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DRAINMOD REFERENCE REPORT

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CHAPTER 6

APPLICATION OF DRAINMOD - EXAMPLES

The purpose of this chapter is to present examples of the use of DRAINMOD for designing and evaluating water management systems. Four sets of examples will be considered. First, alternative designs of a combination surface-subsurface drainage system are analyzed for four soils at three locations. The results are presented such that the least expensive alternative can be selected for each case. The use of a drainage system for controlled drainage or subirrigation is considered in the second example set. In the third example, DRAINMOD is used to determine the amount of waste water that can be applied to a disposal site that has surface and subsurface drainage. The storage capacity required to hold waste water which cannot be applied during the wet season of the year until the summer months when it can be irrigated is also determined. Finally, the model is used to show the effects of root depth on the occurrence and frequency of drought stress on crops in North Carolina. The purpose of this example is to demonstrate the potential effects of removing physical and chemical barriers to root growth on water availability to plants and the frequency of drought stress.

Example Set 1 - Combination surface-subsurface drainage systems

Combination surface-subsurface drainage systems are analyzed for four soils at three locations: Wilmington, North Carolina, Columbus, Ohio, and Jacksonville, Florida. The results in this example were presented as an ASAE paper (Skaggs, 1978c). The soils used at all locations are North Carolina soils and may not be typical of soils at Columbus or Jacksonville. The analyses for these locations show the affects of changes in climate and planting dates on the drainage system design needs.

Soils

Four soils were chose for analysis in this example: Bladen loam, Lumbee sandy loam, Rains sandy loam, and Wagram loamy sand. The soil properties were determined in a study to test the validity of the model (Skaggs, 1978b). Methods for determining the properties and the soils are discussed in more detail in Chapter 10. All soils are assumed to have relatively flat surfaces with poor drainage in their natural states. The Bladen and Wagram soils have relatively uniform profiles while Lumbee and Rains have layered profiles. As noted in Chapter 4, the Wagram soil is normally well drained in its natural state and does not require artificial drainage. However, the loamy sand considered here has a nearly level surface and is underlain by a heavy subsoil that may be assumed impermeable so artificial drainage is needed. Downward water movement in all soils is restricted by an impermeable layer at a uniform depth; the depth of the layer is soil dependent and is within 3 m of the surface for the soils considered herein. Soil properties used as inputs in DRAINMOD are tabulated in Table 6-1. The soil water characteristic and the relationship between water table depth and upward water movement are given in Table 10-5 and Figures 5-4 and 5-6, respectively. The relationship given in Figure 5-4 for Portsmouth s.l. was used for the Bladen soil.

Table 6-1. Summary of input soil property data used in examples in this chapter.

Soil	Bladen l.	Lumbee s.l.		Rains s.l.		Wagram l.s.	Portsmouth s.l.
Depth to restricting layer (m)	3.0	1.7		1.4		1.8	2.0
Saturated hydraulic conductivity layer depth (m)	uniform	0 - 1.0	1.0 - 1.5	0 - 1.1	1.1 - 1.4	uniform	uniform
K (mm/hr)	10	10	30	43	10	60	30
Saturated water content (cm^3/cm^3)	0.41	0.34		0.37		0.30	0.40
Water content at lower limit available to plants (cm^3/cm^3)	0.15	0.12		0.09		0.05	0.13
Minimum water-free pore space for tillage (spring) (mm)	30	28		39		35	30
Minimum daily rain to stop field operations (spring) (mm)	10	15		12		15	12
Minimum time after rain before it is possible to restart tillage (spring) (days)	2	1		2		1	2

Crop Data

It was assumed that corn was to be grown on a continuous basis in all simulations conducted. The growing season was assumed to be 120 days in duration with the planting and harvesting dates dependent on location as shown in Table 6-2. Although the depth and distribution of plant roots depend on many factors including soil type, water content, fertility, physical and chemical barriers in the soil, and others, the effective root zone depth is assumed here to depend only on time after planting. The root distribution given by the 60 percent curve in Figure 2-22 (with a minor correction so that the minimum root depth was 3 cm to account for the thin surface layer that can be dried by evaporation) was used for all soils and locations.

