Tabrizi (1982c). The references section contains numerous DRAINMOD-related publications.

Although our original simulations included a comprehensive matrix of drain spacing and depth values (Patterson et al., 1997; Prenger et al., 1997), simulations for the current analysis focused on drain spacings of 5 m (~16'), 10 m (~33'), and 15 m (~50'),.and a maximum drain depth of 140 cm (~4.6') for the general case. In some soil series, a shallower soil profile depth had to be used as there was an impermeable layer above the 140 cm depth, or a lack of profile information. This was the case for Loudonvile and Millsdale, with maximum drain depths of 90 cm (~2.95') and 100 cm (~3.28'), respectively. These depths are noted in Table 2 next to each of these two soil series. For all of the undrained cases analyzed, a drain spacing of 1000 m (~3,281') and a drain depth of 60 cm (~2') cm were used. The drainage coefficient was 1.27 cm/day (3/8 in/day) which is the most common drainage coefficient for agricultural subsurface drainage in Ohio (Atherton et al., 2004). For each of the Case Studies, all parameters were kept the same as for the General Case, except for the parameter of interest.

The climatic data were obtained from nearby NOAA weather stations based on the station's geographic location associated with the area of Ohio with the largest spatial concentration of the selected soil series. In the case of missing or limited climatic data, data from the next closest station was used. The heat index values used for Northern, Central and Southern regions of Ohio were 46, 50, and 57, respectively. Daily maximum and minimum temperature data were used in Thornthwaite's equation to calculate the potential evapotranspiration. The weather stations used for each soil are detailed in Appendix A.

DRAINMOD outputs a very large results summary, for daily, monthly, and annual water balance computations. A MATLAB program was used to extract parts of the output for further analysis. The selected simulation outputs included date, rainfall depth (cm), infiltration depth (cm), actual evapotranspiration (ET) depth (cm), drainage volume depth (cm), water table level (cm), runoff depth (cm), and water loss depth (cm), on a daily, a monthly, and an annual basis. Spreadsheets were used to further convert, analyze and graph the results. All DRAINMOD output is in Metric units. In many cases in this report, we include both Metric and English units for the results.

General Case Analysis

For the General Case, drain spacings of 5 m (~16'), 10 m (~33'), and 15 m (~50'), and a maximum drain depth of 140 cm (~4.6') was used for all soil series except for Loudonvile and Millsdale, with maximum drain depths of 90 cm (~2.95') and 100 cm (~3.28'), respectively. For the General Case, seepage was not considered, land slope was assumed to be between 0 and 2% (A slope, as per USDA terminology used in county soil survey publications), and daily wastewater application was not considered.

Case Studies Analysis

The case studies were conducted at the request of Ohio county sanitarians in January 2005. For these simulations, additional input parameters were required beyond those of the General Case. Four soils (Blount, Crosby, Hoytville, Mahoning) were analyzed for a set of four cases (see Table 3): effect of daily wastewater application in addition to precipitation; effect of land slope; use of a shallower curtain drain depth; and use of a gravel envelope to increase the effective radius of the curtain drain.

The following drain depths and drain spacings were used for these Case Studies: Drain depth at 0.6 m with drain spacings at 5, 10, and 15 m; Drain depth at 0.9 m with drain spacings at 5, 10, and 15 m; and Drain depth at 1.4 m with drain spacings at 5, 10, and 15 m. For the slope analysis, the drain depth was at 1.4 m with drain spacings at 5, 10, and 15 m for both land slopes, 3 and 6%. To consider a gravel envelope around the drain, the drain effective radius was changed from the value of 0.51 cm used for a 4” diameter corrugated plastic pipe to 6 cm (0.2 in to 2.4 in diameters). These were calculated as per DRAINMOD user's manuals. The undrained case was analyzed the same as for the General Case.

The daily loading of wastewater to the on-site system was modeled as a daily irrigation depth for each day of the year. The irrigation interval was modeled using a loading rate of 49.7 L/day/m of trench (4 g/day/ft of trench; recommended by ODH). This loading rate was adjusted for two different drain spacings, 5 and 15 m, therefore yielding two different net irrigation rates, 1.0 and 0.33 cm/day. To model wastewater irrigation applications with subsurface drainage design using DRAINMOD (Skaggs and Nassehzadeh-Tabrizi, 1982c), the daily loading rate must be distributed at a uniform depth over the width of the drain spacing. Also, DRAINMOD applies this depth of wastewater every day, regardless of soil conditions. The undrained ase was also modeled with these loading rates.

The recommended linear loading rates were converted to a depth measurement based on either the 5 or 15 m spacing. From the 5- and 15-m spacings, wastewater application depths were calculated as 1.0 and 0.33 cm/day, respectively. These loading values illustrate how the same total daily amount of water is spread over a wider area (i.e., wider drain spacing). The daily irrigation depth value of 1.0 cm/day was increased to 1.25 cm/day (0.5 in/day) to evaluate a possible excessive application. The calculations and unit conversions are shown below in Figure 2 in Systems International (metric) and U.S. Customary units.

Case	Drain Depth (cm)			Drain Spacing (m)				Slope (%)		Irrigation (cm/day)		Effective Radius (cm)		Comment
	60	90	140	5	10	15	1000	3	6	0.33	1.0	0.51	6	
General	X	X	X	X	X	X						X		
Slope			X	X	X	X		X	X			X		100-m slope length
Wastewater Application as Irrigation			X	X	X	X				X	X	X		
Effective Radius			X	X	X	X							X	
Undrained	X						X					X		
Undrained, with Irrigation	X						X			X				

Table 3. Matrix summarizing the parameters studied for both the General Case and the Case Studies. "X" indicates the modeling and analysis was conducted.

Equation 1: SI (5 m spacing)

$$\frac{4gal}{day*ft}*\frac{3.84lit}{gal}*\frac{3.28ft}{m}*\frac{10^{-3}m^3}{lit}*\frac{1}{5m}*\frac{100cm}{m}=\frac{1.01cm}{day}$$

Equation 2: SI (15 m spacing)

$$\frac{4gal}{day*ft}*\frac{3.84lit}{gal}*\frac{3.28ft}{m}*\frac{10^{-3}m^3}{lit}*\frac{1}{15m}*\frac{100cm}{m}=\frac{0.334cm}{day}$$

Equation 3: U.S. Customary (5 m spacing)

$$\frac{4gal}{day*ft}*\frac{1ft}{12in}*\frac{231in^3}{gal}*\frac{1}{5m}*\frac{1m}{39.37in}=.39\frac{in}{day}$$

Equation 4: U.S. Customary (15 m spacing)

$$\frac{4gal}{day*ft}*\frac{1ft}{12in}*\frac{231in^3}{gal}*\frac{1}{15m}*\frac{1m}{39.37in}=.13\frac{in}{day}$$

Figure 2. Daily wastewater application loading conversions in Systems International (metric) and U.S. Customary units.

An example of analysis results is shown in Table 4, which provides the modeling results for Crosby silt loam, with daily wastewater application, effective radius, and slope modeled. The General Case is provided for comparison. The results are the average number of days/year over a 45-year record where the water table exceeded any of the three criteria. Table 4 is essentially Table G2.2 from Appendix G, which provides the results for all three drain spacings for all four case study soil series. These results are discussed in a later section of the report.

Drain Spacing (m)	5			10			15			Undrained		
WTD (cm) <=	30	60	90	30	60	90	30	60	90	30	60	90
General Case												
140 cm Drain depth	2	3	10	5	18	77	16	66	148	186	200	221
Application Loading Rate (as Irrigation)_												
4 gal/day/ft trench (0.33 cm/day)	4	8	31	20	96	235	73	227	278	325	338	349
4 gal/day/ft trench (1.25 cm/day)	184	226	359	335	364	364	357	364	364	365	365	365
Slope (%)												
3	2	3	10	5	18	77	16	66	148			
6	2	3	10	5	18	76	16	65	148			
Shallower Depth (cm)												
60	7	21	162	39	164	204						
90	7	21	162	15	75	181						
Effective Radius (cm)												
6	1	3	9	5	17	75	15	65	147			

Table 4. Average number of days/year when criteria exceeded for Crosby silt loam (Table G2.2 from Appendix G) using a 45-year climatic record. Results for the General Case are for conditions where daily wastewater application, effective radius, and slope were not applied.

For the land slope simulations, slopes of 3% and 6% were analyzed. These values were chosen because the dominant slope for the soils used in the soil survey was either an ‘A’ slope or a ‘B’ slope. In county soil surveys, an ‘A’ slope represents a land slope between zero and two percent, while a ‘B’ represents a slope from two to six percent. Therefore, the values of six percent, the worse case scenario, and three percent, which is the median between zero and six, were chosen. The zero percent slope case is the same as for the General Case.

For the shallower drain depth case, we fully expect that a shallower drain depth will yield poorer results, but decided this was an opportunity to show this effect. Two shallower drain depths were chosen: 60 and 90 cm (approximately 2 and 3 ft). These values were compared to the General Case of a 140 cm drain depth (approximately 4.5 ft).

The effective drain radius was analyzed to model a gravel envelope surrounding the drain. The effective radius was estimated for the case where a 4-in corrugated plastic pipe was contained within a 12" x 12" layer of gravel. The value of 6 cm was calculated according to the method used described in the DRAINMOD manuals. By comparison, the General Case simulations used an effective drain radius of 0.51 cm (0.2") which corresponds to a 4-in corrugated plastic pipe without a gravel envelope.

Conceptual On-Site System

We assumed a single trench, 91.44 cm (3 ft) in width and 60.96 cm (2 ft) in depth, bounded on both sides with a curtain drain. Although this may not often be the case in application, we consider it a best case. The curtain drains were assumed to be located approximately 2.1 m (~7 ft) from each side of the trench, and approximately 140 cm (4.5 ft) beneath the surface. This General Case conceptualization is illustrated in Figure 3.

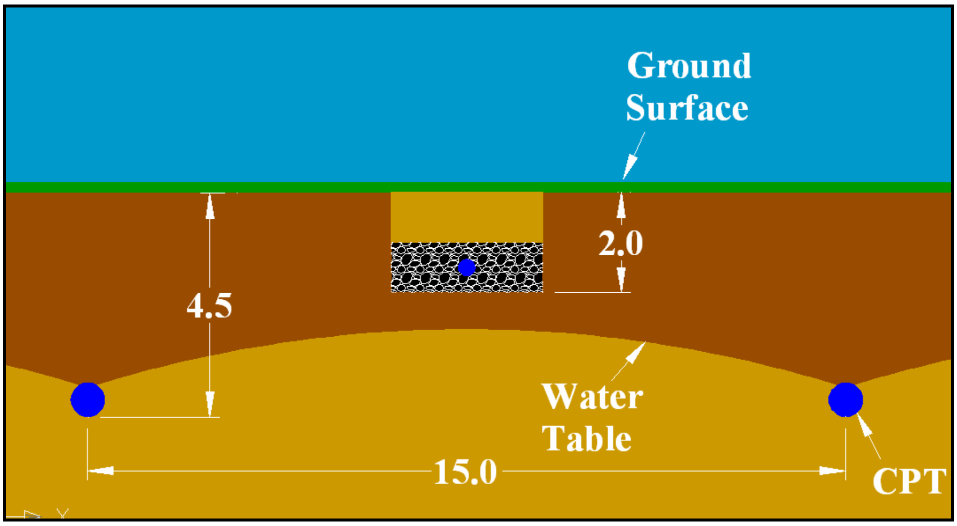


Figure 3. General Case conceptual treatment trench and curtain drains (CPT is corrugated plastic tubing).

In Figure 3, the combination of depth and spacing to be modeled with DRAINMOD would be 140 cm and 5 m, respectively. Note that DRAINMOD conducts a water balance and predicts the water table level at the mid-point between two parallel drains. The mid-point is at the center line of the wastewater treatment trench. We could model a large number of drain spacing and depth combinations, and compare the predicted daily average water table levels to each of the three water table depth (WTD) criteria: 30, 60, and 90 cm. For each year of the simulation, the number of days when the water table depth equaled or exceeded each criterion could be counted. The overall annual average number of days (NOD) could be summarized on an annual basis. Since DRAINMOD has the ability to output a large amount of information, a MATLAB program was used to extract the required daily output data. A second MATLAB program was used to determine the number of days the criteria were met. The same counting process was conducted for the 10- and 15-m spacings to verify that the wider spacings increased the number of days that each criterion is equaled or exceeded. For each case, the number of days per each simulation year, the criteria, and the annual precipitation were illustrated.

In this study, we also wanted to statistically assess the frequency with which a criterion was equaled or exceeded. We used a Cumulative Distribution Function analysis. A Cumulative Distribution Function (CDF) of a random variable X (number of days, NOD) is defined as $F(x) = P(X \leq x)$ for $x \geq 0$ while the Probability Proportional to Frequency (PPF) is defined as 1-CDF. The CDF was calculated by using MINITAB statistical software and as a result, the recurrence interval (RI) of the water table time distribution could also be predicted by RI=1/PPF. Appendix B provides for each soil series modeled for the General Case two numerical summaries: one with general output and one recurrence table; and two pages of figures. Using Crosby as an example, selected summary types will be discussed in a later section of the report.

Table 5 summarizes of all of the case study simulation conditions and parameters. Note that land slopes of 3 and 6% were not simulated for Hoytville since this soil series almost never occurs on a land slope greater than 1%.

Parameters	Soil Series Parameter Values	Blount	Crosby	Hoytville	Mahoning
Wastewater Application (cm/day)	0.33	X	X	X	X
	1.25	X	X	X	X
Slope (%)	3	X	X		X
	6	X	X		X
Shallower Drain Depth (cm)	60	X	X	X	X
	90	X	X	X	X
Effective Drain Radius (cm) (gravel envelope)	6	X	X	X	X

Table 5. Summary of all Case Study parameters for the Case Study soil series.

For all of the Case Studies listed in Table 5, the maximum, minimum, and average NOD were illustrated for each WTD criteria of 30, 60 and 90 cm. Also, an illustration was created for each drain spacing (5, 10, 15 m) showing the NOD for each year for each WTD criteria, as well as the annual precipitation. Then, for each soil series, a set of graphs was generated illustrating the recurrence of each NOD value, for each drain spacing and WTD combination. Lastly, three figures are produced for each parameter which combines the various parameter values. All of these data and results are presented in the Appendices.

The results below are largely focused on those from the simulations and analyses for Crosby silt loam. For the General Case simulations and analyses, the types of results (tables and figures, etc.) shown below for Crosby are the same for the other 57 soils. For the Case Study simulations and analyses, the types of results shown below for Crosby silt loam are the same for the other three Case Study soil series, Blount, Hoytville, and Mahoning. All of these are also included in the Appendices.

RESULTS

General Case Results

Table 6 (from Appendix Table G1.1) provides a summary of the General Case results for all 58 soil series modeled in this study. The undrained case is included for a number of these soil series. Table 7 (from Appendix Table B11.1) shows the number of days (NOD) for Crosby when the water table depth (WTD) criteria were met or exceeded for each of the nine drain spacing - drain depth combinations. These results are illustrated in Figure 4 (from Appendix Figure B11.1).

The Crosby results in Figure 4 are for the period 1951 to 1995. These results follow a specific trend, in that the NOD for the WTD less than 90-cm criteria are greater than the values obtained for the WTD less than 60 cm and 30 cm, and subsequently the NOD for the WTD less than 60-cm criteria are greater than the values obtained for the WTD less than 30 cm. This trend holds for all soil series as can be noted in Table 6.

Table 8 (from Appendix Table B11.2) shows the correlation between the NOD and the Probability Proportional Frequency (PPF), as well as the Recurrence Interval (RI). For example, there is a 7% probability that the WTD will occur five or more days in any given year under the combination of the 5-m spacing and the WTD less than or equal to the 30-cm criteria. The corresponding RI is 15 years, which means that we should expect that the five-day value for the NOD should occur once every 15 years. However, this is only an indication of what might occur and does not mean that it will occur once every 15 years. In reality this results could occur two consecutive years, etc. Figure 5 (from Appendix Figure B11.4) illustrates the recurrence for the 5-m spacing and WTD less than 30-cm combination. All tables and figures for all 58 soil series are located in Appendix B.

