

Evaluating Drainage Design Parameters For Wastewater Irrigation Applications To Minimize Impact On Surface Waters^{*}

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ABSTRACT

DRAINMOD, an agricultural water management computer model, was used to evaluate the hydrology for a wastewater irrigation scenario for an Ohio community. This model was used to simulate the runoff potential of the proposed site under drainage and wastewater irrigation, to evaluate subsurface drainage system design parameters and irrigation interval, and to predict the effect of wastewater irrigation on potential crop yield. A 40-year climatic record and USDA Soils5 data were used as inputs to the model to evaluate hydrologic response over a range of input values of irrigation rate and interval, and drain spacing and depth. Simulation results indicate that an irrigation interval of 1 or 2 days could meet the annual irrigation application criteria of 67 cm. Frequency analysis of runoff over the 40-year period for the 2-day irrigation interval revealed that approximately 99% of all days produced zero runoff. A response surface of average annual irrigation depth for the 2-day irrigation interval indicated that the target depth of 67 cm could be attained with a range of drain spacing (7.5 to 12.5 m) and depth (85 to 150 cm) combinations. Within the range of drain spacing and depths evaluated with wastewater irrigation at the 2-day irrigation interval, relative crop yield increased when an increase in drain depth was coupled with a decrease in drain spacing.

Keywords. DRAINMOD, Modeling, Runoff, Subsurface drainage, Nonpoint source pollution

INTRODUCTION

Wastewater reuse on agricultural lands is a wastewater disposal alternative that helps to protect the environment and possibly provide a benefit for agricultural purposes. With the appropriate pretreatment, land application of wastewater is technically feasible for final treatment and disposal of municipal, industrial, and agricultural wastewaters. In some cases, land

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treatment of wastewater through irrigation is less expensive compared to extensive tertiary treatment, mainly because the elimination of the adverse effects of direct stream discharge allows lower levels of pretreatment. Irrigating treated wastewater helps recycle nutrients, and reduce the demand on other water supplies for irrigation of crops, turf, or timber. Wastewater reuse through irrigation is becoming an attractive option for some Ohio communities (Mancl and Rector, 1997).

Proper land treatment of wastes must be controlled to achieve a specified degree of treatment through natural biological, physical, and chemical processes within the plant-soil-water matrix (Reed and Crites, 1984). Since biological oxidation and reduction occur principally within the top few feet of soil (Crites, 1976), the applied wastewater must be able to infiltrate the soil and be retained for a period sufficient for treatment within the biologically active zone (Sopper and Kardos, 1973). Filtration can occur at the soil surface and within the soil matrix. Chemical precipitation, ion exchange, biological transformation, and adsorption occur as the water percolates through the soil. Infiltrated wastewater may be withdrawn through evapotranspiration, percolate to the water table, or move laterally as interflow to discharge to surface waters.

For any type of irrigation to cropland, the drainage characteristics of the soil are very important. Loehr et al. (1979) indicate that excessively drained soils provide such rapid removal of water that treatment by soil processes may be minimized. In contrast, soils of the poorly drained classes are seldom suitable for waste application unless some form of artificial drainage is installed. Moderately well-drained soils would appear to meet both infiltration and drainage requirements for wastewater application (Parizek, 1973). Skaggs and Nassehzadeh-Tabrizi (1982) stated that if wastewater applications are limited by drainage conditions, then the water has to be applied in small amounts at very frequent intervals. They suggested that subsurface drainage can be used to enhance infiltration and percolation, thus creating the potential for increased wastewater applications, and possibly reducing land area requirements.

In Ohio, over 50% of the existing cropland acreage has received drainage improvement (Fausey et al., 1995). Ohio's agricultural soils largely are poorly to somewhat poorly drained, and respond well to drainage improvement. Other factors that will affect the success of an irrigation application are infiltration rate, water table conditions, restrictive layers, water holding capacity, topography, cropping management, rainfall amount and distribution, and other local factors.

Mathematical models can be used to select the optimum application rate and frequency to assess water resource, soil, and plant quality, and to assist in predicting long-term effects for land treatment of wastewater (Iskandar, 1981). However, there appears to be no single published methodology devoted to modeling all the processes involved in land treatment. Fedler and Borrelli (1995) give some principles and procedures used to design effective wastewater land treatment systems. They also discuss how to bridge the gap between agricultural production and engineering. Sometimes engineers forget that sound agricultural practices are necessary for cropland treatment systems to remain effective for the long term, and agricultural producers sometimes forget that the land application site is primarily for treating wastewater, and not for maximizing profit from crop production.