Drainage System Parameters

Three field surface drainage intensities corresponding to the average surface storage depths o 2.5, 12.5, and 25 mm were considered in the simulations. This range is consistent with the results of field studies of surface storages on fields with and without improved surface drainage in eastern North Carolina. The subsurface drainage component was provided by parallel 102 mm (4 inch) drain tubes placed at a range of depths and spacings as given in Table 6-3. Convergence near the drains was accounted for by defining an equivalent depth as discussed in Chapter 2. An effective drain tube radius of 5.1 mm (0.51 cm) was used in calculating d_e. Simulations were conducted for four drain depths and five spacings for each soil at each location, as indicated in Table 6-3. Table 6-3 gives the values of drain depths, spacings, surface drainage, soils, and locations used in the simulations. Simulations were conducted for all combinations of these variables.

Table 6-2. Planting and harvesting dates for corn that were used in the simulations for three locations.

	Jacksonville, Florida	Wilmington, North Carolina	Columbus, Ohio
Planting date	March 3	April 15	May 5
Harvesting date	July 3	August 15	September 5
Seedbed preparation period	February 1 - March 2	March 15 - April 15	April 15 - May 5

Table 6-3. Range of drainage system parameters, soils, and locations for which simulations were conducted.

Drain depths (m)	0.75	1.0	1.25	1.50*	
Drain spacing					
Wagram (m)	15	30	45	60	90
Bladen (m)	7.5	15	30	60	90
Lumbee and Rains (m)	7.5	15	30	45	60
Surface depression storage (mm)	2.5	12.5	25		
Soils	Bladen l, Lumbee s.l., Rains s.l., Wagram l.s.				
Locations	Columbus, OH; Wilmington, NC; Jacksonville, FL				

* The greatest drain depth for the Rains soil was the depth of the restrictive layer, 1.4 m, rather than the 1.5 m used for the other soils.

Climatological input data consisted of hourly precipitation records and maximum and minimum daily temperatures. These data were obtained from storage in HISARS (Wiser, 1975) for Wilmington, North Carolina, for the 26-year period, 1950-1975. Data from Jacksonville, Florida, and Columbus, Ohio, were obtained from the National Climatic Center, Asheville, North Carolina, and stored in HISARS format for automatic retrieval by DRAINMOD. Simulations for Jacksonville and Columbus were conducted for 25 years of record (1949 to 1973).

Results - Alternative Drainage System Designs

Results of the simulations were analyzed to identify alternatives of surface and subsurface systems that would satisfy trafficability and crop protection requirements.

Trafficability

The effect of drain spacing on the number of working days during the 1-month period (March 15 - April 15) prior to planting is shown in Figure 6-1 for two soils at Wilmington, North Carolina. Relationships are plotted on a 5-year recurrence interval (5 YRI) basis for both good (s = 2.5 mm) and poor (s = 25 mm) surface drainage. The results show that trafficability is strongly dependent on the drain spacing. The effect of surface drainage on the number of working days during the seedbed preparation period depends on the soil and the drain spacing. For example, a drain spacing of 21 m on the Lumbee soil would give 10 working days on a 5 YRI basis for poor surface drainage as compared to 13 working days for good surface drainage (Figure 6-1). On the other hand, improving the field surface drainage for the Wagram soil with a 40 m drain spacing would only increase the working days