Table 6. Average annual number of days when water table depth criteria was equaled or exceeded. All soil series - General Case analysis results; Drain depth = 140 cm; Slope = 0-2% (from Appendix Table G1.1)													Undrained Case[1]		
Drain Spacing (m)				5			10			15			1000m		
Water Table Depth Criteria (cm) <=				30	60	90	30	60	90	30	60	90	30	60	90
Soil Series	Years Record[2]	Soil Type	PPT[3] (cm)												
Adrian	40	MUCK	85.23	0	0	0	0	0	0	0	0	0	182	244	307
Avonburg	20	SIL	98.94	12	20	66	16	40	128	21	67	153	-	-	-
Barkcamp	31	CL	86.31	0	1	2	0	1	2	0	1	2	-	-	-
Blount	47	SICL	95.51	7	9	14	10	15	33	18	31	68	197	202	209
Canfield	28	GR-SIL GR	87.29	1	3	12	5	12	61	9	30	122	-	-	-
Carlisle	28	MUCK	87.22	0	0	0	0	0	0	0	0	0	-	-	-
Centerburg	47	SIL	95.51	2	3	5	2	4	12	5	9	32	175	185	200
Clermont	20	SIL	98.94	29	51	88	84	123	155	133	161	176	-	-	-
Conneaut	20	SIL	53.95	1	2	5	3	8	24	7	17	53	-	-	-
Coshocton	47	SH-SIL CN	95.51	1	1	2	1	1	3	1	2	5	-	-	-
Crosby	44	SL	93.98	2	3	10	5	18	77	16	66	148	186	200	221
Doles	30	SIL	93.74	6	9	17	11	23	56	21	47	104	-	-	-
Eel	47	CL	95.51	0	1	2	1	1	2	1	1	4	163	176	196
Eldean	44	CL	87.39	0	1	16	0	4	155	1	26	224	-	-	-
Ellsworth	28	SIL	87.22	10	22	85	25	72	156	57	126	172	-	-	-
Fairpoint	31	SIL	95.07	5	7	11	1	1	3	1	2	4	-	-	-
Fitchville	28	SIL	87.28	2	4	6	3	5	11	5	9	21	-	-	-
Frenchtown	20	SIL L	53.98	1	2	4	2	4	15	4	8	37	-	-	-
Genessee	47	FSL SL	95.51	1	1	2	1	1	3	1	2	5	165	179	198
Glenford	28	SIL	87.29	3	5	9	5	8	19	9	16	40	-	-	-
Haney	26	FSL SL	74.19	0	0	1	0	1	13	1	7	72	-	-	-
Haskins	26	SL	96.07	7	16	101	10	31	166	16	62	180	237	248	257
Hoytville	40	CL	93.98	9	13	18	12	18	34	20	35	63	196	200	205
Kokomo	47	MK-SIL	95.51	1	2	4	3	5	20	6	15	66	176	187	205
Lewisburg	34	SIL	93.98	7	10	26	14	35	104	29	81	155	199	207	218
Loudonville(90)	47	L SIL	95.51	1	1	2	1	1	3	1	2	5	-	-	-

Table 6. Average annual number of days when water table depth criteria was equaled or exceeded. All soil series - General Case analysis results; Drain depth = 140 cm; Slope = 0-2% (from Appendix Table G1.1)														Undrained Case[1]		
Drain Spacing (m)				5			10			15			1000m		
Water Table Depth Criteria (cm) <=				30	60	90	30	60	90	30	60	90	30	60	90
Soil Series	Years Record[2]	Soil Type	PPT[3] (cm)												
Luray	36	SIL	101.81	5	7	12	6	9	15	8	12	23	-	-	-
Mahoning	46	SIL	93.96	22	44	97	49	110	157	94	149	172	216	218	221
Melvin	28	L FSL	87.29	1	1	3	1	2	7	3	5	17	-	-	-
Mermill	40	SICL	82.40	7	13	40	9	17	97	12	28	136	198	205	211
Miamian	45	CL	93.98	9	13	19	11	16	26	13	23	40	197	203	209
Millgrove	26	L	74.19	0	0	1	0	0	1	0	0	1	143	161	182
Millsdale(100)	40	CL	82.40	0	2	227	1	114	283	19	191	308	180	268	341
Muskego	19	SP MUCK	88.18	0	0	0	0	0	0	0	0	1	-	-	-
Nappanee	26	SIL	74.19	9	13	20	14	25	41	29	45	74	182	186	189
Omulga	30	C SIC	93.74	11	13	18	11	15	25	13	20	38	-	-	-
Paulding	41	SIC C	79.40	51	56	64	120	125	131	152	154	157	-	-	-
Pewamo	26	SICL	74.19	4	7	11	5	9	16	7	13	27	165	171	178
Rarden	30	SIC	93.74	0	4	165	4	132	263	29	172	278	-	-	-
Ravenna	28	SIC	87.22	1	2	6	3	8	26	7	21	70	-	-	-
Rittman	26	SIL	96.07	4	7	19	9	19	85	15	45	154	239	246	254
Roselms	41	C SIC	79.40	26	42	69	81	104	127	124	139	149	-	-	-
Rossmoyne	20	SIL	98.94	14	17	21	17	20	31	19	26	46	-	-	-
Sarahsville	31	CL	86.31	33	38	47	97	138	146	120	178	183	-	-	-
Saranac	19	L SIL	88.18	6	9	15	7	11	20	10	18	34	-	-	-
Sebring	26	SIL	96.07	4	7	14	9	16	29	17	26	50	226	228	233
Shoals	36	SIC C	101.81	2	2	5	2	3	6	2	4	10	-	-	-
Sleeth	47	SIC C	95.51	0	0	0	0	0	0	0	0	0	224	352	365
Switzerland	34	SIL	102.49	0	4	256	0	49	304	1	144	329	176	288	364
Tedrow	40	S	82.40	0	0	0	0	0	0	0	0	0	255	355	355
Toledo	40	SIL	82.40	13	16	25	23	27	36	46	52	65	204	205	206
Upshur	31	SICL	86.31	0	0	0	0	0	0	0	0	0	-	-	-

Table 6. Average annual number of days when water table depth criteria was equaled or exceeded. All soil series - General Case analysis results; Drain depth = 140 cm; Slope = 0-2% (from Appendix Table G1.1)												**Undrained Case[1]**		
Drain Spacing (m)				**5**			**10**			**15**			**1000m**	
Water Table Depth Criteria (cm) <=				**30**	**60**	**90**	**30**	**60**	**90**	**30**	**60**	**90**	**30**	**60**	**90**
Soil Series	**Years Record[2]**	**Soil Type**	**PPT[3] (cm)**												
Wadsworth	26	GR-SIL GR	96.07	2	3	8	4	10	39	10	32	104	226	235	247
Wauseon	40	SIL	82.40	3	8	40	4	10	101	4	12	131	185	199	209
Wellston	31	MUCK	83.08	0	0	0	0	0	0	0	0	0	-	-	-
Wheeling	46	GR-SIL GR	89.92	0	0	5	0	1	30	1	5	101	-	-	-
Willette	46	SIL	87.75	0	2	13	0	9	76	1	36	155	-	-	-
Wooster	28	SICL	87.29	0	0	0	0	1	3	1	2	11	-	-	-

1. Undrained case analyzed for selected soil series.
2. The number of years of the climatic record used for the specific soil series.
3. Long-term annual precipitation.

Table 7. Crosby silt loam; Drain depth = 140 cm; Slope = 0-2% (from Appendix Table B11.1)										
	Drain Spacing[1] (m)									
Years (n=47)	5			10			15			
WTD[2] (cm) <=	30	60	90	30	60	90	30	60	90	PPT[3] (cm)
1951	2	4	12	7	32	112	25	98	161	94.46
1952	3	5	14	7	29	104	22	87	146	96.60
1953	0	0	4	1	10	65	11	57	128	70.18
1954	0	0	2	0	4	41	3	36	107	74.57
1955	2	3	9	3	13	81	13	66	176	98.40
1956	0	0	3	1	8	72	8	62	129	83.46
1957	6	10	20	12	25	85	21	68	181	101.88
1958	3	6	15	10	19	58	18	46	132	104.78
1959	4	5	13	4	18	73	13	55	158	101.17
1960	0	0	0	0	1	35	2	31	106	66.52
1961	0	2	12	10	27	85	21	73	155	101.85
1962	0	0	0	0	5	45	7	42	98	70.46
1963	2	3	7	4	12	31	7	26	53	61.47
1964	5	6	16	8	21	58	15	51	78	80.19
1965	0	0	1	0	6	62	11	54	122	77.37
1966	0	0	5	1	6	40	7	30	135	81.97
1967	0	1	9	5	21	80	16	69	162	84.91
1968	3	4	7	5	9	42	8	37	115	87.25
1969	0	1	6	4	11	53	10	38	145	88.67
1970	0	1	4	3	6	30	5	19	120	69.14
1971	0	0	0	0	2	61	8	53	117	84.40
1972	0	0	3	2	9	80	12	75	184	90.96
1973	0	0	5	1	17	71	11	64	167	97.74
1974	0	1	4	1	10	107	15	93	174	102.69
1975	2	3	10	6	20	95	21	85	132	104.37
1976	0	0	0	0	5	43	4	42	91	65.10
1977	2	3	6	5	18	70	13	60	136	90.35
1978	0	0	8	4	15	67	16	55	146	99.06
1979	1	2	12	6	20	88	18	76	169	109.98
1980	4	4	10	7	21	86	20	72	169	104.04
1981	2	4	11	4	15	89	17	81	161	110.97
1982	2	5	16	7	28	116	26	98	157	108.48
1983	0	0	9	3	24	97	20	88	197	96.14
1984	0	0	2	1	17	111	17	96	202	91.41
1985	1	4	16	10	28	91	27	76	162	90.96
1986	0	3	13	5	23	84	20	70	149	109.02
1987	0	0	1	0	2	25	3	22	76	62.74
1988	3	4	13	7	21	77	15	67	151	92.89
1989	2	6	22	12	41	126	33	106	213	125.15
1990	7	13	31	23	49	141	41	123	239	151.76
1991	0	3	11	3	26	108	23	96	151	94.36
1992	0	2	12	5	17	74	15	67	155	103.10
1993	5	10	23	15	42	145	34	126	209	132.66
1994	1	2	8	5	15	67	14	53	154	88.32
1995	6	11	24	13	32	86	26	69	190	127.10
Average[4]	2	3	10	5	18	77	16	66	148	93.98

1. For each drain spacing, drain depth was 140 cm.
2. PPT = Precipitation
3. WTD = Water table depth criteria
4. Average number of days per year (rounded)

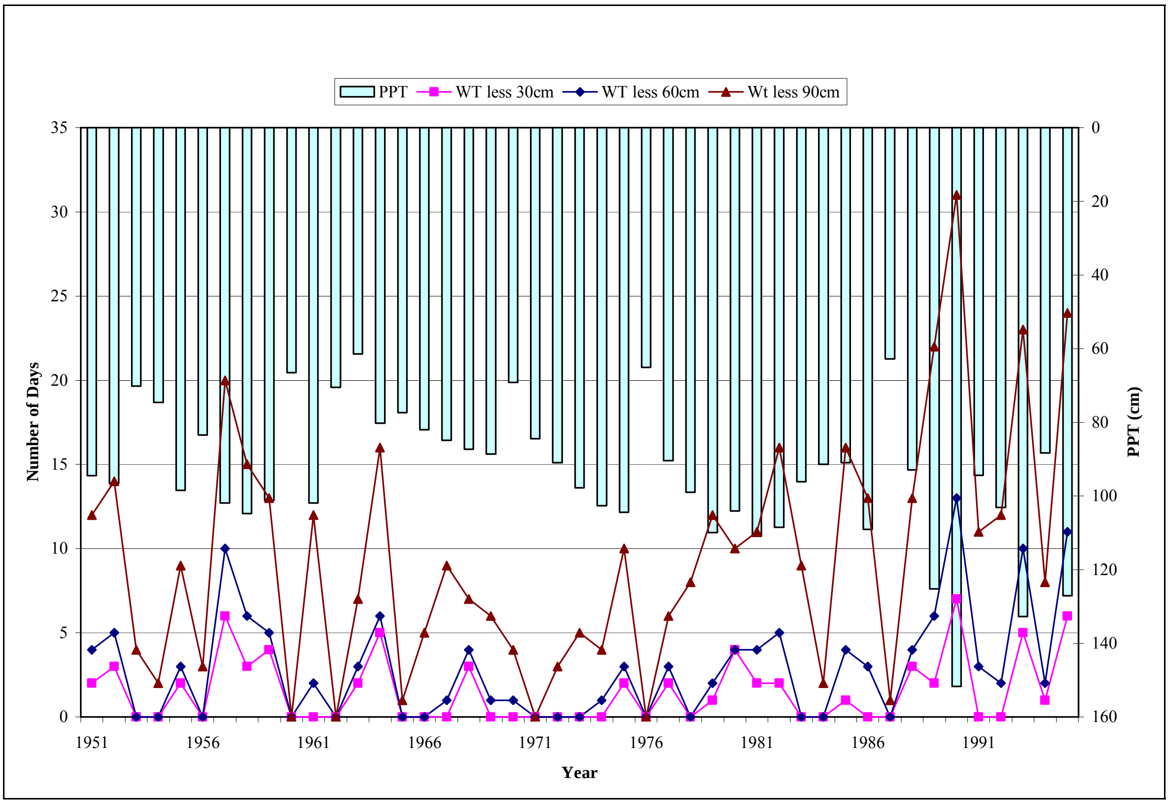


Figure 4. For Crosby soil loam, the number of days per year that the predicted water table equaled or exceeded the WTD criteria of 30 cm, 60 cm, and, or 90 cm, for a drain depth of 140 cm, a drain spacing of 5 m, and land slope = 0-2%. The precipitation for each year of the record is shown at the top of the graph.

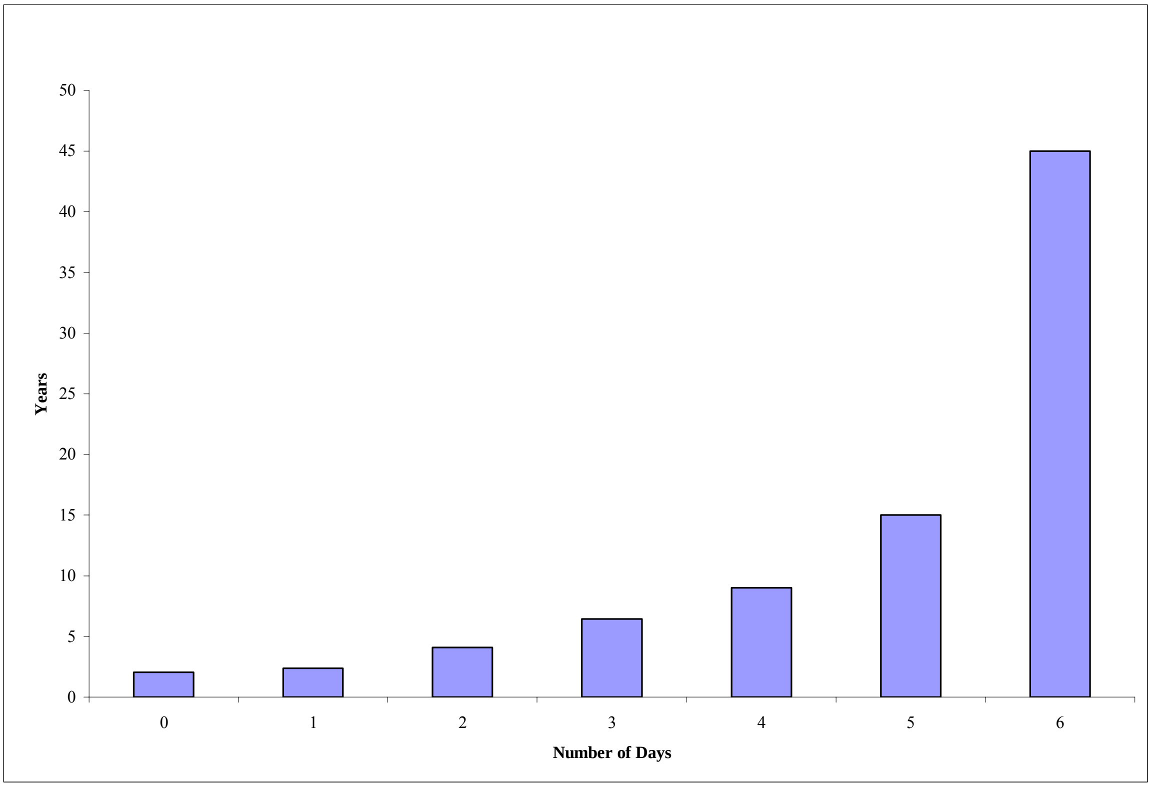


Figure 5. Recurrence of equaling or exceeding the WTD criterion of 30 cm, for Crosby silt loam with a drain depth of 140 cm and a drain spacing of 5 m (from Appendix Figure B11.4).