In Ohio, Mancl and Rector (1997) indicate that with suitable drainage providing soil conditions favorable for water movement and treatment processes within the soil profile, a predetermined amount of wastewater can be applied to agricultural lands without overloading the

soil with constituents of the wastewater. This process is based upon crop removal of nitrate, phosphorus and other nutrients from the soil.

When wastewater irrigation systems are developed chiefly for the purpose of wastewater reuse, the objective is to apply the water according to irrigation needs (US EPA, 1992). Under current Ohio Environmental Protection Agency (Ohio EPA) policy, the maximum weekly application rate is 10 cm. The purpose of this project was to determine drainage system parameters and a suitable wastewater application policy for a potential site in Ohio. The selection of drainage system and application frequency parameters was based upon the Ohio EPA policies for daily application rate and runoff control.

A useful tool for evaluating the hydrologic interaction between subsurface drainage system design parameters and wastewater irrigation applications is the agricultural water management computer model DRAINMOD. This model can be used to predict the drainage system design requirements necessary to obtain the optimal irrigation frequency for a proposed site. In addition, output from the model's water balance computations can be used to evaluate runoff potential. The overall objective was to demonstrate the utility and procedures of using the model for evaluating wastewater irrigation scenarios in Ohio. The specific objectives are: 1) To evaluate runoff potential; 2) To evaluate optimal subsurface drainage system design parameters and wastewater application frequency; and 3) To evaluate the effects of irrigation on the potential yield of a corn crop.

METHODS

Proposed Site

The Village of West Mansfield, Ohio is evaluating the use of irrigation as part of the treatment process and ultimate disposal for their wastewater. The village is located in eastern Logan County. The wastewater is a medium strength domestic wastewater. The village proposes to apply the wastewater to a field adjacent to facultative lagoons at the edge of the village. The volume of wastewater to be applied annually was estimated to be 141,000 m³. A local farmer is intending to lease the property to grow corn and soybeans.

The proposed irrigation site covers 21 ha of gently sloping (0-2%) land in eastern Logan County and western Union County. The field is bounded by a fence on the north and northeast, a stream on the southeast (discharge outlet), trees on the south and southwest, and a tree line on the northwest. No subsurface drainage system presently exists on this field. The soil types are Blount silt loam (70%), Morely silt loam (20%), and Wetzel silty clay loam (10%).

Modeling Approach

The objectives of agricultural land drainage systems are to remove excess surface and subsurface water from cropland, and to enhance trafficability and crop growth. These objectives are also important for land systems used for wastewater treatment. Two important objective functions for design of these systems are application volume and frequency. The drainage system should also provide soil conditions favorable for treatment processes (Skaggs and Nassehzadeh-Tabrizi, 1982). An unsaturated soil depth of 60 cm has been recommended as the minimum requirement for adequate land treatment of wastewater since bacteria, viruses, phosphorus, and

other potential pollutants are removed primarily in the unsaturated zone (Parker et al., 1977; Otis et al., 1977).

The model DRAINMOD (Skaggs, 1980) was used for the hydrologic evaluation. This model calculates, on a hour-by-hour or day-by-day basis, the response of the water table and the soil water regime above it to rainfall, evapotranspiration (ET), and the use of various water management strategies, such as subsurface drainage and wastewater irrigation. The model keeps track of the depth of irrigation, water table depth, drainage volume, and ET on a daily basis, with monthly and yearly summaries (Skaggs, 1980). The model calculates a parameter called SEW-30, which is the summation of the height of the water table above 30 cm times the number of days of occurrence. The parameter SEW-30 has been correlated with corn yield (Skaggs, 1980). Thus, a given drainage design and irrigation strategy combination can be analyzed for a long period of climatological record to assess its suitability for agricultural production and the environment.

Land treatment of wastewater is simulated in DRAINMOD by specifying the irrigation volume and frequency, and the time over which wastewater is to be applied. The sprinkler irrigation component of the model was used to simulate land application of a given volume of wastewater on a preset frequency. As an alternative to applying wastewater in a fixed volume/fixed time for each irrigation interval, a varied volume/varied time scenario (apply all within 24 hour period) can be evaluated (Skaggs, 1996, personal communication). In addition, it was realized that when the wastewater application-time starts before planting date and ends after harvesting time of crop, the model keeps wastewater application between the given application-time interval without considering whether the plant is on the field.

In the model, a water balance is conducted in the soil profile. The program checks to determine whether the drained pore volume is sufficient to accept the volume to be applied at the time of the next scheduled wastewater application. If space is not available, the event can be postponed until the next day or skipped until the next scheduled application, depending upon the strategy selected by the user (Skaggs and Nassehzadeh-Tabrizi, 1982). The volume of wastewater that will be applied depends on the drained volume in the soil profile. The soil profile should have a drained pore volume equal to or greater than the volume of wastewater to be applied at the scheduled time of application.