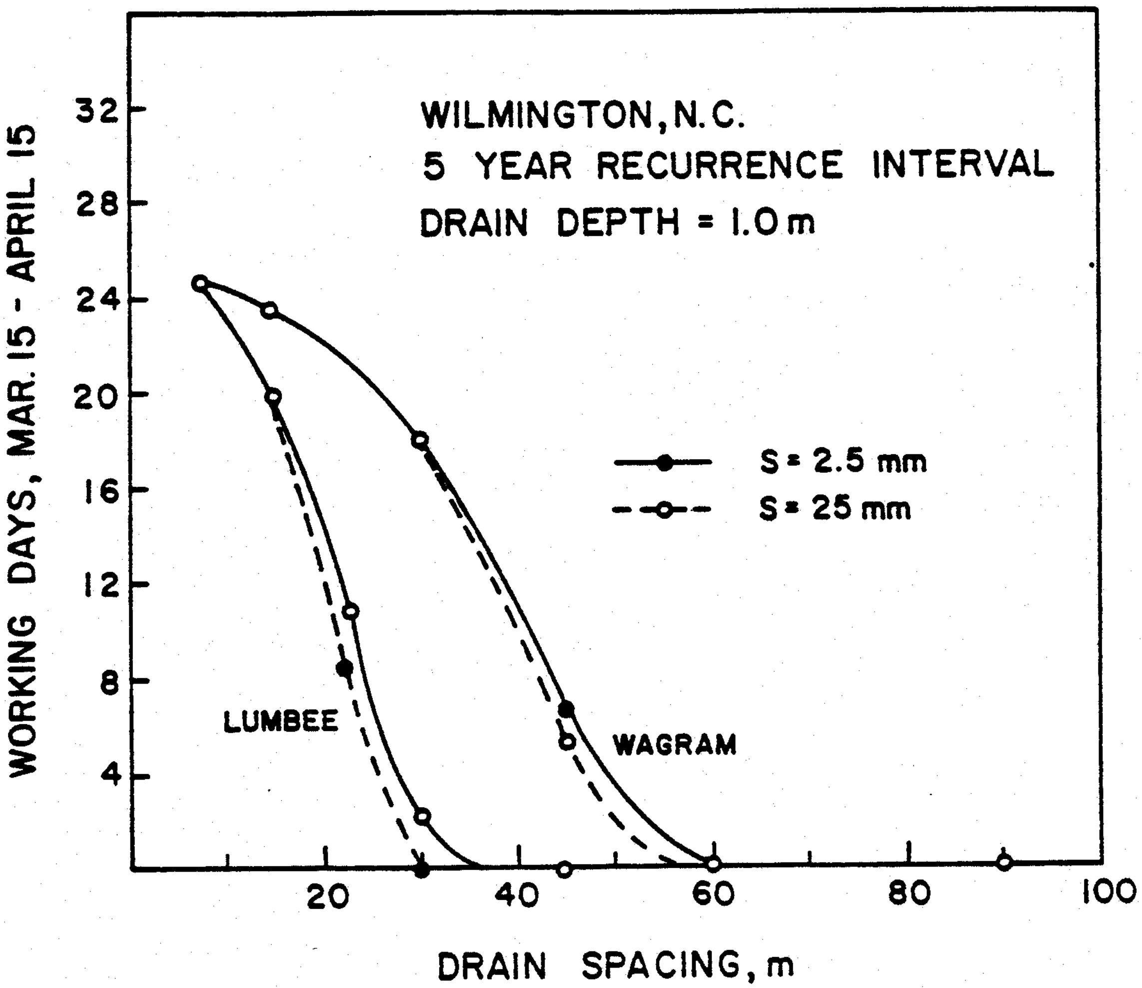

Figure 6-1. Working days on Lumbee sandy loam and Wagram loamy sand during the month prior to corn planting at Wilmington, North Carolina, as a function of drain spacing for good (s = 2.5 mm) and poor (s = 25 mm) surface drainage.

from 10 to 11 on a 5 YRI basis. In general, the effect of field surface drainage on trafficability will be larger for the tighter soils with close drain spacings than for soils that require less intensive subsurface drainage. However, the results plotted in Figure 6-1 show clearly that the quality of surface drainage has only a small effect of the drain spacing required to insure a given number of working days during the seedbed preparation period. In the above example, the 21 m spacing required to provide 10 working days with poor surface drainage on Lumbee could only be increased to 23 m for good surface drainage. Similar results for the effect of field surface drainage were observed for all soils at all locations. In order for trafficable conditions to exist, there must be a minimum air volume (water-free pore space) in the profile. Because seedbed preparation follows the winter period when water tables are often high, trafficable conditions depend on the rate that water can be removed from the profile. ET is relatively low during this period so the major pathway for water removal is subsurface drainage. Surface drainage is only effective in removing water from the surface before it can infiltrate into the profile and in reducing the water stored on the surface after rainfall ceases. Land forming and smoothing to provide good surface drainage does not remove water from the soil profile; it only affects the amount of water that must be removed from the soil surface before water table drawdown can begin. Thus, trafficability has a strong dependence on subsurface drainage and only a weak dependence on surface drainage on these soils.