Table 8. Recurrence analysis for Crosby silt loam; Drain depth = 140 cm; Slope = 0-2% (from Appendix Table B11.2)

Water Table Depth <= 30 cm									Water Table Depth <= 60 cm									Water Table Depth <= 90 cm								
DS[1] = 5 m			DS = 10 m			DS = 15 m			DS = 5 m			DS = 10 m			DS = 15 m			DS = 5 m			DS = 10 m			DS=15m		
Days	PPF[2]	RI[3]	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI
0	0.49	2	0	0.84	1	2	0.98	1	0	0.67	2	1	0.98	1	19	0.98	1	0	0.91	1	25	0.98	1	53	0.98	1
1	0.42	2	1	0.71	1	3	0.93	1	1	0.58	2	2	0.93	1	22	0.96	1	1	0.87	1	30	0.96	1	76	0.96	1
2	0.24	4	2	0.70	1	4	0.91	1	2	0.49	2	4	0.91	1	26	0.93	1	2	0.82	1	31	0.93	1	78	0.93	1
3	0.16	6	3	0.61	2	5	0.89	1	3	0.36	3	5	0.87	1	30	0.91	1	3	0.78	1	35	0.91	1	91	0.91	1
4	0.11	9	4	0.50	2	7	0.82	1	4	0.22	5	6	0.80	1	31	0.89	1	4	0.71	1	40	0.89	1	98	0.89	1
5	0.07	15	5	0.37	3	8	0.76	1	5	0.16	6	8	0.78	1	36	0.87	1	5	0.67	2	41	0.87	1	106	0.87	1
6	0.02	45	6	0.33	3	10	0.73	1	6	0.09	11	9	0.73	1	37	0.84	1	6	0.62	2	42	0.84	1	107	0.84	1
			7	0.22	5	11	0.67	2	10	0.04	22	10	0.69	1	38	0.82	1	7	0.58	2	43	0.82	1	115	0.82	1
			8	0.20	5	12	0.64	2	11	0.02	45	11	0.67	2	42	0.78	1	8	0.53	2	45	0.80	1	117	0.80	1
			10	0.13	8	13	0.58	2				12	0.64	2	46	0.76	1	9	0.47	2	53	0.78	1	120	0.78	1
			12	0.09	12	15	0.56	2				13	0.62	2	51	0.73	1	10	0.42	2	58	0.73	1	122	0.76	1
			13	0.07	15	15	0.49	2				15	0.56	2	53	0.69	1	11	0.38	3	61	0.71	1	128	0.73	1
			15	0.04	23	16	0.44	2				17	0.49	2	54	0.67	2	12	0.29	3	62	0.69	1	129	0.71	1
						17	0.40	3				18	0.44	2	55	0.62	2	13	0.22	5	65	0.67	2	132	0.67	2
						18	0.36	3				19	0.42	2	57	0.60	2	14	0.20	5	67	0.62	2	135	0.64	2
						20	0.29	3				20	0.38	3	60	0.58	2	15	0.18	6	70	0.60	2	136	0.62	2
						21	0.22	5				21	0.29	3	62	0.56	2	16	0.11	9	71	0.58	2	145	0.60	2
						22	0.20	5				23	0.27	4	64	0.53	2	20	0.09	11	72	0.56	2	146	0.56	2
						23	0.18	6				24	0.24	4	66	0.51	2	22	0.07	15	73	0.53	2	149	0.53	2
						25	0.16	6				25	0.22	5	67	0.47	2	23	0.04	23	74	0.51	2	151	0.49	2
						26	0.11	9				26	0.20	5	68	0.44	2	24	0.02	45	77	0.49	2	154	0.47	2
						27	0.09	11				27	0.18	6	69	0.40	3				80	0.44	2	155	0.42	2
						33	0.07	15				28	0.13	8	70	0.38	3				81	0.42	2	157	0.40	3
						34	0.04	23				29	0.11	9	72	0.36	3				84	0.40	3	158	0.38	3
						41	0.02	45				32	0.07	15	73	0.33	3				85	0.36	3	161	0.33	3
												41	0.04	23	75	0.31	3				86	0.31	3	162	0.29	3
												42	0.02	45	76	0.27	4				88	0.29	3	167	0.27	4
															81	0.24	4				89	0.27	4	169	0.22	5
															85	0.22	5				91	0.24	4	174	0.20	5

Table 8. Recurrence analysis for Crosby silt loam; Drain depth = 140 cm; Slope = 0-2% (from Appendix Table B11.2)

Water Table Depth <= 30 cm									Water Table Depth <= 60 cm									Water Table Depth <= 90 cm								
DS[1] = 5 m			DS = 10 m			DS = 15 m			DS = 5 m			DS = 10 m			DS = 15 m			DS = 5 m			DS = 10 m			DS=15m		
Days	PPF[2]	RI[3]	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI
															87	0.20	5				95	0.22	5	176	0.18	6
															88	0.18	6				97	0.20	5	181	0.16	6
															93	0.16	6				104	0.18	6	184	0.13	8
															96	0.11	9				107	0.16	6	190	0.11	9
															98	0.07	15				108	0.13	8	197	0.09	11
															106	0.04	23				111	0.11	9	202	0.07	15
															123	0.02	45				112	0.09	11	209	0.04	23
																					116	0.07	15	213	0.02	45
																					126	0.04	23			
																					141	0.02	45			

1. DS = Drain spacing (m)
2. PPF = Probability of recurrence; For example, for the combination of 5-m spacing and WTD <= 30-cm criteria, the results highlighted above indicate that there is a 7% probability that this criteria will be met for 5 or more days in any given year.
3. RI = Recurrence Interval (year) = 1/PPF; For example, we should expect this to occur once every 15 years.

Case Studies

Wastewater Application

The 1.25-cm/day depth represents an extreme case of waste water application while the 0.33-cm/day rate represents a midway point between no application and the 1.25-cm/day case. The 1.25-cm/day rate equates to an annual application depth of 456.56 cm (179.75 in). The 0.33-cm/day rate equates to an annual application depth of 120.53 cm (47.45 in). Remember most counties on Ohio receive an annual average of 36 to 40 inches of precipitation, so these applications rates are three to more than ten times the annual precipitation.

Loading Rate 0.33 cm/day

Table 9 provides that NOD for Crosby for each of the nine combinations with the 0.33-cm/day application rate. The 0.33-cm/day rate represents a midway point between no wastewater application and the 1.25-cm/day application rate. The amount of precipitation shown in this table is only rainfall and does not include the wastewater application depth. In the year with the least precipitation, 1963, the NOD doubled in the case of the 30-m and 60-m WTD criteria for the 5- spacing case, and in the case of the 90-cm WTD criteria, the NOD more than doubled as compared to the NOD in the general case (Table 7). In the year with the greatest amount of precipitation, 1990, the NOD value for the WTD criteria of 30 cm was three times the NOD for the general case, while the NOD values for the WTD criteria of 60 cm and 90 cm were both slightly more than twice the value of NOD for the general case (Table 7). This trend was also seen in the 10-m and 15-m spacing results.

In Figure 6 (from Appendix Figure D1.1), the maximum, average and minimum NOD are plotted for the three drain spacings and the undrained case. Figure 6 illustrates that as the drain spacing increases, the expected NOD also increases. This trend holds for almost all soil series. In the undrained case, the expected minimum NOD is 252 days/yr, which suggests that for more than 70% of the year, this wastewater application rate on a site with the Crosby soil series without curtain drains promotes a higher water table. Figure 7 (from Appendix Figure D1.4) shows the NOD for the period from 1951 to 1995.

Table 10 (from Appendix Table D1.2) contains a correlation between the NOD and the Probability Proportional Frequency (PPF), as well as the Recurrence Interval (RI) for the 0.33-cm/day application rate on Crosby. For the combination of the 5-m spacing and WTD less than or equal to the 30-cm criteria, there is a 27% probability that the WTD will occur five or more days in any given year. The corresponding return interval is four years, which means that we should expect the five day value for the NOD to occur once every four years. Figure 8 (from Appendix Figure D1.7) illustrates the recurrence for the 5-m spacing and WTD less than 30-cm depth combination. In Appendices D13 and D14, respectively, are tables and figures for Crosby with the undrained case and the undrained case with wastewater application. All similar tables and figures for Blount, Hoytville, and Mahoning are located in Appendices C, E, and F, respectively.

Table 9. Crosby silt loam; Drain depth = 140 cm; Irrigation depth = 0.33 cm/day (from Appendix Table D1.1)

Years (n=47)	Drain Spacing[1] (m)									
	5			10			15			
WTD[2] <= (cm)	30	60	90	30	60	90	30	60	90	PPT[3] (cm)
1951	4	6	45	25	121	205	81	202	248	94.46
1952	5	8	37	27	109	206	76	202	269	96.60
1953	0	1	21	12	71	183	58	178	194	70.18
1954	0	0	17	9	60	221	53	216	253	74.57
1955	3	6	25	16	93	241	66	235	291	98.40
1956	0	3	16	10	88	215	64	209	276	83.46
1957	13	16	40	27	105	227	78	217	263	101.88
1958	8	13	31	21	81	292	69	281	337	104.78
1959	5	10	31	16	97	217	76	209	246	101.17
1960	0	1	12	7	65	203	50	197	250	66.52
1961	2	6	37	25	116	247	79	240	300	101.85
1962	0	1	15	8	66	211	53	208	254	70.46
1963	4	6	18	10	37	177	39	167	242	61.47
1964	9	15	29	21	80	174	62	170	200	80.19
1965	0	1	19	10	72	224	53	218	251	77.37
1966	0	2	14	10	74	251	63	245	279	81.97
1967	2	5	30	21	95	225	76	219	245	84.91
1968	3	5	25	13	75	241	57	239	299	87.25
1969	3	12	29	20	80	241	73	229	287	88.67
1970	2	3	11	6	60	208	44	198	230	69.14
1971	0	1	22	14	77	221	58	216	295	84.40
1972	0	3	25	18	108	258	79	253	297	90.96
1973	0	4	27	15	95	248	76	235	301	97.74
1974	4	10	35	21	133	262	91	255	296	102.69
1975	5	9	36	19	108	250	76	242	317	104.37
1976	0	0	14	6	73	232	54	222	279	65.10
1977	3	5	26	17	98	209	79	205	237	90.35
1978	1	9	36	23	102	250	80	238	308	99.06
1979	4	11	39	27	110	282	90	268	332	109.98
1980	6	10	33	21	113	258	78	249	281	104.04
1981	5	11	43	27	111	274	83	262	327	110.97
1982	6	13	46	30	122	245	94	240	306	108.48
1983	2	8	35	22	124	256	85	249	279	96.14
1984	0	3	31	21	119	246	87	233	274	91.41
1985	9	17	38	29	96	205	77	200	236	90.96
1986	7	12	40	28	93	247	77	232	312	109.02
1987	0	3	17	9	65	178	52	174	221	62.74
1988	5	10	35	23	94	229	70	224	262	92.89
1989	10	22	52	39	127	263	100	249	310	125.15
1990	21	33	75	51	144	279	114	267	332	151.76
1991	2	4	34	23	107	211	77	205	250	94.36
1992	7	13	34	22	98	281	79	271	339	103.10
1993	13	22	61	42	155	284	110	271	312	132.66
1994	2	7	29	17	80	214	66	209	277	88.32
1995	14	21	48	33	106	277	82	260	298	127.10
Average[4]	4	8	31	20	96	235	73	227	278	93.98

1. For each drain spacing, drain depth was 140 cm.
2. PPT = Precipitation
3. WTD = Water table depth criteria
4. Average number of days per year (rounded)

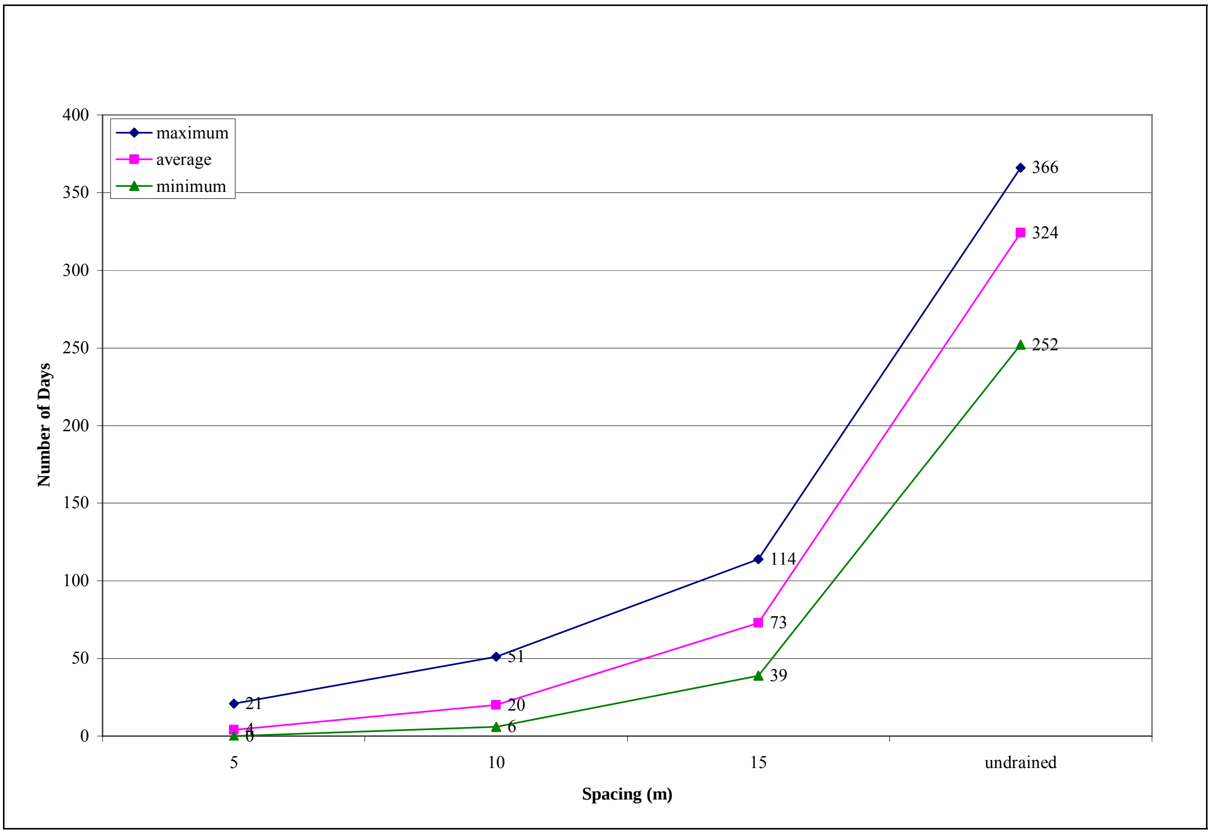


Figure 6. Average number of days with the water table higher than 30 cm for a drain depth of 140 cm and a 0.33-cm/day wastewater application depth (from Appendix Figure D1.1).