Model Inputs

Records of daily maximum and minimum temperatures, and hourly precipitation from Findlay, Ohio were used in this study. These records spanned a period of 50 years, from January 1940 to August 1989. The 40-year period of January 1949 to December 1988 was used mainly because it was the longest period with the least amount of missing data. Findlay is located approximately 71 km north of the study area. Marysville is the next nearest weather station (23 km southeast), but its record spanned only 15 years. The longer record period was used to minimize extreme variations in weather patterns.

The USDA Soils5 database was used to generate the required soil parameters. Blount silt loam characteristics were used throughout the simulations since it was the dominant soil type in the study area. A depth to bedrock (i.e., impeding layer) of 152 cm, and saturated water content and wilting point values of 0.37 and 0.25 cm³/cm³, respectively, were used in the simulations. Saturated hydraulic conductivity values used were 2.78 cm/hr for the top 25 cm of the soil profile, and 0.48 for the 25 to 152 cm depth. A drainage coefficient of 2 cm/day was used for all

simulations. Corn growth characteristics and inputs were developed based upon guidance in the DRAINMOD User's Manual (Workman et al., 1990), and the Ohio Agronomy Guide (OSU Extension, 1996).

Ten drain depths, ranging from 60 to 150 cm, and six drain spacings, ranging from 5 to 40 m, comprise the drainage system alternatives. A seventh spacing of 100 m was used to represent a "no drainage system" scenario. A drain diameter of 10 cm, effective drain radius of 0.51 cm, and surface storage value of 1-cm were selected and held constant for all simulations. The 1.5-cm depth for depression storage was selected as a worst-case value for these simulations since actual cropping management at the site is unknown. An irrigation rate of 0.12 cm/hr, duration of 5 hr, and total possible irrigation days of 274 were used to evaluate the range in irrigation interval of 1 to 10 days. The number of possible wastewater irrigation days was determined after excluding frozen soil days (91). The target annual irrigation depth of 67 cm was determined based upon the land application area of 21 ha and an annual wastewater volume of 141, 000 m³. This research focused upon the hydrology of the system, and did not consider wastewater constituents.

Model Output Analysis

Output data analysis was used to identify a range of drain spacing and depth combinations, and irrigation interval(s) that would accommodate the target annual irrigation depth within the 274-day constraint. Two small programs written in FORTRAN language were used to facilitate extraction and organization of specific data from the output files. Runoff depth, drain discharge volume, SEW-30, and overall relative yield for each drain spacing/depth/irrigation interval combination were also compiled. Therefore, the selection of acceptable irrigation interval, drain spacing and depth combinations were made based upon maximizing average annual irrigation depth and relative yield, while minimizing average annual runoff depth.

RESULTS AND DISCUSSION

Optimum Irrigation Interval

Values of optimum irrigation interval were determined by plotting the maximum annual irrigation depth for each irrigation interval (Fig. 1). This irrigation depth at each irrigation interval was the largest irrigation depth among all such depths computed for that irrigation interval, with its specific drain spacing and depth combination. For example, a maximum irrigation depth of 82.2 cm for the two-day irrigation interval was the result of the simulation using the 5-m drain spacing, 150-cm drain depth combination. The horizontal line represents the target annual irrigation depth of 67 cm. From this preliminary analysis, an irrigation interval of one or two days will be required to meet the target annual irrigation depth of 67 cm. These two irrigation intervals provided the largest possible relative yield and smallest SEW-30 values (Fig. 2). These results (Fig. 1 and 2) were used to reduce our large matrix of possible simulations to a more manageable level. As it can be seen from the Fig. 2, the relative yield also decreases while

the SEW-30 decreases with respect to the increases in irrigation interval. This contradiction is due to the increasing effects of drought conditions on the relative yield.