Subsurface drainage for a given soil depends primarily on the depth and spacing of drains. Working days for the Lumbee soil at Wilmington, North Carolina, are plotted versus drain spacing for several drain depths in Figure 6-2. These results show that the drain spacing can be considerably increased by increasing the depth. For example, the 23 m spacing required at a 1.0 m depth to give 10 working days (5 YRI basis) could be increased by 30 percent to 30 m by increasing the depth to 1.25 m. A depth of 1.5 m would allow a 34 m spacing (48 percent increase) for the same number of working days. These results indicate that the drains should be placed as deep as possible so as to increase spacings and decrease costs. However, the drain depth may be limited by the depth of restricting layers or the elevation of the drainage outlet. For the Lumbee soil, a layer of higher K exists below a 1 m depth. However, in many soils, the conductivity decreases with depth so there is less advantage of increasing the drain depth. Another factor that may be important for some soils is the possibility of excess drainage when very deep drains are used. Results of

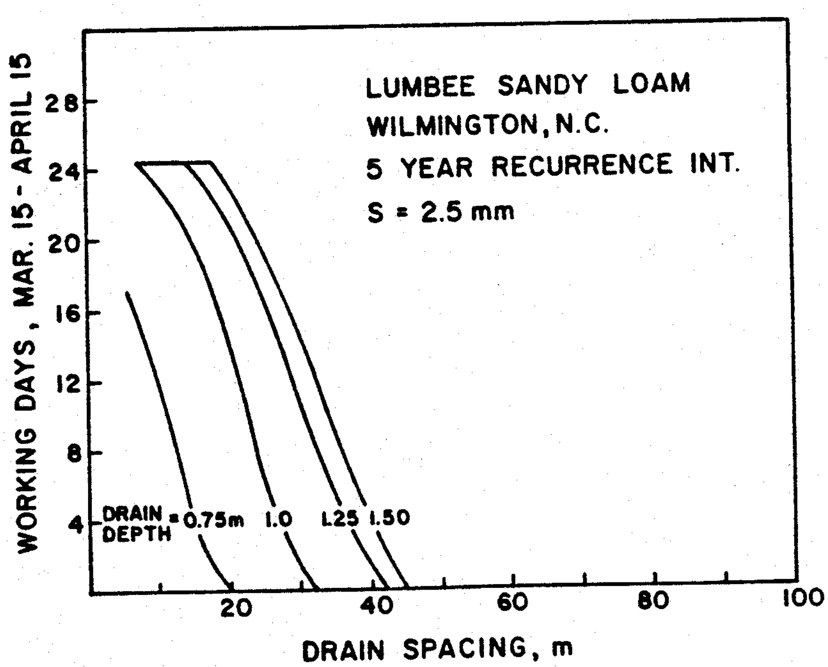

Figure 6-2. Working days versus drain spacing for four drain depths on a Lumbee sandy loam soil with good surface drainage at Wilmington, North Carolina.

the simulations showed that excess drainage was not a problem with the Lumbee soil as the number of drought days were only increased from 34 to 37 (again on a 5 YRI basis) by increasing the drain depth 0.75 to 1.5 m. However, this will not always be the case and the possibility of excessive drainage should be considered when deep drains are proposed.

Relationships between the number of working days and drain spacings are plotted in Figure 6-3 for Wagram and Bladen soils at all three locations. The relationships for the three locations were surprisingly close for all soils, as indicated by the results given in Figure 6-3. The drain spacings required to provide 10 working days were less than 2 m different among the three locations for both Bladen and Wagram soils. It is important to recall that the planting dates are different for each location so that working days are determined for the period February 1 to March 2 for Jacksonville compared to April 5 to May 5 for Columbus. If the planting dates were the same, there would be considerable difference in the working day relationships between locations, as shown by the dotted curve in Figure 6-3, which was obtained for the Jacksonville location using the planting date and growing season from Columbus.

Working day - drain spacing relationships for all four soils are plotted in Figure 6-4 for the Columbus, Ohio location. Similar relationships for the Lumbee and Wagram soils at Wilmington, North Carolina, are plotted in Figure 6-5 for recurrence intervals of 5, 10, and 25 years. An interesting point here is the relatively small differences in drain spacing among the three recurrence intervals. Taking 10 working days on the Lumbee soil, as an example, a drain spacing of 23 m would be required for design on a 5 YRI basis while the 25 YRI basis would require an 18 m spacing.