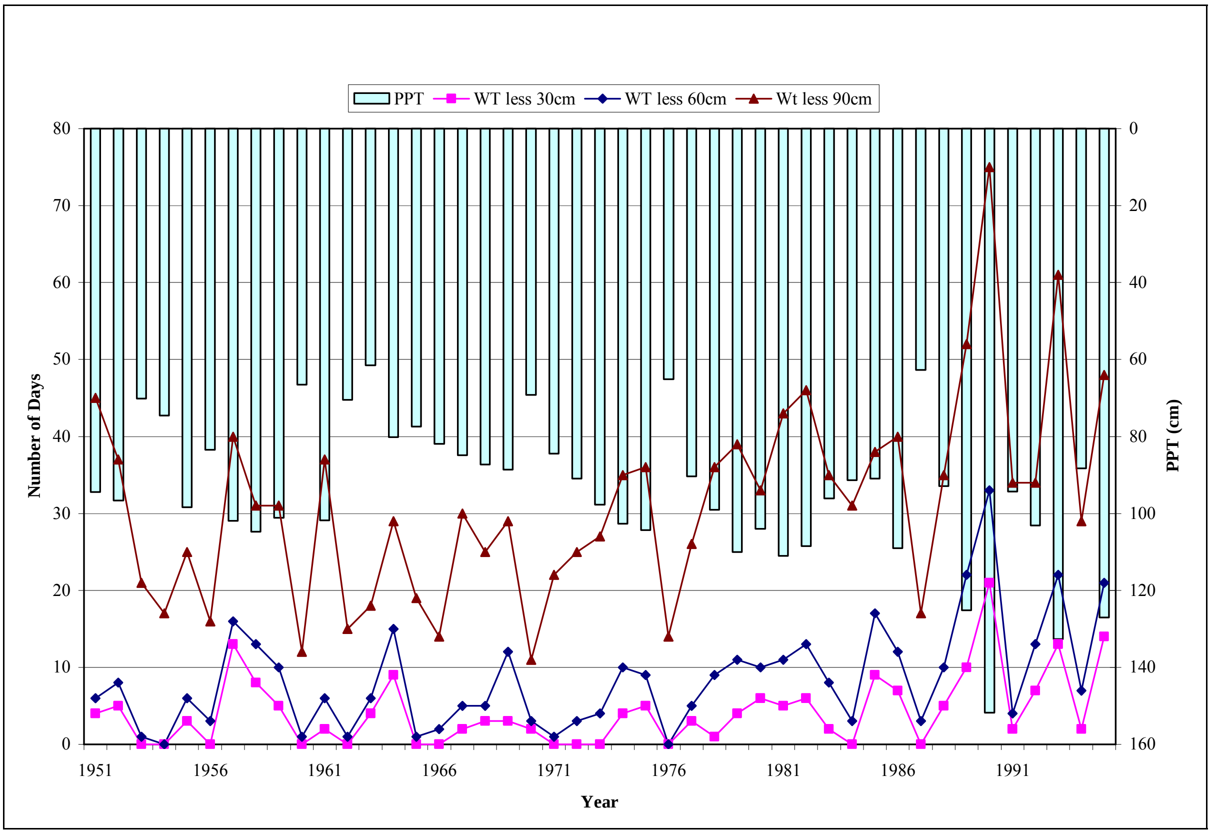


Figure 7. For Crosby silt loam, the number of days per year that the predicted water table equaled or exceeded the WTD criteria of 30 cm, 60 cm, and, or 90 cm, for a drain depth of 140 cm, a drain spacing of 5 m, land slope = 0-2%, and wastewater application rate of 0.33 cm/day. The precipitation for each year of the record is shown at the top of the graph.

Table 10. Recurrence analysis for Crosby silt loam; Drain depth = 140 cm; Irrigation depth = 0.33 cm/day (from Appendix Table D1.2)

Water Table Depth <= 30cm									Water Table Depth <= 60cm									Water Table Depth <= 90cm								
DS[1] = 5 m			DS = 10 m			DS = 15 m			DS = 5 m			DS = 10 m			DS = 15 m			DS = 5 m			DS = 10 m			DS = 15 m		
Days	PPF[2]	RI[3]	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI
0	0.71	1	6	0.96	1	39	0.98	1	0	0.96	1	37	0.98	1	167	0.98	1	11	0.98	1	174	0.98	1	194	0.98	1
1	0.69	1	7	0.93	1	44	0.96	1	1	0.84	1	60	0.93	1	170	0.96	1	12	0.96	1	177	0.96	1	200	0.96	1
2	0.56	2	8	0.91	1	50	0.93	1	2	0.82	1	65	0.89	1	174	0.93	1	14	0.91	1	178	0.93	1	221	0.93	1
3	0.47	2	9	0.91	1	52	0.91	1	3	0.71	1	66	0.87	1	178	0.91	1	15	0.89	1	183	0.91	1	230	0.91	1
4	0.38	3	9	0.87	1	53	0.84	1	4	0.67	2	71	0.84	1	197	0.89	1	16	0.87	1	203	0.89	1	236	0.89	1
5	0.27	4	10	0.87	1	54	0.82	1	5	0.60	2	72	0.82	1	198	0.87	1	17	0.82	1	205	0.84	1	237	0.87	1
6	0.22	5	10	0.78	1	57	0.80	1	6	0.51	2	73	0.80	1	200	0.84	1	18	0.80	1	206	0.82	1	242	0.84	1
7	0.18	6	12	0.76	1	58	0.76	1	7	0.49	2	74	0.78	1	202	0.80	1	19	0.78	1	208	0.80	1	245	0.82	1
8	0.16	6	13	0.73	1	62	0.73	1	8	0.44	2	75	0.76	1	205	0.76	1	21	0.76	1	209	0.78	1	246	0.80	1
9	0.11	9	14	0.71	1	63	0.71	1	9	0.40	3	77	0.73	1	208	0.73	1	22	0.73	1	211	0.73	1	248	0.78	1
10	0.09	11	15	0.69	1	64	0.69	1	10	0.31	3	80	0.67	2	209	0.67	2	25	0.67	2	214	0.71	1	250	0.73	1
13	0.04	23	16	0.64	2	66	0.64	2	11	0.27	4	81	0.64	2	216	0.62	2	26	0.64	2	215	0.69	1	251	0.71	1
14	0.02	45	17	0.60	2	69	0.62	2	12	0.22	5	88	0.62	2	217	0.60	2	27	0.62	2	217	0.67	2	253	0.69	1
			18	0.58	2	70	0.60	2	13	0.16	6	93	0.58	2	218	0.58	2	29	0.56	2	221	0.62	2	254	0.67	2
			19	0.56	2	73	0.58	2	15	0.13	7	94	0.56	2	219	0.56	2	30	0.53	2	224	0.60	2	262	0.64	2
			20	0.53	2	76	0.47	2	16	0.11	9	95	0.51	2	222	0.53	2	31	0.47	2	225	0.58	2	263	0.62	2
			21	0.40	3	77	0.40	3	17	0.09	11	96	0.49	2	224	0.51	2	33	0.44	2	227	0.56	2	269	0.60	2
			22	0.36	3	78	0.36	3	21	0.07	15	97	0.47	2	229	0.49	2	34	0.40	3	229	0.53	2	274	0.58	2
			23	0.29	3	79	0.27	4	22	0.02	45	98	0.42	2	232	0.47	2	35	0.33	3	232	0.51	2	276	0.56	2
			25	0.24	4	80	0.24	4				102	0.40	3	233	0.44	2	36	0.29	3	241	0.44	2	277	0.53	2
			27	0.16	6	81	0.22	5				105	0.38	3	235	0.40	3	37	0.24	4	245	0.42	2	279	0.47	2
			28	0.13	7	82	0.20	5				106	0.36	3	238	0.38	3	38	0.22	5	246	0.40	3	281	0.44	2
			29	0.11	9	83	0.18	6				107	0.33	3	239	0.36	3	39	0.20	5	247	0.36	3	287	0.42	2
			30	0.09	11	85	0.16	6				108	0.29	3	240	0.31	3	40	0.16	6	248	0.33	3	291	0.40	3
			33	0.07	15	87	0.13	8				109	0.27	4	242	0.29	3	43	0.13	7	250	0.29	3	295	0.38	3
			39	0.04	23	90	0.11	9				110	0.24	4	245	0.27	4	45	0.11	9	251	0.27	4	296	0.36	3
			42	0.02	45	91	0.09	11				111	0.22	5	249	0.20	5	46	0.09	11	256	0.24	4	297	0.33	3
						94	0.07	15				113	0.20	5	253	0.18	6	48	0.07	15	258	0.20	5	298	0.31	3
						100	0.04	23				116	0.18	6	255	0.16	6	52	0.04	23	262	0.18	6	299	0.29	3

Table 10. Recurrence analysis for Crosby silt loam; Drain depth = 140 cm; Irrigation depth = 0.33 cm/day (from Appendix Table D1.2)

Water Table Depth <= 30cm									Water Table Depth <= 60cm									Water Table Depth <= 90cm								
DS[1] = 5 m			DS = 10 m			DS = 15 m			DS = 5 m			DS = 10 m			DS = 15 m			DS = 5 m			DS = 10 m			DS = 15 m		
Days	PPF[2]	RI[3]	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI
						110	0.02	45				119	0.16	6	260	0.13	8	61	0.02	45	263	0.16	6	300	0.27	4
												121	0.13	8	262	0.11	9				274	0.13	8	301	0.24	4
												122	0.11	9	267	0.09	11				277	0.11	9	306	0.22	5
												124	0.09	11	268	0.07	15				279	0.09	11	308	0.20	5
												127	0.07	15	271	0.02	45				281	0.07	15	310	0.18	6
												133	0.04	23							282	0.04	23	312	0.13	8
												144	0.02	45							284	0.02	45	317	0.11	9
																								327	0.09	11
																								332	0.04	23
																								337	0.02	45

1. DS = Drain spacing (m)
2. PPF = Probability of recurrence; For example, for the combination of 5-m spacing and WTD <= 30-cm criteria, the results highlighted above indicate that there is a 27% probability that this criteria will be met for 5 or more days in any given year.
3. RI = Recurrence Interval (year) = 1/PPF; For example, we should expect this to occur once every 4 years.

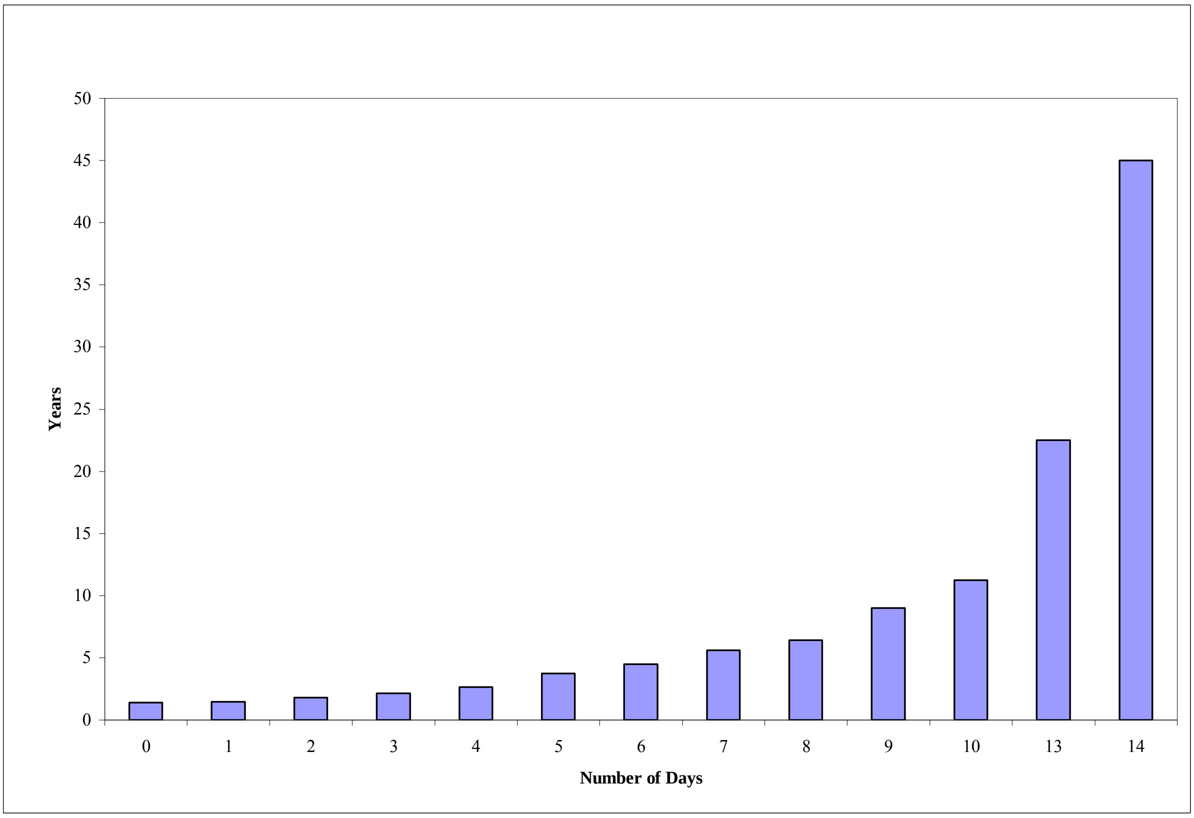


Figure 8. Recurrence interval for Crosby silt loam: drain depth = 140 cm; wastewater application rate of 0.33 cm/day; WTD criteria <= 30 cm; and drain spacing = 5 m (from Appendix Figure D1.7). For the result NOD = 14 (WTD criteria equaled or exceeded 14 days per year), the recurrence interval is 45 years.

Loading Rate 1.25 cm/day

Recall that the 1.25-cm/day application depth represents what we considered to be an extreme case of wastewater application. Table 11 (from Appendix Table D2.1) provides the number of days the water table depth criteria were exceeded or equaled for Crosby soil loam for each of the nine drain spacing - water table depth combinations, with the 1.25-cm/day application rate. The precipitation amount in this table is only rainfall, and does not include the wastewater depth. In the year with the least precipitation, 1963, the NOD was about 30 times the NOD for Crosby for the General Case over all WTD criteria within the 5-m spacing. In the year with the greatest precipitation, 1990, the water table depth for all WTD criteria exceeded 247 days per year for all spacings.

In Figure 9 (from Appendix Figure D2.1), the maximum, average and minimum NOD are plotted for the three drain spacings and the undrained case. This graph shows that as the drain spacing increases, the expected NOD also increases. In the undrained case, the expected minimum NOD is 346days/yr, which suggests that in 95% of the year, excessive wastewater applications produce water table conditions that inundate the on-site system with no curtain drains. Figure 10 (from Appendix Figure D2.4) shows the NOD for the period 1951 to 1995.

Table 12 (from Appendix Table D2.2) shows the correlation between NOD and the Probability Proportional Frequency (PPF) and the Recurrence Interval (RI). For example, for the 5-m spacing, the NOD was 144 days/year with an 87% probability that the WTD will equal or exceed the 30-cm criteria. The corresponding RI is one year, which means that we expect the 144 day value to occur every year. Figure 11 (from Appendix Figure D2.7) shows recurrence for the 5-m spacing and WTD less than 30-cm combination. All other cases for Crosby soil series are located in Appendix D.