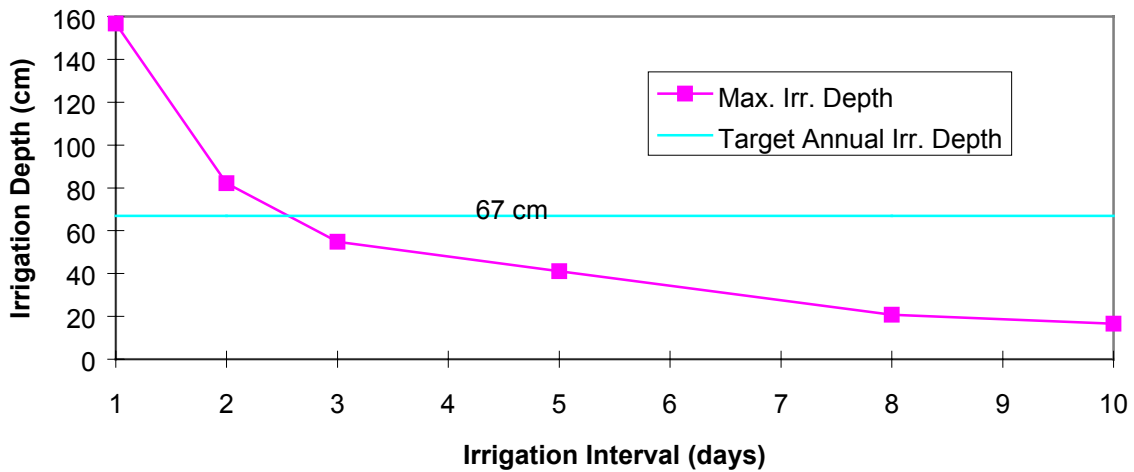


Figure 1. Illustration of irrigation interval versus maximum irrigation depth, used to identify potential irrigation intervals for further analysis.

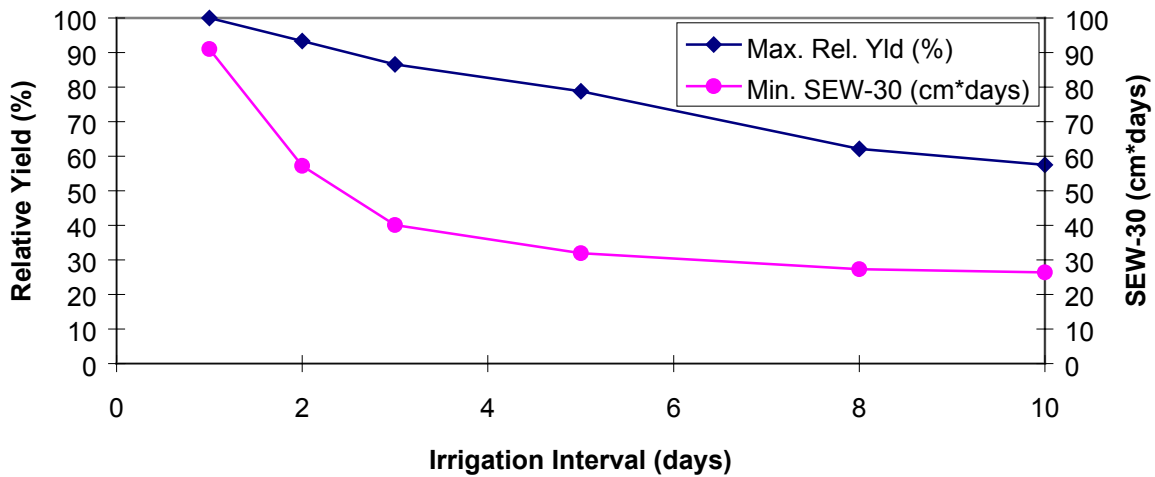


Figure 2. Maximum relative yield and minimum SEW-30 values versus irrigation interval.

The acceptable combinations of drain spacing and depth were determined by plotting a response surface of maximum average annual irrigation depth with drain spacing and depth (Fig. 3). By introducing a 67-cm isoline into the average annual irrigation depth response surface, we were able to identify a range of drain depth and spacing combinations that would allow us to achieve the target depth. This response surface indicates that an acceptable irrigation depth can be attained with the drain spacing and depth combinations of 5 to 10 m and 80 to 150 cm, respectively, as given in table 1. The response surface of average annual irrigation depth for the one-day irrigation interval (not shown) indicated that the target annual irrigation depth could be attained with the drain spacing and drain depth combinations of 5 to 15 m and 70 to 150 cm, respectively (table 1).