The results presented in Figures 6-1 through 6-5 show that trafficability during the seedbed preparation period is heavily dependent on the factors controlling the rate of subsurface drainage: drain spacing, depth, and soil properties. While surface drainage may have a significant effect on the number of working days for a given soil and drain spacing, it has a relatively small effect on the subsurface drainage intensity required to insure a given number of working days on a 5 year recurrence interval basis. Location had a relatively small effect for the cases considered. It is clear, however, that, in general, drainage requirements for trafficability depend heavily on the local climate, planting date (Figure 6-3), and the level of protection desired (Figure 6-5).

SEW-30

The effect of drain spacing and surface drainage on SEW-30 is shown in Figure 6-6 for Lumbee and Wagram soils. The quality of surface drainage has a much greater effect on SEW-30 than on trafficability as can be seen by comparing Figures 6-1 and 6-6. The results given in Figure 6-6 show three combinations of surface and subsurface drainage that will provide a given level of SEW-30 on a 5 YRI basis. Consider the Lumbee soil, for example. A SEW-30 value of 100 cm days can be obtained with drain spacings of 23, 16, or 12 m for surface drainage corresponding to depressional storage values of s = 2.5, 12.5, or 25 mm, respectively. All of these combinations would provide 10 or more working days for seedbed preparation (Figure 6-1), so the

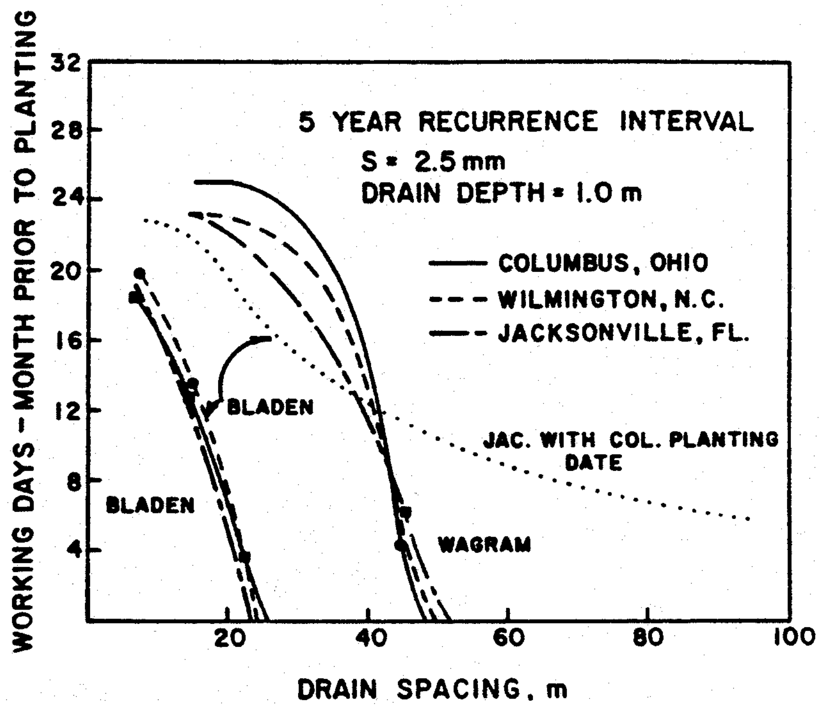

Figure 6-3. Working days during the 1-month period prior to planting versus drain spacing for two soils at all three locations. The dotted curve (...) is the relationship obtained for Jacksonville, when planting dates and growing season from Columbus, Ohio, are used.