Table 11. Crosby silt loam; Drain depth = 140 cm; Irrigation depth = 1.25 cm/day (from Appendix Table D2.1)										
	Drain Spacing[1] m									
Year (n=47)	5			10			15			
WTD[2] cm <=	30	60	90	30	60	90	30	60	90	PPT (cm)[3]
1951	129	150	301	273	304	304	295	304	304	94.46
1952	180	213	361	333	365	366	361	366	366	96.60
1953	163	201	347	317	365	365	356	365	365	70.18
1954	156	191	352	327	365	365	360	365	365	74.57
1955	220	247	357	333	365	365	360	365	365	98.40
1956	148	199	365	341	366	366	360	366	366	83.46
1957	225	249	360	333	365	365	355	365	365	101.88
1958	150	242	365	346	365	365	363	365	365	104.78
1959	182	229	363	328	365	365	354	365	365	101.17
1960	135	186	364	333	366	366	359	366	366	66.52
1961	178	225	362	346	365	365	359	365	365	101.85
1962	157	194	358	336	365	365	356	365	365	70.46
1963	70	105	363	343	365	365	357	365	365	61.47
1964	115	174	357	328	366	366	352	366	366	80.19
1965	149	190	358	332	365	365	354	365	365	77.37
1966	169	225	358	337	365	365	362	365	365	81.97
1967	172	223	357	334	365	365	352	365	365	84.91
1968	169	206	361	335	366	366	360	366	366	87.25
1969	171	232	363	345	365	365	354	365	365	88.67
1970	179	213	363	335	365	365	348	365	365	69.14
1971	164	213	364	342	365	365	354	365	365	84.40
1972	231	262	363	343	366	366	363	366	366	90.96
1973	217	264	361	338	365	365	358	365	365	97.74
1974	219	258	361	342	365	365	357	365	365	102.69
1975	197	248	356	325	365	365	363	365	365	104.37
1976	144	209	366	343	366	366	357	366	366	65.10
1977	146	219	355	318	364	365	358	365	365	90.35
1978	195	250	363	344	365	365	358	365	365	99.06
1979	220	271	365	344	365	365	362	365	365	109.98
1980	216	257	360	338	366	366	361	366	366	104.04
1981	207	241	365	344	365	365	358	365	365	110.97
1982	194	239	365	345	364	365	360	365	365	108.48
1983	238	267	361	328	365	365	357	365	365	96.14
1984	219	253	363	347	366	366	359	366	366	91.41
1985	195	217	363	341	365	365	353	365	365	90.96
1986	178	238	365	344	365	365	363	365	365	109.02
1987	115	152	356	331	365	365	351	365	365	62.74
1988	215	242	342	315	366	366	360	366	366	92.89
1989	248	268	363	346	365	365	361	365	365	125.15
1990	247	280	363	346	365	365	362	365	365	151.76
1991	172	208	358	323	365	365	354	365	365	94.36
1992	211	264	366	347	366	366	363	366	366	103.10
1993	266	295	361	342	365	365	360	365	365	132.66
1994	199	229	360	342	365	365	360	365	365	88.32
1995	204	248	363	335	365	365	357	365	365	127.10
Average[4]	184	226	359	335	364	364	357	364	364	93.98

1. For each drain spacing, drain depth was 140 cm.
2. WTD = Water table depth criteria
3. PPT = Precipitation
4. Average number of days per year (rounded)

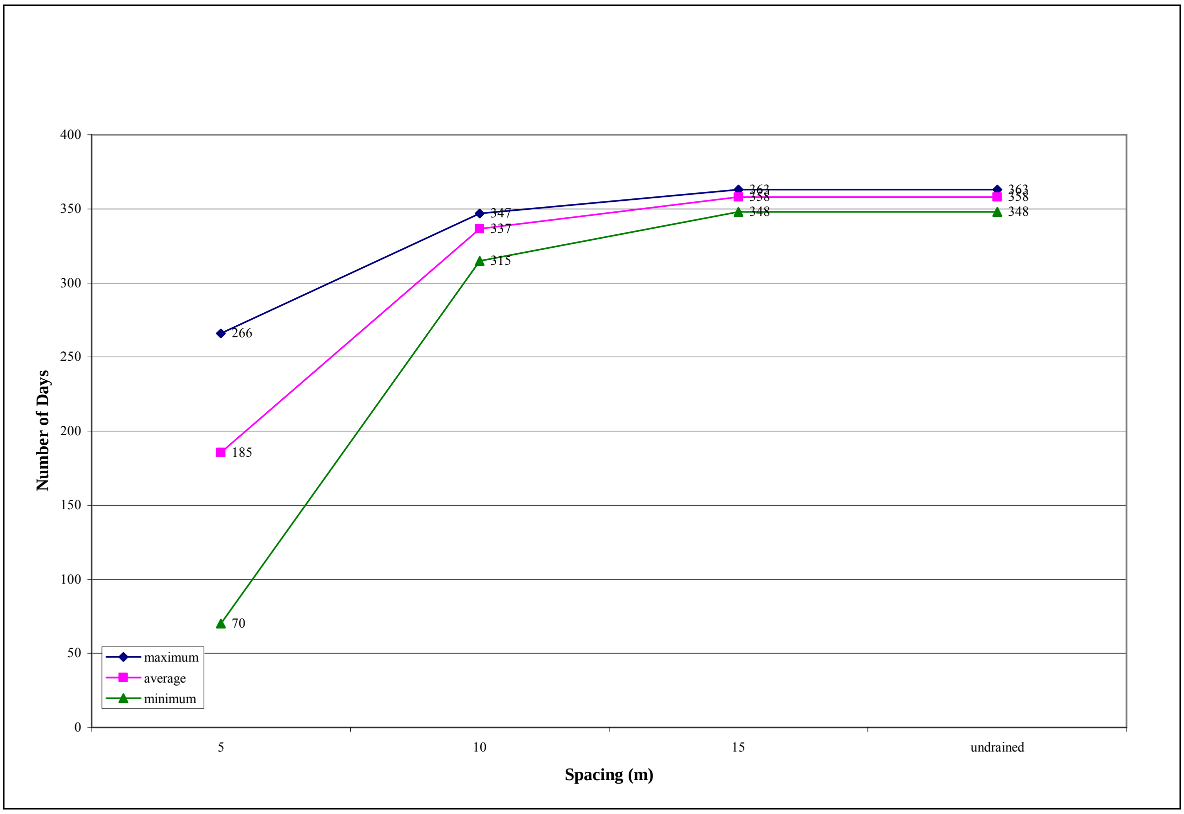


Figure 9: For Crosby silt loam, the average number of days with the water table higher than 30 cm for a drain depth of 140 cm and a 1.25-cm/day wastewater application depth (from Appendix Figure D2.1).

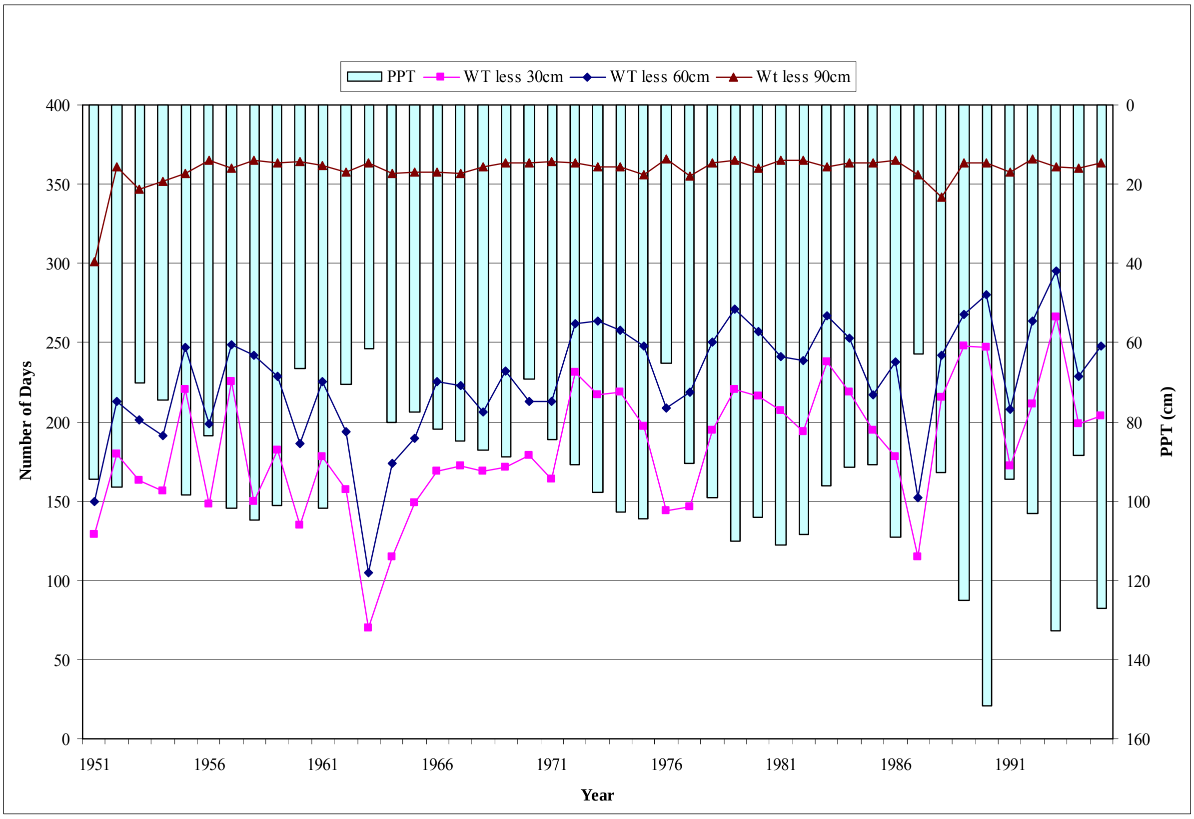


Figure 10. For Crosby silt loam, the number of days per year that the predicted water table equaled or exceeded the WTD criteria of 30 cm, 60 cm, and, or 90 cm, for a drain depth of 140 cm, a drain spacing of 5 m, land slope = 0-2%, and wastewater application rate of 1.25 cm/day. The precipitation for each year of the record is shown at the top of the graph.

Table 12. Recurrence analysis for Crosby silt loam; Drain depth = 140 cm; Irrigation depth = 1.25 cm/day (from Appendix Table D2.2)

Water Table Depth <= 30 cm									Water Table Depth <= 60 cm									Water Table Depth <= 90 cm								
DS[1] = 5 m			DS = 10 m			DS = 15 m			DS = 5 m			DS = 10 m			DS = 15 m			DS = 5 m			DS = 10 m			DS = 15 m		
Days	PPF[2]	RI[3]	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI
70	0.98	1	273	0.98	1	295	0.98	1	105	0.98	1	304	0.98	1	304	0.98	1	301	0.98	1	304	0.98	1	304	0.98	1
115	0.93	1	315	0.96	1	348	0.96	1	150	0.96	1	364	0.93	1	365	0.24	4	342	0.96	1	365	0.24	4	365	0.24	4
129	0.91	1	317	0.93	1	351	0.93	1	152	0.93	1	365	0.22	5				347	0.93	1						
135	0.89	1	318	0.91	1	352	0.89	1	174	0.91	1							352	0.91	1						
144	0.87	1	323	0.89	1	353	0.87	1	186	0.89	1							355	0.89	1						
146	0.84	1	325	0.87	1	354	0.76	1	190	0.87	1							356	0.84	1						
148	0.82	1	327	0.84	1	355	0.73	1	191	0.84	1							357	0.78	1						
149	0.80	1	328	0.78	1	356	0.69	1	194	0.82	1							358	0.69	1						
150	0.78	1	331	0.76	1	357	0.58	2	199	0.80	1							360	0.62	2						
156	0.76	1	332	0.73	1	358	0.49	2	201	0.78	1							361	0.49	2						
157	0.73	1	333	0.64	2	359	0.42	2	206	0.76	1							362	0.47	2						
163	0.71	1	334	0.62	2	360	0.24	4	208	0.73	1							363	0.22	5						
164	0.69	1	335	0.56	2	361	0.18	6	209	0.71	1							364	0.18	6						
169	0.64	2	336	0.53	2	362	0.11	9	213	0.64	2							365	0.04	23						
171	0.62	2	337	0.51	2				217	0.62	2															
172	0.58	2	338	0.47	2				219	0.60	2															
178	0.53	2	341	0.42	2				223	0.58	2															
179	0.51	2	342	0.33	3				225	0.53	2															
180	0.49	2	343	0.27	4				229	0.49	2															
182	0.47	2	344	0.18	6				232	0.47	2															
194	0.44	2	345	0.13	7				238	0.44	2															
195	0.40	3	346	0.04	22				239	0.42	2															
197	0.38	3							241	0.40	3															
199	0.36	3							242	0.36	3															
204	0.33	3							247	0.33	3															
207	0.31	3							248	0.29	3															
211	0.29	3							249	0.27	4															
215	0.27	4							250	0.24	4															
216	0.24	4							253	0.22	5															

Table 12. Recurrence analysis for Crosby silt loam; Drain depth = 140 cm; Irrigation depth = 1.25 cm/day (from Appendix Table D2.2)																										
Water Table Depth <= 30 cm									Water Table Depth <= 60 cm									Water Table Depth <= 90 cm								
DS[1] = 5 m			DS = 10 m			DS = 15 m			DS = 5 m			DS = 10 m			DS = 15 m			DS = 5 m			DS = 10 m			DS = 15 m		
Days	PPF[2]	RI[3]	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI
217	0.22	5							257	0.20	5															
219	0.18	6							258	0.18	6															
220	0.13	8							262	0.16	6															
225	0.11	9							264	0.11	9															
231	0.09	11							267	0.09	11															
238	0.07	15							268	0.07	15															
247	0.04	23							271	0.04	23															
248	0.02	45							280	0.02	45															

1. DS = Drain spacing (m)
2. PPF = Probability of recurrence; For example, for the combination of 5-m spacing and WTD <= 30-cm criteria, the results highlighted above indicate that there is an 87% probability that this criteria will be met for 144 or more days in any given year.
3. RI = Recurrence Interval (year) = 1/PPF; For example, we should expect this to occur once every year.

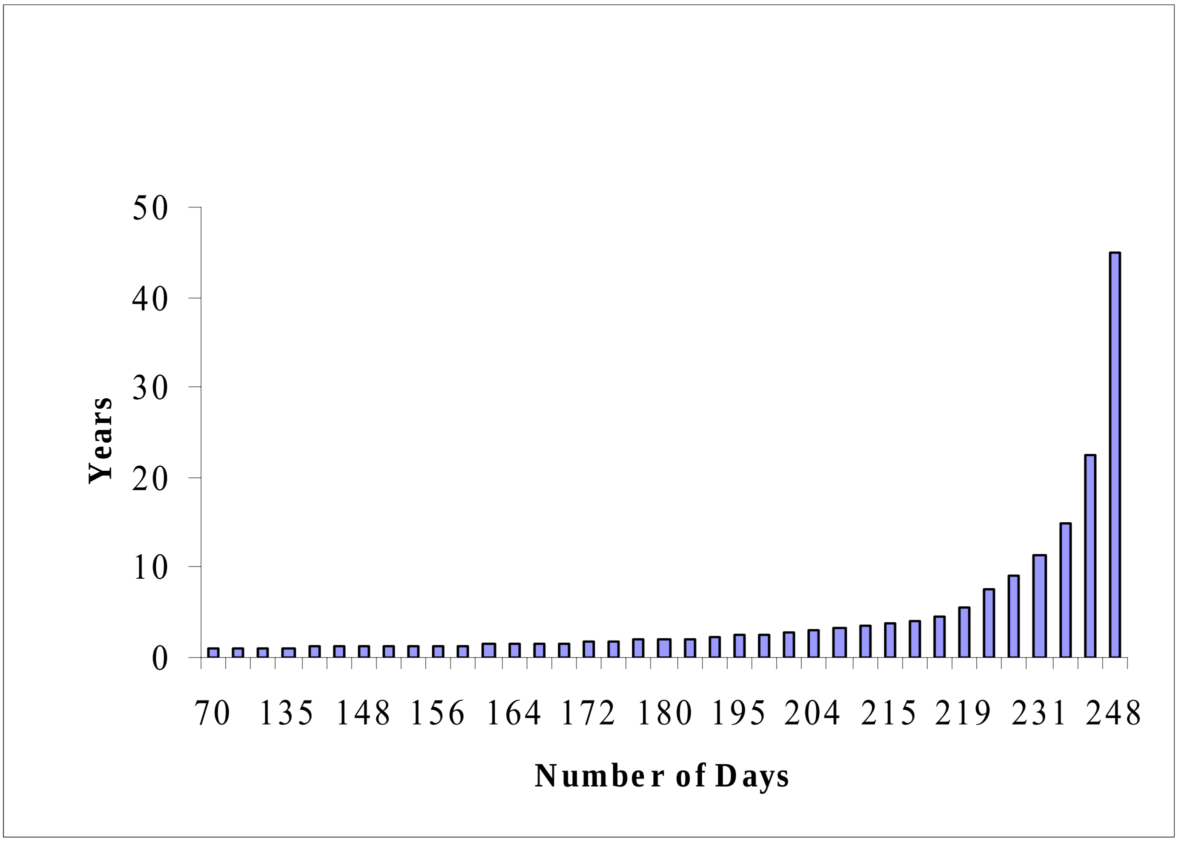


Figure 11. Recurrence interval for Crosby silt loam: drain depth = 140 cm; wastewater application rate of 1.25 cm/day; WTD criteria <= 30 cm; and drain spacing = 5 m (from Appendix Figure D2.7). For the result NOD = 144 (WTD criteria equaled or exceeded 144 days per year), the recurrence interval is 1 year.

Wastewater Application Rate Comparison

Figure 12 (Appendix Table D3.3) compares the effect of all three cases of wastewater application depth (no application-General Case; 0.33 and 1.25 cm/day application) on the number of days that the water table depth criteria were equaled or exceeded. The trend of number of days increases as drain spacing increases is illustrated, as well as when wastewater application depth is increased. Note that for the 1.25 cm/day rate over all drain spacings, the number of days exceeds 342.