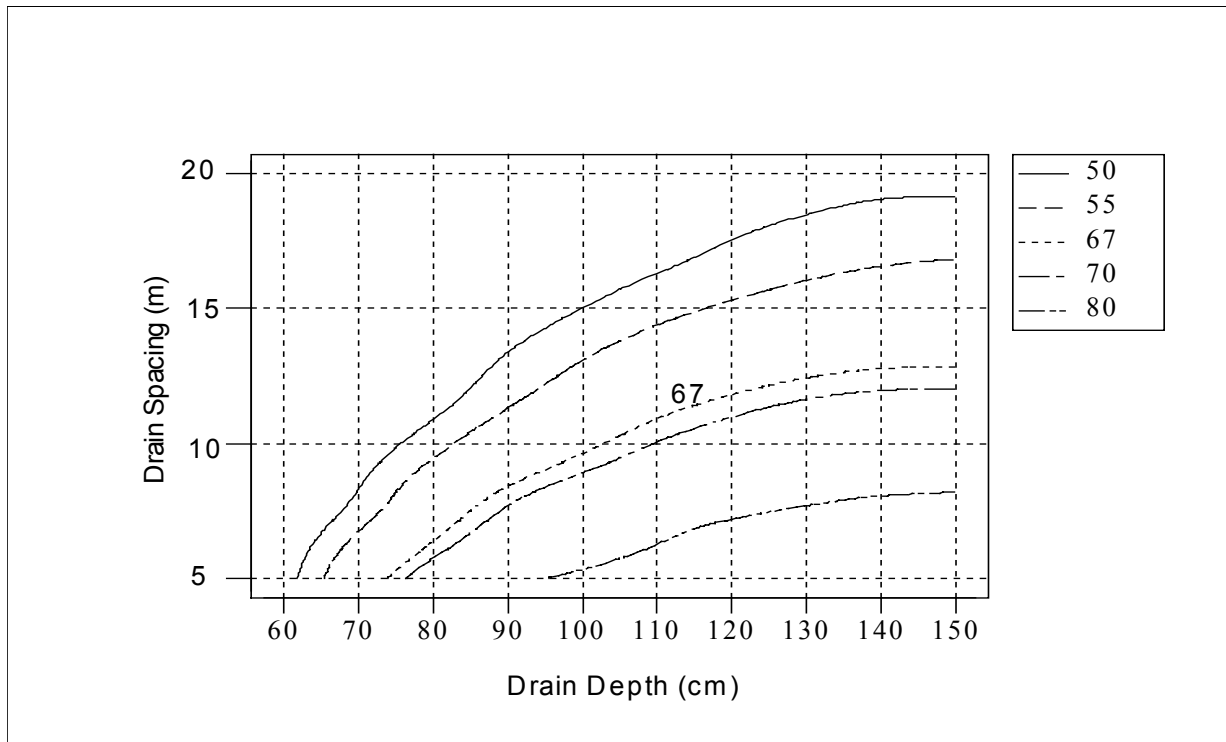


Figure 3. Response surface of average annual irrigation depth (cm) for the two-day irrigation interval as a function of drain spacing and depth. Drain spacing and depth combinations that fall beneath the 67-cm isoline meet the acceptance criterion.

Table 1 also includes the maximum irrigation depth for the four other irrigation intervals evaluated with their respective drain spacing-depth combinations. These specifications will not meet our target application depth criterion. In addition, when no drainage system was modeled on the study area, the average annual irrigation depth was less than 30 cm.

One objective of this study was to evaluate runoff potential. The range of average annual runoff depths for the drain spacing and depth combinations that meet the targeted annual application depth is given in table 1. The smallest acceptable average annual runoff depth of 3.76 cm was achieved with the 5-m drain spacing and 150-cm depth combination. This depth is approximately 4% of annual precipitation. Frequency analysis of all runoff depths over the 40-year period for the two-day irrigation interval revealed that approximately 99% of all days produced zero runoff. A plot of Weibull transformed probability versus runoff depths for the drain spacing of 5-m and drain depth of 100-cm of the 2-day irrigation interval is given in Figure 4. In addition, the percentages of rain events caused runoff for the recommended drain depth-spacing combinations of 2-day irrigation interval were calculated and presented in Figure 5. This percentage for the undrained condition was about 27.5. Of course, some parts of these runoff events occurred during the non-wastewater application period.