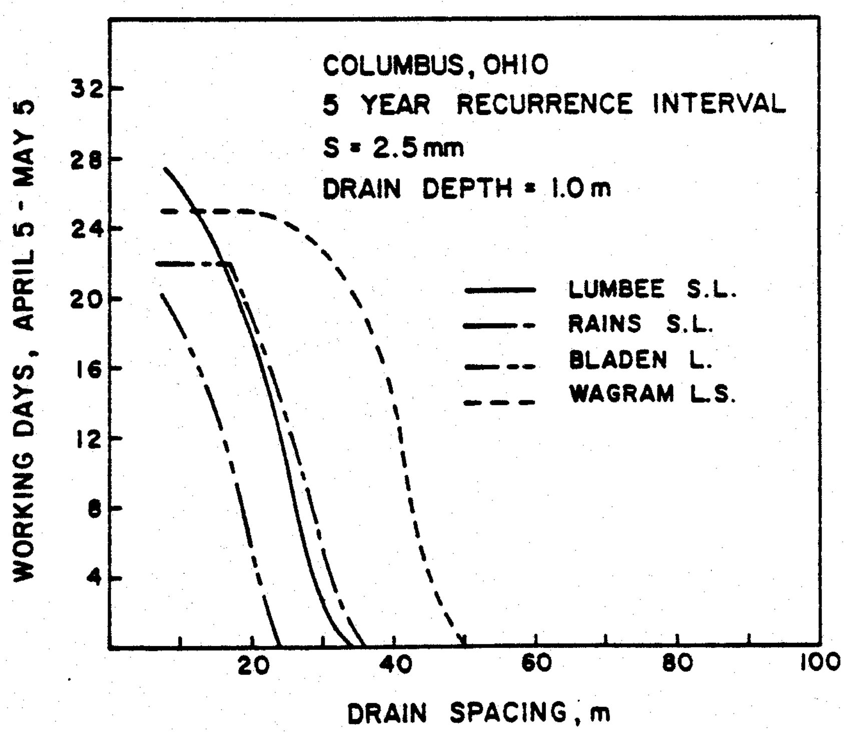

Figure 6-4. Working days versus drain spacing for all four soils at Columbus, Ohio.

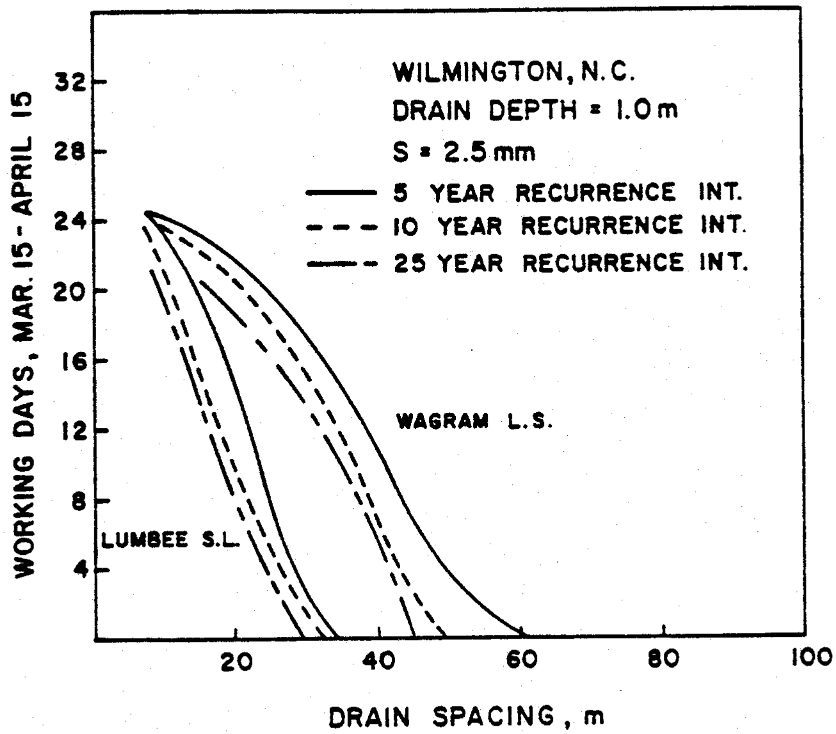

Figure 6-5. Working days versus drain spacing for recurrence intervals of 5, 10, and 25 years on Lumbee and Wagram soils at Wilmington, North Carolina.

least cost system could be selected. If a different number of working days or SEW-30 values are required, the appropriate combinations of surface and subsurface drainage can be selected from Figures 6-1 and 6-6.