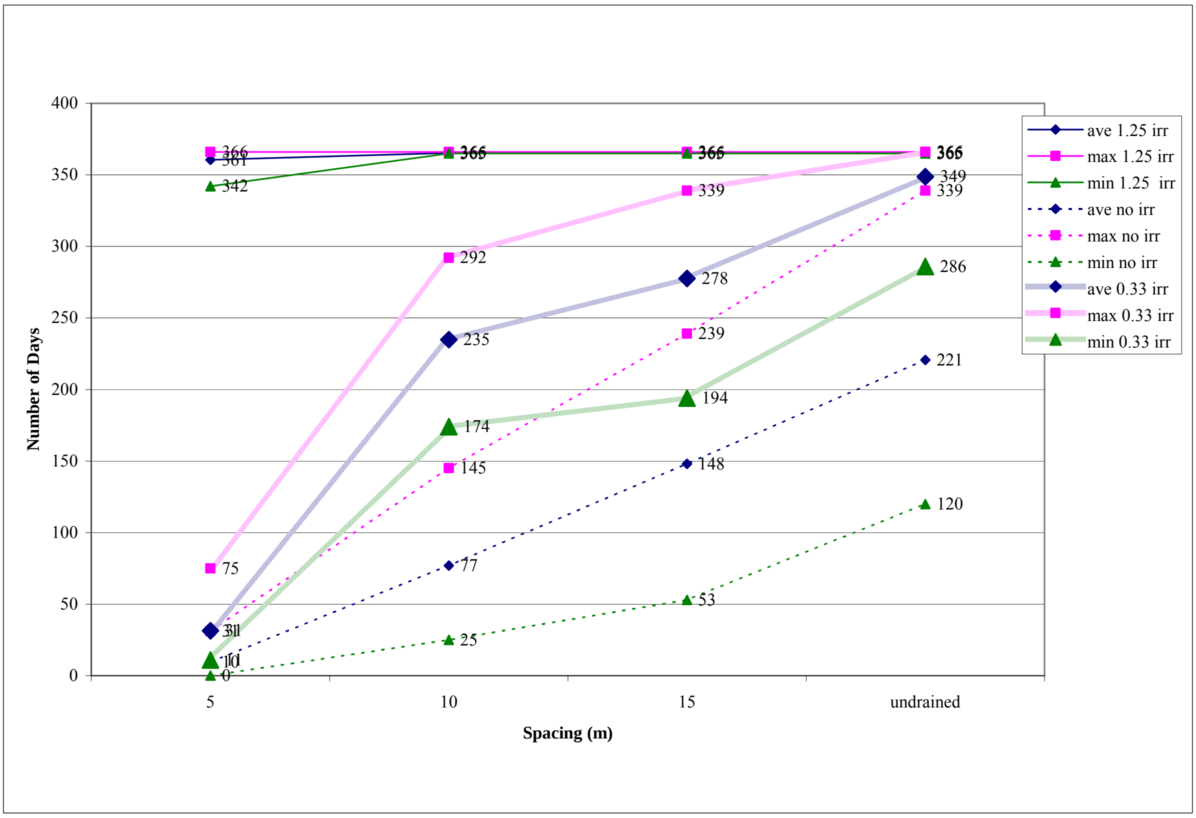


Figure 12. For Crosby silt loam, comparison of the average number of days with the water table higher than 90 cm for a drain depth of 140 cm, four drain spacing cases, and three cases of wastewater application depth (no application; 0.33 and 1.25 cm/day application) (from Appendix Figure D3.3). **(Ave/Max/Min 1.25 IRR is the average/maximum/minimum, respectively, number of days for wastewater application depth of 1.25 cm/day; Ave/Max/Min 0.33 IRR is for the application depth of 0.33 cm/day; and Ave/Max/Min No IRR is for the general case with no wastewater application.)**

<u>Slope</u>

3% and 6% Slope

For the Crosby soil series, land slope values of three and six percent had a negligible effect on the average number of days that the water table depth criteria were equaled or exceeded, compared to results for the Crosby General Case (Slope = 0-2%; see averages in Table 7). Table 13 (from Appendix Table D.4.1) shows the NOD for Crosby for each of the nine combinations. The averages at the bottom of this table are identical to those in Table 7. In Figure 13, the maximum, average and minimum NOD are plotted for the three drain spacings, and Figure 14 (from Appendix Figure D4.4) shows the NOD for the period from 1951 to 1995. Table 14 (from Appendix Table D4.2) contains the correlation between the NOD and the Probability Proportional Frequency (PPF) and the Recurrence Interval (RI). Appendix Figure D4.7 (not shown here) provides a recurrence graph for the 5-m spacing and WTD less than 30-cm combination. All other figures for this and the 6% cases are located in appendix D. Figure 15 (from Appendix Figure D5.3) provides the maximum, average and minimum NOD the three drain spacings for the 6% slope case (all other results from the 6% case are located in the Appendix D, and not shown here). The maximum, average and minimum NODs for all three slope cases (Slope = 0-2% - General Case; 3 and 6%) are compared in Figure 16 (from Appendix Table D6.3). The maximum values from all three slopes are the same at each drain spacing. These results are the same for the average and minimum values. This effect is only verified for modeling slopes between 0-6%.

Table 13. Crosby silt loam; Drain depth = 140 cm; Slope = 3% (from Appendix Table D4.1)										
	Drain Spacing[1] (m)									
Year (n=47)	5			10			15			
WTD[2] ≤ (cm)	30	60	90	30	60	90	30	60	90	PPT[3] (cm)
1951	2	4	12	7	31	112	25	98	161	94.46
1952	3	5	14	7	29	104	22	87	146	96.60
1953	0	0	4	1	10	65	11	57	128	70.18
1954	0	0	2	0	4	41	3	35	107	74.57
1955	2	2	9	3	13	80	13	66	176	98.40
1956	0	0	3	1	8	71	8	62	128	83.46
1957	6	10	20	12	25	85	21	68	181	101.88
1958	3	6	15	10	19	57	18	46	131	104.78
1959	4	5	13	4	19	73	13	54	158	101.17
1960	0	0	0	0	1	34	2	31	106	66.52
1961	0	2	11	10	27	85	21	73	155	101.85
1962	0	0	0	0	5	45	7	42	99	70.46
1963	2	3	7	4	12	31	7	25	52	61.47
1964	5	6	16	8	21	58	17	52	79	80.19
1965	0	0	1	0	6	62	11	54	122	77.37
1966	0	0	5	1	6	40	7	31	135	81.97
1967	0	1	9	5	21	80	16	69	160	84.91
1968	3	4	7	5	9	42	8	37	115	87.25
1969	0	1	6	4	11	53	10	37	145	88.67
1970	0	1	4	3	6	30	5	19	120	69.14
1971	0	0	0	0	2	61	8	53	117	84.40
1972	0	0	3	2	9	80	12	75	184	90.96
1973	0	0	5	1	17	71	11	63	167	97.74
1974	0	1	4	1	10	106	15	93	175	102.69
1975	2	3	10	6	20	95	20	85	132	104.37
1976	0	0	0	0	5	43	4	41	91	65.10
1977	2	3	6	5	18	69	12	60	136	90.35
1978	0	0	8	4	15	67	16	55	146	99.06
1979	1	2	12	6	20	88	18	76	169	109.98
1980	4	4	10	7	21	86	20	72	168	104.04
1981	2	4	11	4	15	89	17	81	162	110.97
1982	2	5	16	7	28	115	26	95	157	108.48
1983	0	0	9	3	24	97	20	88	195	96.14
1984	0	0	2	1	17	111	17	96	202	91.41
1985	1	4	16	9	29	91	27	76	162	90.96
1986	0	3	13	5	23	84	20	69	149	109.02
1987	0	0	1	0	2	26	3	22	77	62.74
1988	3	4	13	7	21	77	15	67	150	92.89
1989	2	6	22	12	41	126	33	106	213	125.15
1990	7	13	31	22	50	141	41	123	239	151.76
1991	0	3	11	3	26	108	23	96	151	94.36
1992	0	2	12	5	17	73	15	65	155	103.10
1993	5	10	23	15	42	145	33	126	209	132.66
1994	1	2	8	5	15	67	14	53	155	88.32
1995	6	11	24	13	32	86	25	69	190	127.10
Average[4]	2	3	10	5	18	77	16	66	148	93.98

1. For each drain spacing, drain depth was 140 cm.
2. PPT = Precipitation
3. WTD = Water table depth criteria
4. Average number of days per year (rounded)

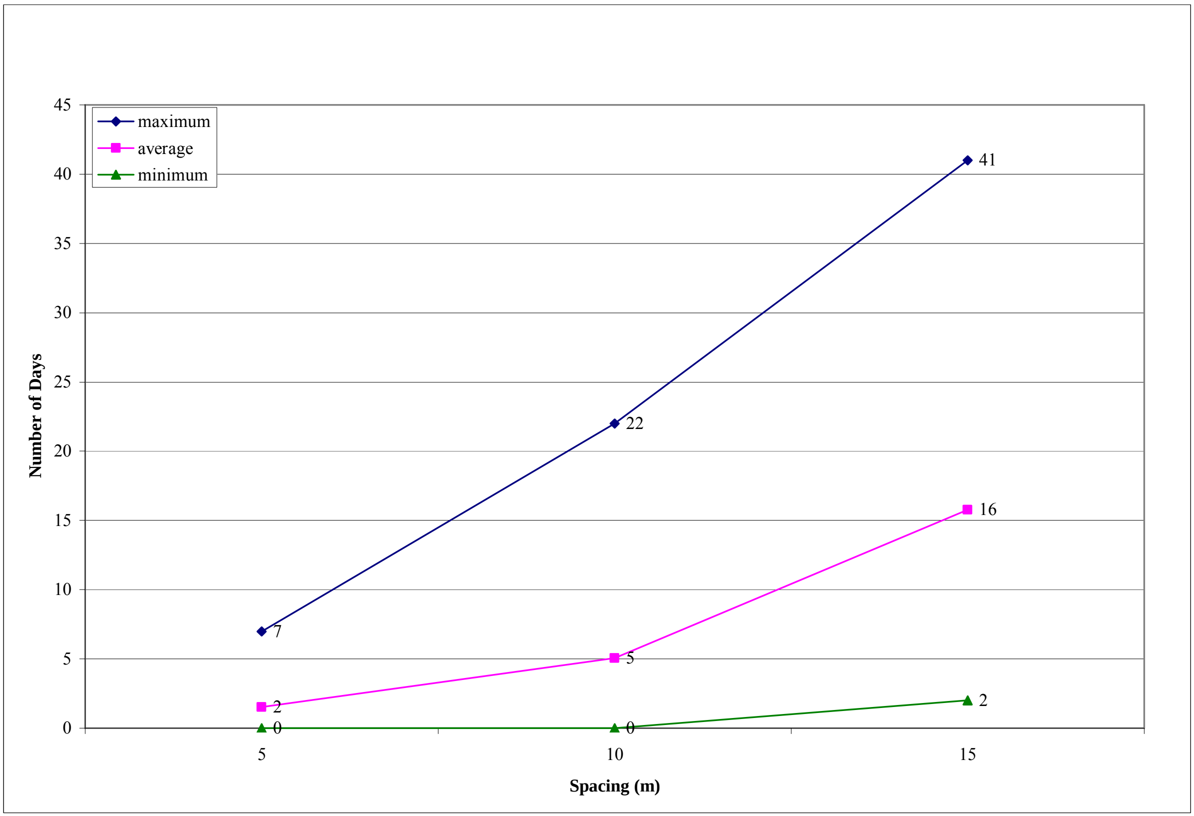


Figure 13. For Crosby silt loam, the average number of days with the water table higher than 30 cm for a drain depth of 140 cm and a 3% slope (from Appendix Figure D4.1).

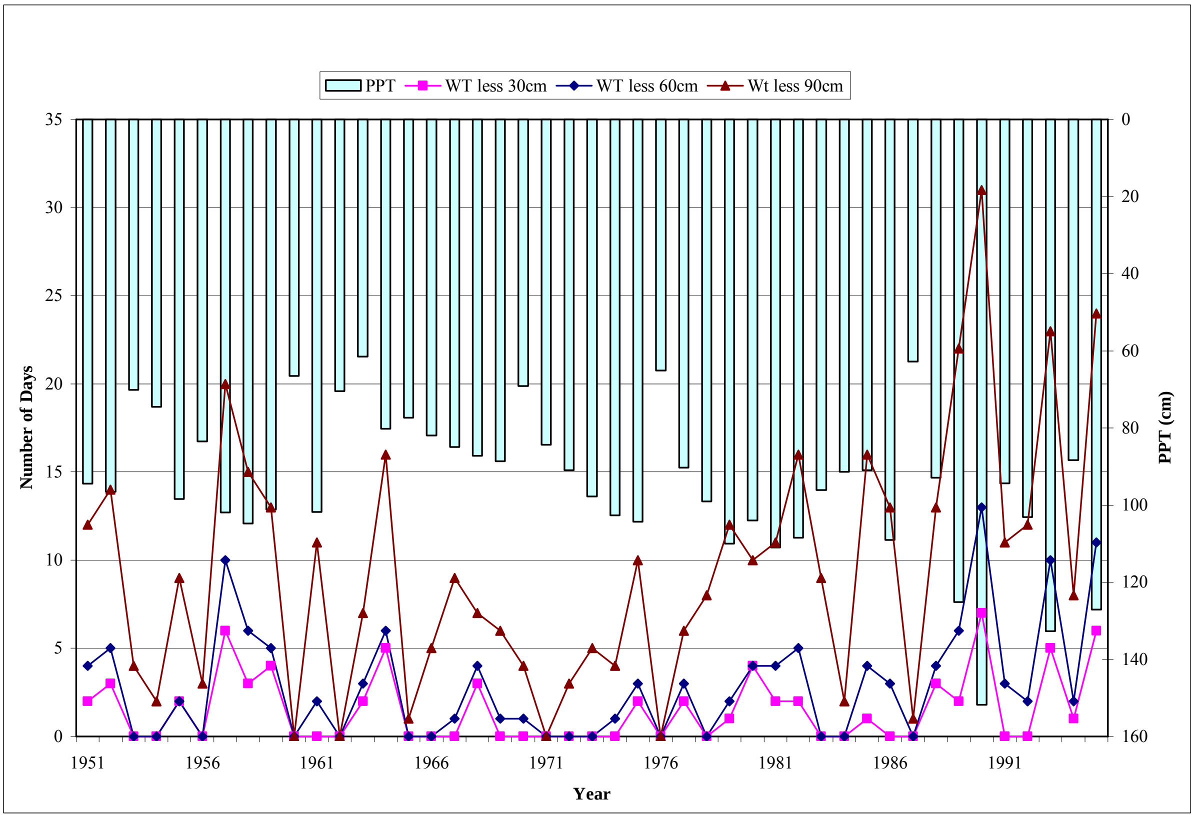


Figure 14. For Crosby silt loam, the number of days per year that the predicted water table equaled or exceeded the WTD criteria of 30 cm, 60 cm, and, or 90 cm, for a drain depth of 140 cm, a drain spacing of 5 m and a land slope of 3%. The precipitation for each year of the record is shown at the top of the graph.