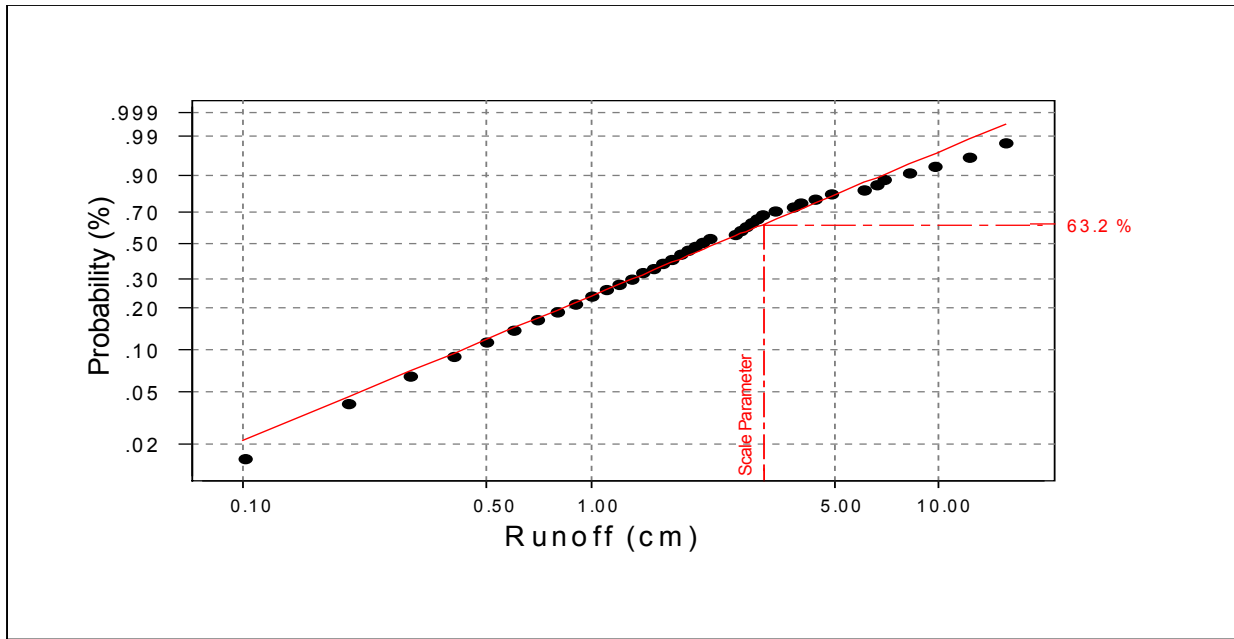


Figure 4. Runoff depth probability for the drain spacing of 5-m and drain depth of 100-cm of 2-day irrigation interval.

Table 1. Average annual wastewater irrigation and runoff depths for the irrigation intervals evaluated, and their respective ranges of drain spacing-depth combinations.

Irrigation Interval (days)	Drain Spacing (m)	Drain Depth Range (cm)	Irrigation Depth (cm)	Runoff Depth (cm)
1	5	70-150	82.3 - 157.0	8.75 - 4.67
	7.5	80-150	82.6 - 144.0	8.85 - 6.09
	10	90-150	77.9 - 118.0	9.58 - 7.47
	15	120-150	70.9 - 77.6	11.0 - 10.9
2	5	80-150	73.9 - 82.2	6.73 - 3.76
	7.5	90-150	70.6 - 80.8	6.90 - 4.69
	10	110-150	70.2 - 76.7	6.88 - 5.65
3	5	150	54.9	3.39
5	5	140	41.2	3.22
8	5	150	20.8	2.91
10	5	130	16.6	3.08