Table 14. Recurrence analysis for Crosby silt loam; Drain depth = 140 cm; Slope = 3% (from Appendix Table D4.2)

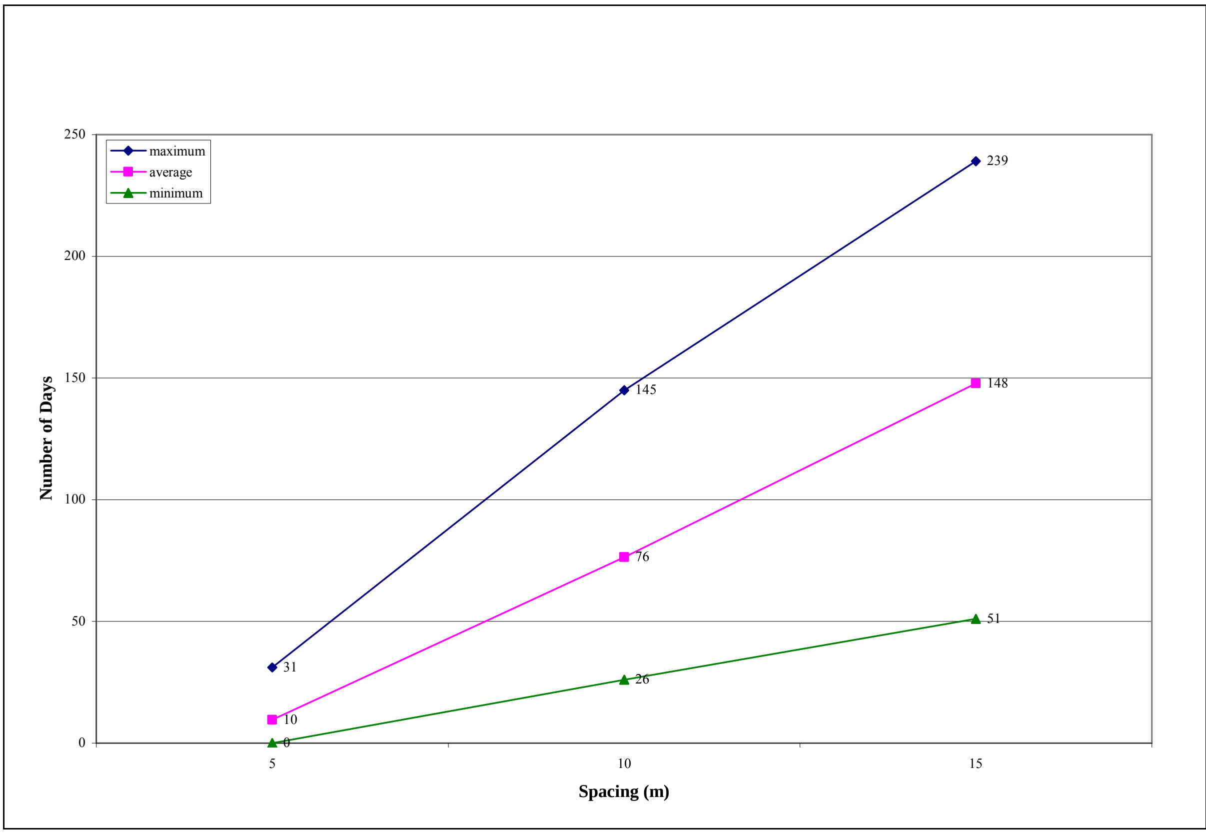
Water Table Depth <= 30 cm									Water Table Depth <= 60 cm									Water Table Depth <= 90 cm								
DS[1] =5 m			DS = 10 m			DS = 15 m			DS = 5 m			DS = 10 m			DS = 15 m			DS = 5 m			DS = 10 m			DS=15m		
Days	PPF[2]	RI[3]	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI
0	0.49	2	0	0.84	1	2	0.98	1	0	0.67	2	1	0.98	1	19	0.98	1	0	0.91	1	26	0.98	1	52	0.98	1
1	0.42	2	1	0.71	1	3	0.93	1	1	0.58	2	2	0.93	1	22	0.96	1	1	0.87	1	30	0.96	1	77	0.96	1
2	0.24	4	2	0.69	1	4	0.91	1	2	0.47	2	4	0.91	1	25	0.93	1	2	0.82	1	31	0.93	1	79	0.93	1
3	0.16	6	3	0.60	2	5	0.89	1	3	0.36	3	5	0.87	1	31	0.89	1	3	0.78	1	34	0.91	1	91	0.91	1
4	0.11	9	4	0.49	2	7	0.82	1	4	0.22	5	6	0.80	1	35	0.87	1	4	0.71	1	40	0.89	1	99	0.89	1
5	0.07	15	5	0.36	3	8	0.76	1	5	0.16	6	8	0.78	1	37	0.82	1	5	0.67	2	41	0.87	1	106	0.87	1
6	0.02	45	6	0.31	3	10	0.73	1	6	0.09	11	9	0.73	1	41	0.80	1	6	0.62	2	42	0.84	1	107	0.84	1
			7	0.20	5	11	0.67	2	10	0.04	22	10	0.69	1	42	0.78	1	7	0.58	2	43	0.82	1	115	0.82	1
			8	0.18	6	12	0.62	2	11	0.02	45	11	0.67	2	46	0.76	1	8	0.53	2	45	0.80	1	117	0.80	1
			9	0.16	6	13	0.58	2				12	0.64	2	52	0.73	1	9	0.47	2	53	0.78	1	120	0.78	1
			10	0.11	9	14	0.56	2				13	0.62	2	53	0.69	1	10	0.42	2	57	0.76	1	122	0.76	1
			12	0.07	15	15	0.49	2				15	0.56	2	54	0.64	2	11	0.36	3	58	0.73	1	128	0.71	1
			13	0.04	22	16	0.44	2				17	0.49	2	55	0.62	2	12	0.29	3	61	0.71	1	131	0.69	1
			15	0.02	45	17	0.38	3				18	0.47	2	57	0.60	2	13	0.22	5	62	0.69	1	132	0.67	2
						18	0.33	3				19	0.42	2	60	0.58	2	14	0.20	5	65	0.67	2	135	0.64	2
						20	0.24	4				20	0.38	3	62	0.56	2	15	0.18	6	67	0.62	2	136	0.62	2
						21	0.20	5				21	0.29	3	63	0.53	2	16	0.11	9	69	0.60	2	145	0.60	2
						22	0.18	6				23	0.27	4	65	0.51	2	20	0.09	11	71	0.56	2	146	0.56	2
						23	0.16	6				24	0.24	4	66	0.49	2	22	0.07	15	73	0.51	2	149	0.53	2
						25	0.11	9				25	0.22	5	67	0.47	2	23	0.04	23	77	0.49	2	150	0.51	2
						26	0.09	11				26	0.20	5	68	0.44	2	24	0.02	45	80	0.42	2	151	0.49	2
						27	0.07	15				27	0.18	6	69	0.38	3				84	0.40	3	155	0.42	2
						33	0.02	45				28	0.16	6	72	0.36	3				85	0.36	3	157	0.40	3
												29	0.11	9	73	0.33	3				86	0.31	3	158	0.38	3
												31	0.09	11	75	0.31	3				88	0.29	3	160	0.36	3
												32	0.07	15	76	0.27	4				89	0.27	4	161	0.33	3
												41	0.04	23	81	0.24	4				91	0.24	4	162	0.29	3
												42	0.02	45	85	0.22	5				95	0.22	5	167	0.27	4
															87	0.20	5				97	0.20	5	168	0.24	4
															88	0.18	6				104	0.18	6	169	0.22	5
															93	0.16	6				106	0.16	6	175	0.20	5

Table 14. Recurrence analysis for Crosby silt loam; Drain depth = 140 cm; Slope = 3% (from Appendix Table D4.2)																										
Water Table Depth <= 30 cm									Water Table Depth <= 60 cm									Water Table Depth <= 90 cm								
DS[1] =5 m			DS = 10 m			DS = 15 m			DS = 5 m			DS = 10 m			DS = 15 m			DS = 5 m			DS = 10 m			DS=15m		
Days	PPF[2]	RI[3]	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI	Days	PPF	RI
															95	0.13	8				108	0.13	8	176	0.18	6
															96	0.09	11				111	0.11	9	181	0.16	6
															98	0.07	15				112	0.09	11	184	0.13	8
															106	0.04	23				115	0.07	15	190	0.11	9
															123	0.02	45				126	0.04	23	195	0.09	11
																					141	0.02	45	202	0.07	15
																								209	0.04	23
																								213	0.02	45

1. DS = Drain spacing (m)

2. PPF = Probability of recurrence; For example, for the combination of 5-m spacing and WTD <= 30-cm criteria, the results highlighted above indicate that there is a 7% probability that this criteria will be met for 5 or more days in any given year.

3. RI = Recurrence Interval (year) = 1/PPF; For example, we should expect this to occur once every 15 years.



Fig

Figure 15. For Crosby silt loam, the average number of days with the water table higher than 30 cm for a drain depth of 140 cm and a 6% slope (from Appendix Figure D5.3).

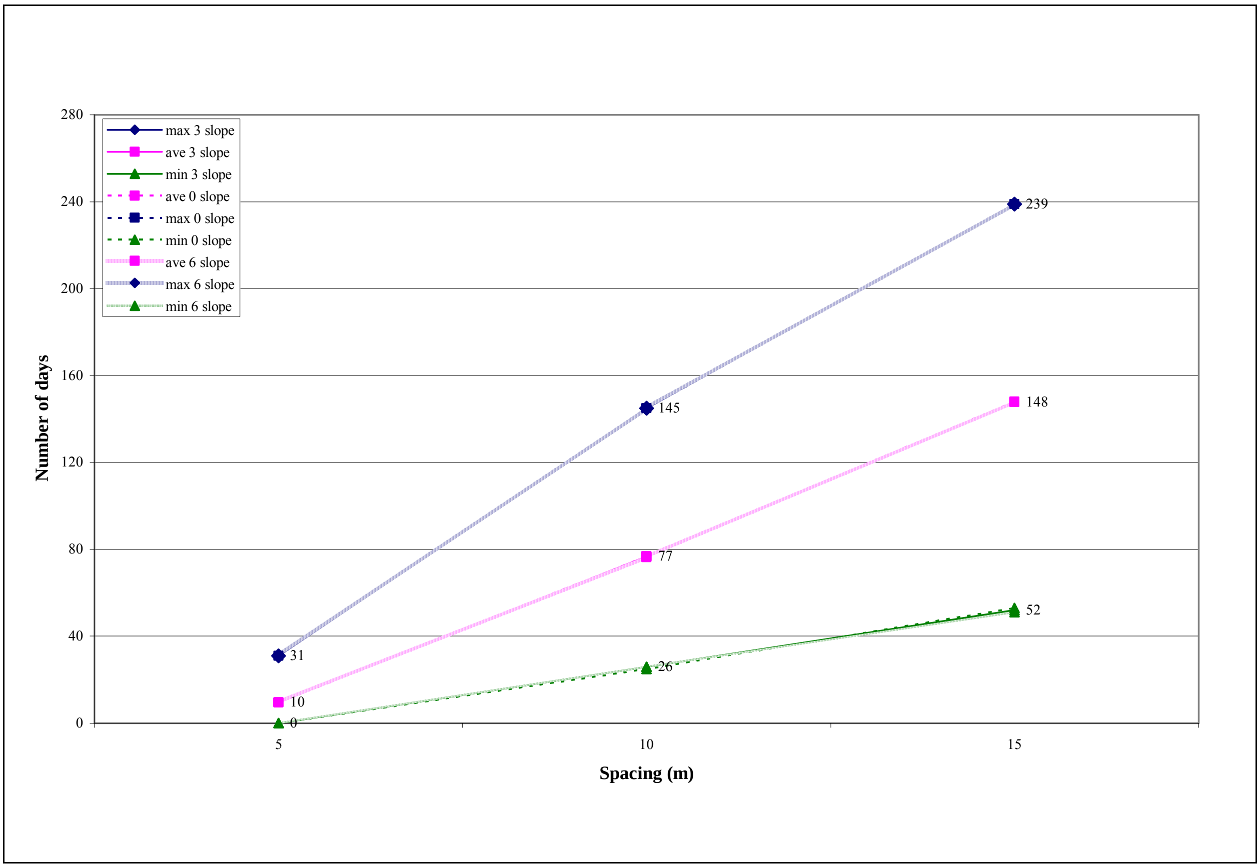


Figure 16. For Crosby silt loam, comparison of the average number of days with the water table higher than 90 cm for a drain depth of 140 cm, three drain spacing cases, and three ranges cases of land slope (0-2, 3, and 6%) (from Appendix Figure D6.3). **(Ave/Max/Min 3 slope is the average/maximum/minimum, respectively, number of days for the 3% slope; others similarly noted).**

Shallower Drain Depth

In general, as drain depth becomes shallower, the effect of the drain on the water table decreases, compared to deeper drain depths. Shallower depths (60-cm and 90-cm) were modeled at the request of the sanitarians. We do not commonly see a 60-cm drain depth on Ohio's cropland. The following results can be compared to those for Crosby's General Case.

Table 15 (from Appendix Table D7) shows the NOD for Crosby silt loam for each of the six drain spacing and WTD criteria combinations with the drain depth of 60 cm. The 15-m spacing results are not shown here; the number of days always increase as drain spacing increases. The averages in Table 15 can be compared to those in Table 7 for the General Case with the 140-cm drain depth. In 1963, the year with the least precipitation, the number of days the 30-cm depth criterion with the 5- spacing case was 2.5 times that of the General Case. As the drain spacing increases, the number of days increases. All other figures and tables for the 60-cm drain depth are located in appendix D.

Results for the 90-cm drain depth are shown in Table 16 (from Appendix Table D8.1), for each of the six drain spacing and WTD criteria combinations (the 15-m spacing again was not modeled). In the year with the least precipitation, 1963, the number of days the 30-cm depth criterion at the 5-m spacing was 2.5 times that of the General Case. All other figures and tables for the 60-cm drain depth are located in appendix D.

As a summary for this analysis, Figure 17 (from Appendix Figure D10.3) compares the effect of varying the drain depth for the 60-cm depth, the 90-cm depth and the 140-cm depth (General case) at the 5-m and 10-m drain spacings and the undrained case.

Table 15. Crosby silt loam; Drain depth = 60 cm (from Appendix Table D7.1)							
	Drain Spacing[1] (m)						
Year (n=47)	5			10			
WTD[2] <= (cm)	30	60	90	30	60	90	PPT[3] (cm)
1951	6	30	168	53	30	168	94.46
1952	8	28	148	46	28	148	96.60
1953	2	16	136	31	16	136	70.18
1954	1	11	148	27	11	148	74.57
1955	5	20	173	40	20	173	98.40
1956	4	12	147	36	12	147	83.46
1957	14	31	178	44	31	178	101.88
1958	11	25	175	36	25	175	104.78
1959	5	22	169	39	22	169	101.17
1960	0	7	146	21	7	146	66.52
1961	7	26	158	51	26	158	101.85
1962	0	8	115	19	8	115	70.46
1963	5	10	103	15	10	103	61.47
1964	11	23	106	29	23	106	80.19
1965	1	13	175	29	13	175	77.37
1966	4	11	164	29	11	164	81.97
1967	6	19	179	43	19	179	84.91
1968	5	13	148	27	13	148	87.25
1969	5	16	168	35	16	168	88.67
1970	4	8	143	19	8	143	69.14
1971	0	16	130	28	16	130	84.40
1972	3	15	184	34	15	184	90.96
1973	2	20	164	41	20	164	97.74
1974	3	17	182	45	17	182	102.69
1975	7	22	141	41	22	141	104.37
1976	0	6	123	17	6	123	65.10
1977	5	18	149	36	18	149	90.35
1978	5	20	167	45	20	167	99.06
1979	9	24	188	42	24	188	109.98
1980	8	21	186	42	21	186	104.04
1981	8	23	182	48	23	182	110.97
1982	11	31	154	52	31	154	108.48
1983	5	24	191	50	24	191	96.14
1984	1	24	196	48	24	196	91.41
1985	15	31	162	46	31	162	90.96
1986	8	27	173	39	27	173	109.02
1987	1	8	104	18	8	104	62.74
1988	9	22	174	39	22	174	92.89
1989	16	38	206	68	38	206	125.15
1990	23	52	223	69	52	223	151.76
1991	6	28	150	47	28	150	94.36
1992	9	22	169	35	22	169	103.10
1993	17	45	224	70	45	224	132.66
1994	7	20	153	35	20	153	88.32
1995	16	34	189	54	34	189	127.10
Average[4]	7	21	162	39	21	162	93.98

1. For each drain spacing, drain depth was 60 cm.
2. PPT = Precipitation
3. WTD = Water table depth criteria
4. Average number of days per year (rounded)

Table 16. Crosby silt loam; Drain depth = 90 cm (from Appendix Table D8.1)							
Year (n=47)	Drain Spacing[1] (m)						PPT[3] (cm)
	5			10			
WTD[2] <= (cm)	30	60	90	30	60	90	
1951	6	30	168	20	100	166	94.46
1952	8	28	148	21	89	154	96.60
1953	2	16	136	13	57	140	70.18
1954	1	11	148	8	52	143	74.57
1955	5	20	173	12	80	210	98.40
1956	4	12	147	8	72	172	83.46
1957	14	31	178	19	77	188	101.88
1958	11	25	175	18	55	205	104.78
1959	5	22	169	13	74	190	101.17
1960	0	7	146	3	49	151	66.52
1961	7	26	158	20	87	186	101.85
1962	0	8	115	4	47	133	70.46
1963	5	10	103	8	30	125	61.47
1964	11	23	106	19	50	108	80.19
1965	1	13	175	8	61	179	77.37
1966	4	11	164	7	42	185	81.97
1967	6	19	179	14	78	205	84.91
1968	5	13	148	8	48	170	87.25
1969	5	16	168	12	55	195	88.67
1970	4	8	143	6	45	150	69.14
1971	0	16	130	9	56	143	84.40
1972	3	15	184	10	87	198	90.96
1973	2	20	164	13	76	189	97.74
1974	3	17	182	10	109	208	102.69
1975	7	22	141	15	83	153	104.37
1976	0	6	123	4	46	140	65.10
1977	5	18	149	14	74	156	90.35
1978	5	20	167	15	69	188	99.06
1979	9	24	188	17	86	218	109.98
1980	8	21	186	17	83	200	104.04
1981	8	23	182	17	89	215	110.97
1982	11	31	154	21	104	168	108.48
1983	5	24	191	19	101	224	96.14
1984	1	24	196	15	106	211	91.41
1985	15	31	162	23	74	169	90.96
1986	8	27	173	21	74	192	109.02
1987	1	8	104	5	36	125	62.74
1988	9	22	174	16	73	186	92.89
1989	16	38	206	28	110	221	125.15
1990	23	52	223	39	132	251	151.76
1991	6	28	150	16	98	158	94.36
1992	9	22	169	14	66	200	103.10
1993	17	45	224	34	128	247	132.66
1994	7	20	153	13	66	166	88.32
1995	16	34	189	21	86	245	127.10
Average[4]	7	21	162	15	75	181	93.98

1. For each drain spacing, drain depth was 90 cm.
2. PPT = Precipitation
3. WTD = Water table depth criteria
4. Average number of days per year (rounded)

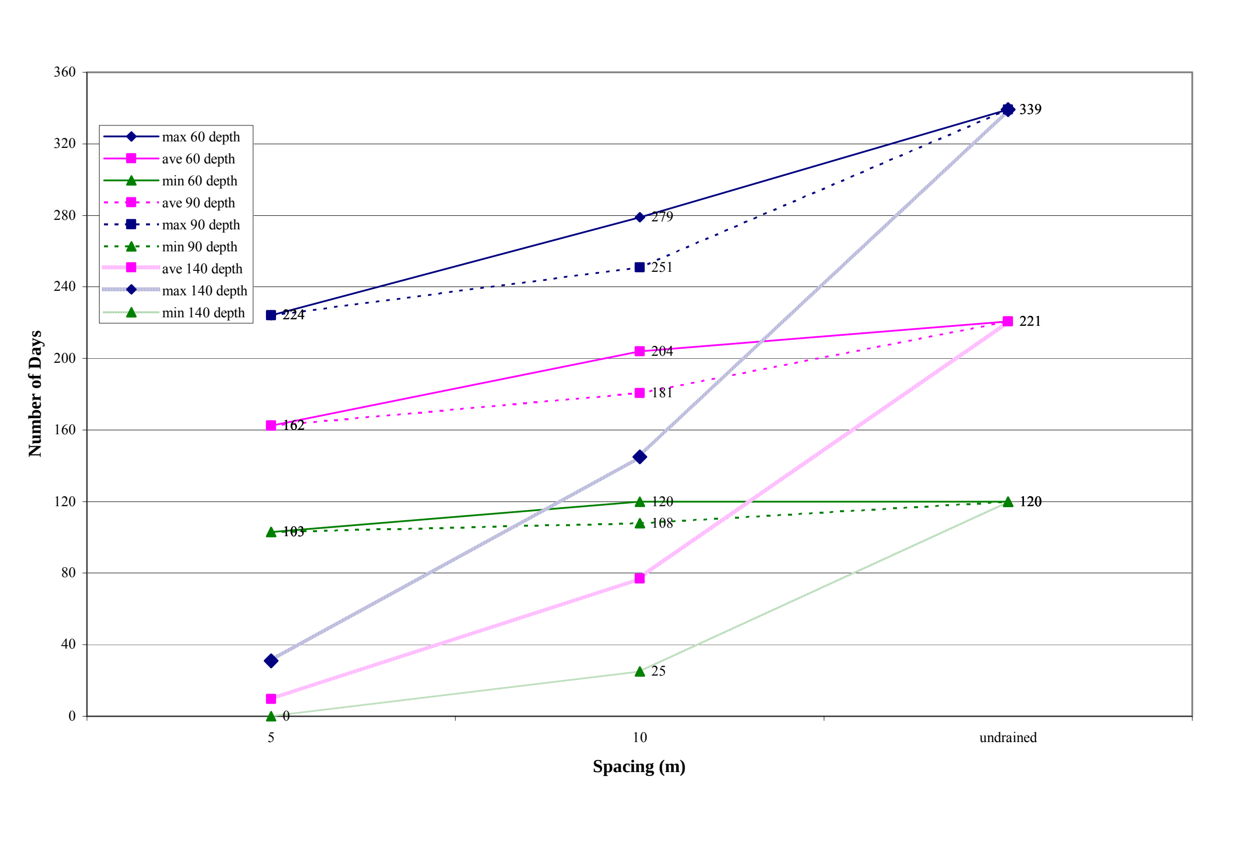


Figure 17. For Crosby silt loam, comparison of the average number of days with the water table higher than 90 cm for three drain depths, 60, 90, and 140 cm, drain spacings of 5 m, 10 m, and undrained, and land slope range of 0-2% (from Appendix Figure D10.3). **(Ave/Max/Min 60 depth is the average/maximum/minimum, respectively, number of days for the 60-cm depth; others similarly noted).**

Effective Drain Radius

For the Crosby soil series, changing the effective radius had negligible effect on the number of days that the WTD criteria were exceeded (Table 17), as the results were almost identical to those for the General Case (Table 7). The result was the same for both the 0.51-cm and 6-cm radii as illustrated in Figure 18. We suggest that for some soil series, the effect of increasing the effective drain radius might be useful. All other figures are located in appendix D.

Table 17. Crosby silt loam effective radius = 6 cm (from Appendix D11.1)										
	Drain Spacing[1] (m)									
Year (n=47)	5			10			15			PPT[3] (cm)
WTD[2] <= (cm)	30	60	90	30	60	90	30	60	90	
1951	2	4	12	7	31	111	25	99	161	94.46
1952	3	4	13	7	28	103	23	86	146	96.60
1953	0	0	4	1	9	65	11	57	128	70.18
1954	0	0	2	0	4	40	3	35	106	74.57
1955	2	3	7	3	13	77	12	65	176	98.40
1956	0	0	3	1	8	70	7	61	127	83.46
1957	6	10	20	12	23	82	20	67	181	101.88
1958	3	6	15	10	19	57	18	46	131	104.78
1959	3	5	13	4	16	72	13	53	157	101.17
1960	0	0	0	0	0	32	2	30	105	66.52
1961	0	2	11	9	26	83	21	71	154	101.85
1962	0	0	0	0	4	44	7	42	97	70.46
1963	2	3	7	4	12	30	7	25	51	61.47
1964	5	6	16	8	21	57	15	51	78	80.19
1965	0	0	1	0	6	61	11	53	122	77.37
1966	0	0	5	1	6	39	6	30	132	81.97
1967	0	1	9	5	20	78	15	69	159	84.91
1968	3	4	7	5	8	42	8	35	115	87.25
1969	0	1	6	4	11	51	10	37	144	88.67
1970	0	1	4	3	6	28	5	18	120	69.14
1971	0	0	0	0	2	59	8	52	117	84.40
1972	0	0	3	2	8	77	11	74	183	90.96
1973	0	0	5	1	16	70	13	62	167	97.74
1974	0	1	3	1	10	105	14	93	174	102.69
1975	1	3	10	5	18	92	20	84	132	104.37
1976	0	0	0	0	4	41	4	40	91	65.10
1977	2	3	6	5	17	68	12	59	136	90.35
1978	0	0	7	4	15	64	16	55	146	99.06
1979	1	2	10	6	19	87	18	75	169	109.98
1980	3	4	10	7	21	83	20	72	167	104.04
1981	2	4	11	4	14	87	16	80	158	110.97
1982	2	5	16	7	27	114	26	95	157	108.48
1983	0	0	8	3	23	95	20	87	194	96.14
1984	0	0	2	1	16	107	15	94	202	91.41
1985	1	4	15	10	28	91	26	76	162	90.96
1986	0	3	13	5	23	82	20	69	148	109.02
1987	0	0	1	0	2	23	2	21	75	62.74
1988	2	4	12	7	21	76	15	67	149	92.89
1989	2	6	22	11	39	125	31	105	213	125.15
1990	7	10	28	23	48	140	40	123	239	151.76
1991	0	2	11	3	26	106	22	95	151	94.36
1992	0	2	10	5	16	73	14	63	154	103.10
1993	5	10	21	15	41	143	33	124	209	132.66
1994	1	2	7	5	15	67	13	53	154	88.32
1995	6	10	24	13	32	86	25	69	190	127.10
Average[4]	1	3	9	5	17	75	15	65	147	93.98

1. For each drain spacing, drain depth was 140 cm.
2. PPT = Precipitation
3. WTD = Water table depth criteria
4. Average number of days per year (rounded)

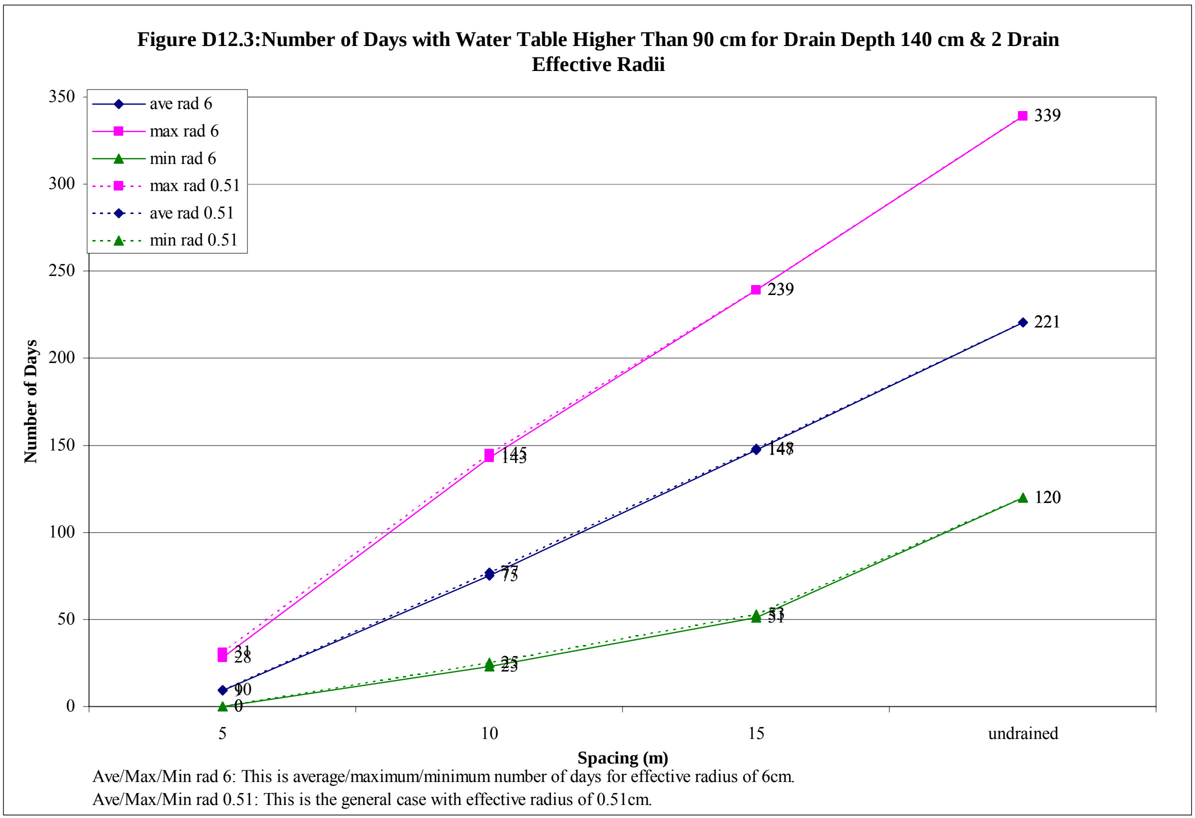


Figure 18. For Crosby silt loam, comparison of the average number of days with the water table higher than 90 cm for three drain spacings of 5 m, 10 m and 15 m, and undrained, and effective radius (from Appendix Figure D12.3).

SUMMARY

This report contains the results of modeling studies that evaluated the performance of subsurface drains to remove excess soil water from the soil profile with application to OSWTS. We evaluated water table levels in selected soil series where curtain drains may be installed near on-site wastewater treatment trenches. Fifty-eight representative soil series were analyzed using the agricultural water management computer model DRAINMOD (Skaggs, 1980a). DRAINMOD can be used to estimate the average daily water table depth midway between two parallel drain pipes on soils where curtain drains may be used with on-site systems; and to assess the effect of daily wastewater application in addition to precipitation; the effect of land slope; the use of a shallower curtain drain depth; and the use of a gravel envelope to increase the effective radius of the curtain drain.

For the 58 soil series selected for this project, DRAINMOD was used to predict the number of days (NOD) each year that the water table depth would meet each of three criteria: water table depth less than or equal to ~1' (30 cm); water table depth less than or equal to ~2' (~60 cm); and water table depth less than or equal to ~3' (90 cm). The analysis for these 58 soils at these three criteria, were for a drain depth of ~4.5' (140 cm) or less if the soils series typically had a shallow profile, and for the drain spacings of 5 m (~16'), 10 m (~33'), and 15 m (~50'). To model the case where there was no subsurface drain, we used a drain spacing of 1000 m (~3,281') for about one-half of these soils series. These simulations and their analyses are termed the General Case. In addition to the General Case modeling and analyses, four soil series (Blount, Crosby, Hoytville, and Mahoning) were further modeled and analyzed for a set of four Case Studies: the effect of daily wastewater application in addition to precipitation; the effect of land slope; the use of a shallower curtain drain depth; and the use of a gravel envelope to increase the effective radius of the curtain drain. For the wastewater application case, two different application depths were chosen: 1.25 cm/day (~0.5 in/day) and 0.33 cm/day (0.13 in/day). For the slope analysis case, land slopes of 3% and 6% were evaluated. The shallow drain depth analysis focused on 60 cm (~24 in) and 90 cm (~36 in). For the gravel envelope case, an effective radius of 6 cm (2.36 in) was evaluated.

For a majority of the soil series modeled, if curtain drains were not installed on these soil series, the overall average number of days with interaction between the water table and the treatment trench bottom exceeds 100 days. Thus, there is potential for near-surface ground water pollution at some level, and potential for the on-site system to not operate properly, and possibly to fail. With a curtain drain installed at the stated drain spacing and depth, the presence of the curtain drain did not eliminate the potential for the water table to interact with the treatment trench for all but three soil series. For these situations, there is risk of near-surface ground water and surface water pollution, and again potential for the on-site system to fail.

The results presented in this report were produced using DRAINMOD, a water balance computer simulation model that has wide application for making decisions in agricultural water management. The soil physical property information need as input for DRAINMOD is typical for the soil series modeled, are not site specific, nor specific to one county in Ohio. These results are very reasonable estimates of the behavior of the water table in the modeled soil series as affected by the presence of subsurface drains. Of course, improved site-specific predictions are possible with highly site-specific soil physics data and on-site long-term climatic data. When site-specific water table observations (5-10 years) are available, the results in this report may be useful as supporting information for decision making.

These results can be used to assess the risk of any potential interaction between untreated, or partially treated, domestic wastewater and near-surface ground water under on-site systems, the potential for on-site system inundation and/or failure, and the potential for untreated, or partially treated, domestic wastewater from on-site systems to be discharged to surface waters.

These results do not predict specific levels of pollution, exact failure of an on-site system, concentrations of pollutants potentially being discharged. However, I believe these results could be very helpful to engineers, scientists, public health specialists in determining a ranking of seasonally high water table soil series in terms of high to moderate risk of undesirable interaction between the near-surface ground water and on-site systems using curtain drains, compared to on-site systems on the same soil series without curtain drains.

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The analysis and compilation of model output was performed by Katherine M. Skalak (Former Research Engineer; now Union SWCD), Ahmed M. AlZoheiry (Former PhD Graduate Associate; now Alexandria University, Egypt), Yun Wang (Former MS Graduate Associate; now Wayne State University), and Dr. Larry C. Brown. The Appendices contain seven sections of archival information and modeling results for the 58 Ohio soils analyzed for this project (available on CD), and summaries are included in the body of the report. Errata: In the Appendices, all references to Crosby "fine sandy loam" should be Crosby "silt loam." A full errata sheet will be issued at a later date. For further information, please contact Dr. Brown at brown.59@osu.edu or 614.292.3826.

SUGGESTED FUTURE WORK

We advise that the Ohio Department of Health and cooperators establish a series of long-term monitoring sites where hourly water table data can be obtained. At this time, we have no long-term record of water table levels as affected by curtain drains adjacent to on-site wastewater treatment systems.

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