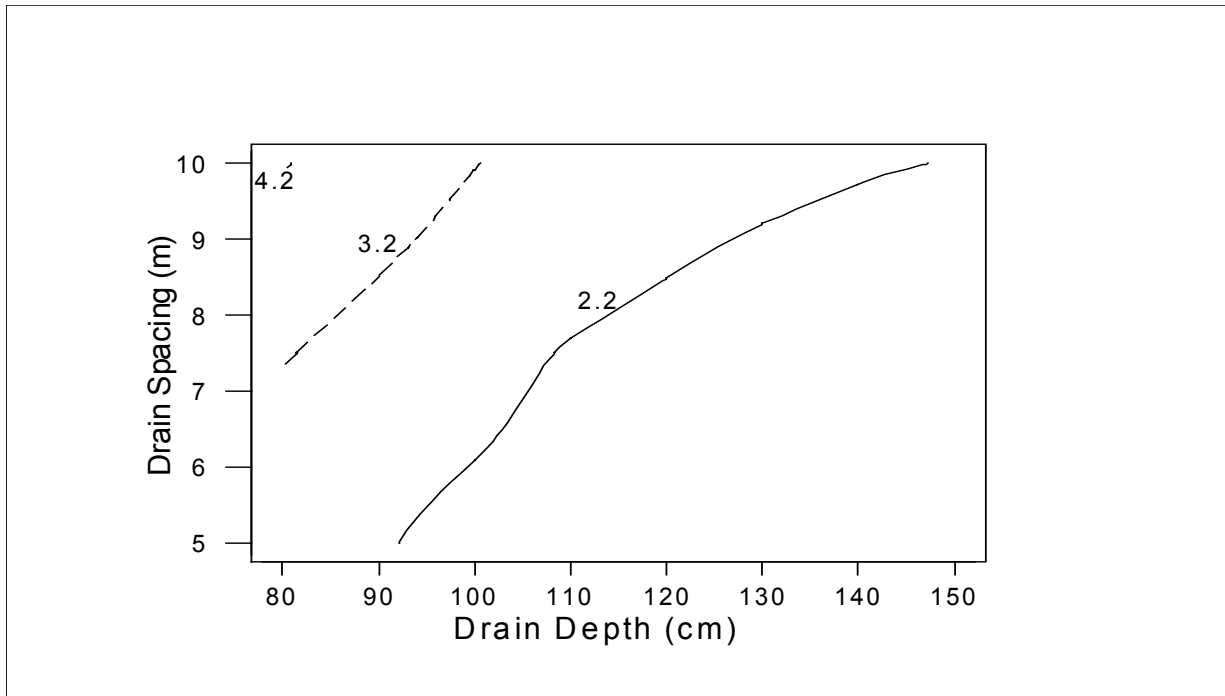


Figure 5. Percentage of rain events caused runoff for the recommended drain depth-spacing combinations of 2-day irrigation interval.

Overall relative yield, with the three components, for the two-day irrigation interval is given in table 2 with the recommended drain spacing-depth combinations. Within each drain spacing, as drain depth increases, the effect of excess water stress decreases. In addition, whenever drain spacing increases, the effect of excess water stress increases. Since we are irrigating and the drain spacing-depth combinations in table 2 meet the target irrigation depth, there is no effect of drought conditions on relative yield. However, the effect of drought conditions on relative yield was seen for the 3-, 5-, 8-, and 10-day irrigation intervals (not shown). In addition, there was little effect on relative yield because of planting delay. A response surface of overall average relative yield for the two-day irrigation interval is illustrated in Fig. 6. From this figure and the data in table 2, overall relative yield for the recommended combinations varied from 73 to 93.4%. When no drainage system was modeled on the study area, the maximum overall relative yield was 10%.

The relative yield results from this study are similar to those found by McMahon et al. (1988) in Virginia, who stated that relative corn yields predicted for the 80-cm drain depth were lower than those predicted at drain depths of 110 and 140 cm, respectively. In addition, they found that SEW-30 values for small drain spacings were less than those for large drain spacings.

Table 2. Overall relative yield with the three components, for the two-day irrigation interval with the recommended drain spacing-depth combinations, and average overall yield within a drain spacing.

Drain Spacing	Drain Depth	Average Relative Yield			
		Excess Moisture (%)	Drought Conditions (%)	Delayed Planting (%)	Overall (%)
(m)	(cm)				
5	80	83.6	99.6	88.8	73.7
	90	85.0	99.7	99.1	83.9
	100	87.0	99.7	100.0	86.6
	110	89.3	99.7	100.0	89.0
	120	91.1	99.7	100.0	90.8
	130	92.4	99.7	100.0	92.0
	140	93.3	99.7	100.0	93.0
	150	93.7	99.7	100.0	93.4
Average		89.4	99.7	98.5	87.8
7.5	90	83.3	99.6	88.3	73.0
	100	85.1	99.5	95.8	80.9
	110	85.6	99.7	99.7	85.0
	120	87.0	99.7	100.0	86.6
	130	88.6	99.7	100.0	88.2
	140	89.6	99.7	100.0	89.3
	150	90.0	99.7	100.0	89.7
Average		87.0	99.7	97.7	84.7
10	110	81.5	99.6	91.0	73.5
	120	83.5	99.5	94.8	78.5
	130	84.6	99.7	97.6	82.2
	140	85.9	99.7	98.9	84.6
	150	85.9	99.7	99.4	85.0
Average		84.3	99.6	96.3	80.8

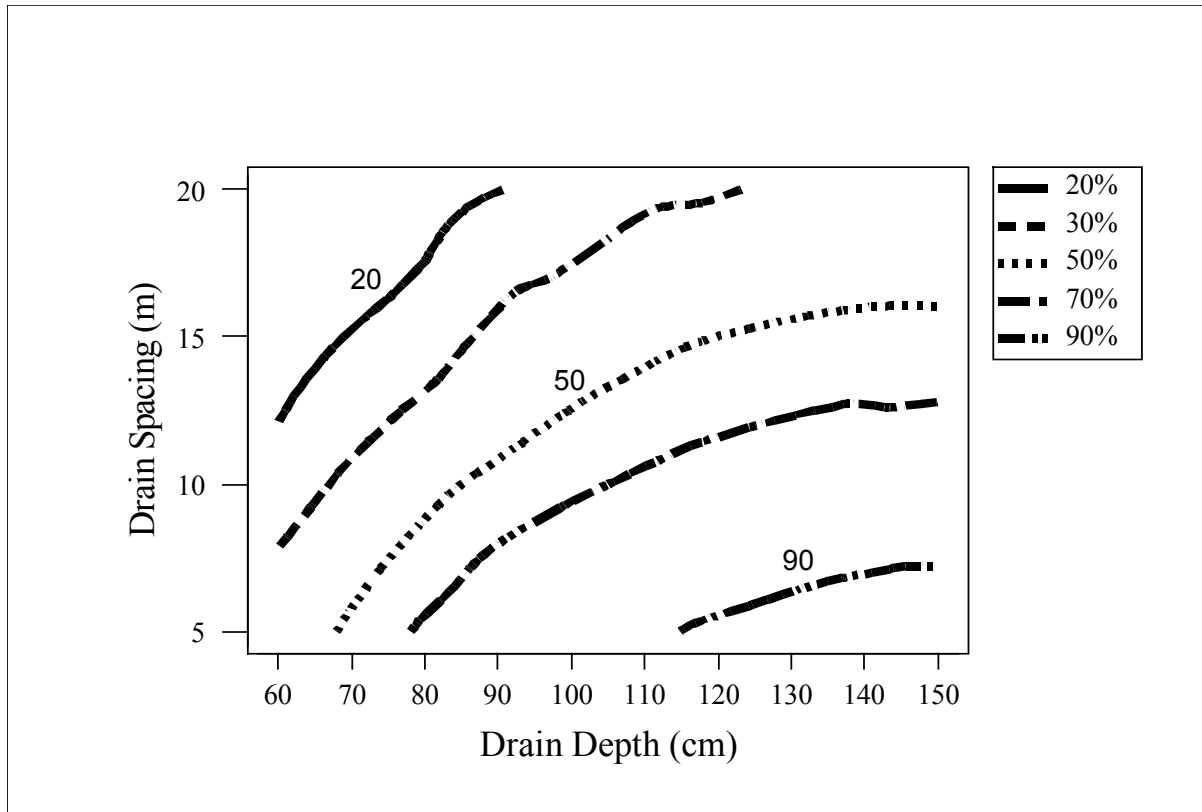


Figure 6. Average overall relative yield for the two-day irrigation interval, and drain spacing and depth combinations.

A simple analysis was performed to evaluate the economics of the more intensive drain spacings recommended for the wastewater irrigation scenario versus a typical drain spacing for conventional agricultural production. For this analysis, we made the following assumptions: cost did not vary with drain depth between 80 and 150 cm; a permanent drainage main and sprinkler irrigation system were already installed; the main was installed along the one long side of (600 m) the field, and laterals were to be installed perpendicular to this main and parallel to each other. Therefore, our analysis is a comparison of costs for lateral spacings. In this analysis, we used a 102 mm lateral diameter. Installation and material prices used in this analyses were \$0.72 and \$0.69 per meter, respectively, and are average costs obtained from commercial drainage firms in central Ohio. These costs were increased 25% for fittings and contingencies.

Cost estimates for the recommended lateral spacings for the two-day irrigation interval were calculated and then normalized on the least cost. For the 10-, 7.5-, and 5-m spacings, the relative cost for materials, installation and contingencies was approximately \$1.00, 1.34 and 2.03, respectively. The average cost per ha was estimated at \$1,712, 2,300, and 3,424 for the 10-, 7.5-, and 5-m spacings, respectively. The estimated cost of a typical 15-m drain spacing on Blount soil for conventional corn production is \$1,141 per ha, with a relative cost of \$0.67. Using the mean of the average overall yields for each drain spacing in table 2, the costs for the more intensive system may not be covered completely by the improvement in relative yields. However, the number one objective is to land apply the wastewater, not maximize crop yield.

But certainly, when compared to the cost for other secondary or tertiary treatment methods, the lateral cost is attractive.

SUMMARY

In this project, a land treatment of wastewater scenario for a site in central Ohio was simulated to determine suitable drainage system parameters and wastewater application policy which can supply an annual target irrigation depth of 67 cm. In this simulation, the agricultural water management computer model DRAINMOD was used to evaluate the drainage system parameters of seven drain spacings (5, 7.5, 10, 15, 20, 40, and 100 m) and ten drain depths (from 60 to 150 cm) combinations with six irrigation intervals (1-, 2-, 3-, 5-, 8-, and 10-day). Blount silt loam characteristics from the USDA Soils5 database, a 40-year spanned climatological data, drainage system characteristics, and wastewater application amount with its policy for corn were used as input data into the model. The model predictions were the maximum irrigation depth, relative yield, SEW-30, and runoff depth for daily basis with monthly and yearly summaries. After analyzing the output irrigation depths, one- and two-day irrigation intervals were required to meet the target annual irrigation depth. The analyses also revealed that an acceptable irrigation depth for two-day irrigation interval can be attained with a drain spacing ranging from 5 to 10 m with a drain depth ranging from 80 to 150 cm. In addition, relative yields for these acceptable design ranged from 73 to 94%.

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