The results for the Lumbee soil demonstrate the utility of using DRAINMOD to evaluate alternative designs of combination surface-subsurface drainage systems. The required number of working days and drainage protection for crop growth as indicated by SEW-30 values can be provided with a drain spacing of 12 m and poor surface drainage (s = 25 mm) or with a spacing of 23 m and good surface drainage (s = 2.5 mm). Both systems will do the required job so the farmer can choose the alternative that requires the least investment, although other factors such as maintenance costs and compatibility with the farming operation must also be considered. Another parameter that must be considered is drain depth (Figure 6-7). By placing the drains at a depth of 1.5 m rather than 1.0 m, the spacing could be increased from 23 m to 30 m for good surface drainage (s = 2.5 mm). This alternative would also be satisfactory from the trafficability aspect as it would result in 14 working days on a 5 YRI basis (Figure 6-2). Again, it is emphasized that the drain depth may be limited by other factors such as restrictive layers and the depth of the drainage outlet. Of course, possible increased costs of placing drains at a deeper depth must also be considered.

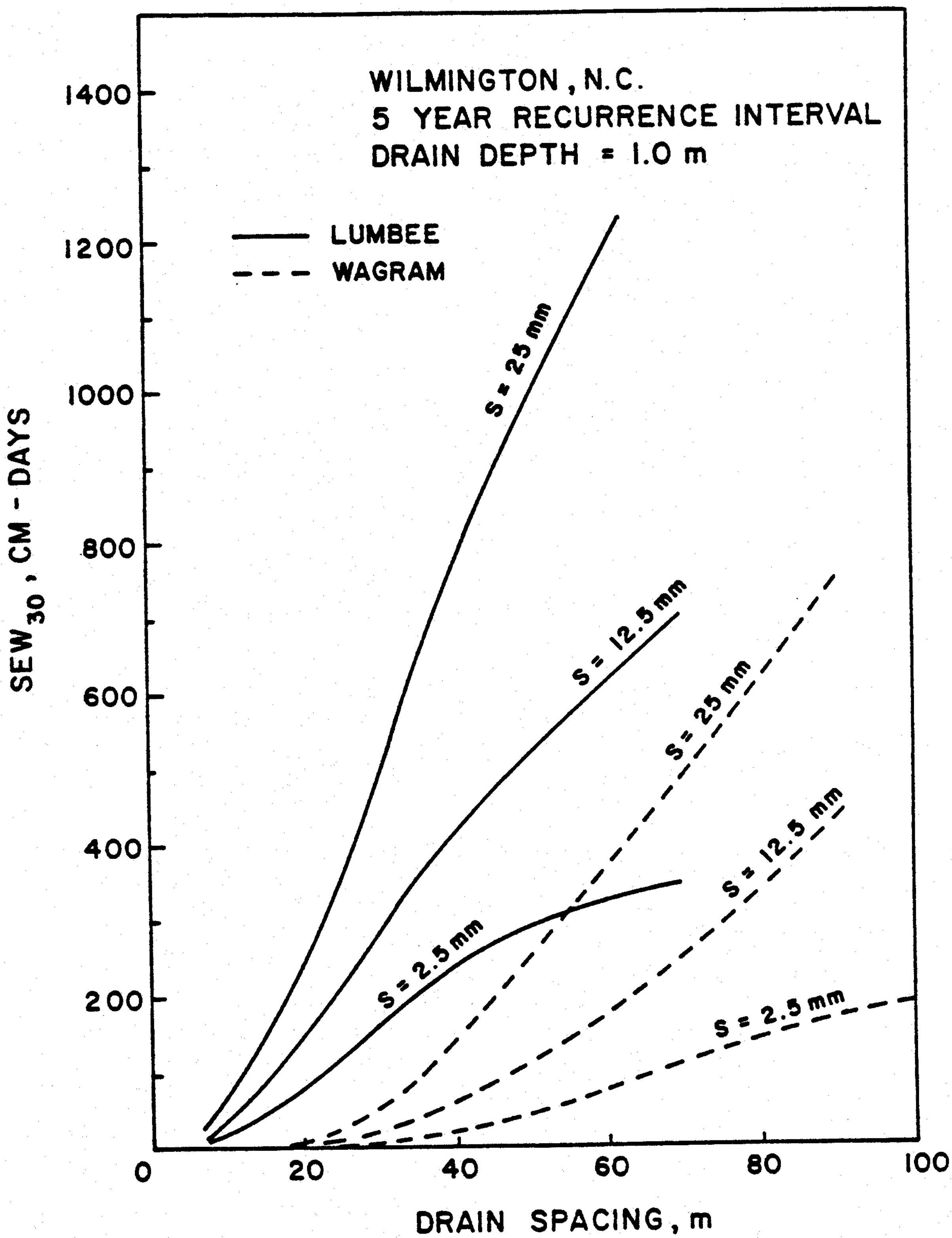

Figure 6-6. SEW-30 versus drain spacing for 3 levels of surface drainage on Lumbee and Wagram soils at Wilmington, North Carolina.

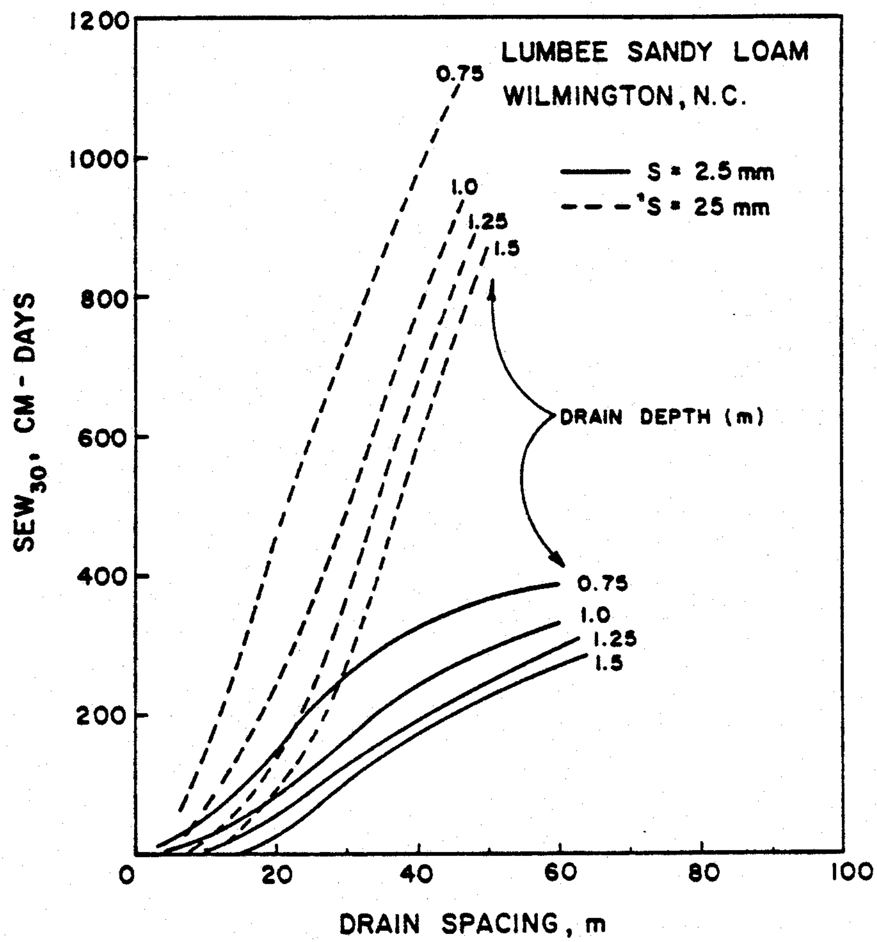

Figure 6-7. The effect of drain spacing and depth on SEW-30 values for a Lumbee soil at Wilmington, North Carolina. Relationships are given for both good (s = 2.5 mm) and poor (s = 25 mm) surface drainage.

Relationships between SEW-30 and drain spacing are plotted in Figure 6-8 for all four soils at Columbus, Ohio. Drain spacings required for a given SEW-30 value were somewhat greater at Columbus than at Wilmington or Jacksonville (Figure 6-9). This was true for all four soils and simply results from the fact that the precipitation is greater at Jacksonville and Wilmington than at Columbus. The average precipitation during the 4-month growing season was 440 mm at Jacksonville, 410 mm at Wilmington, and 370 mm at Columbus.

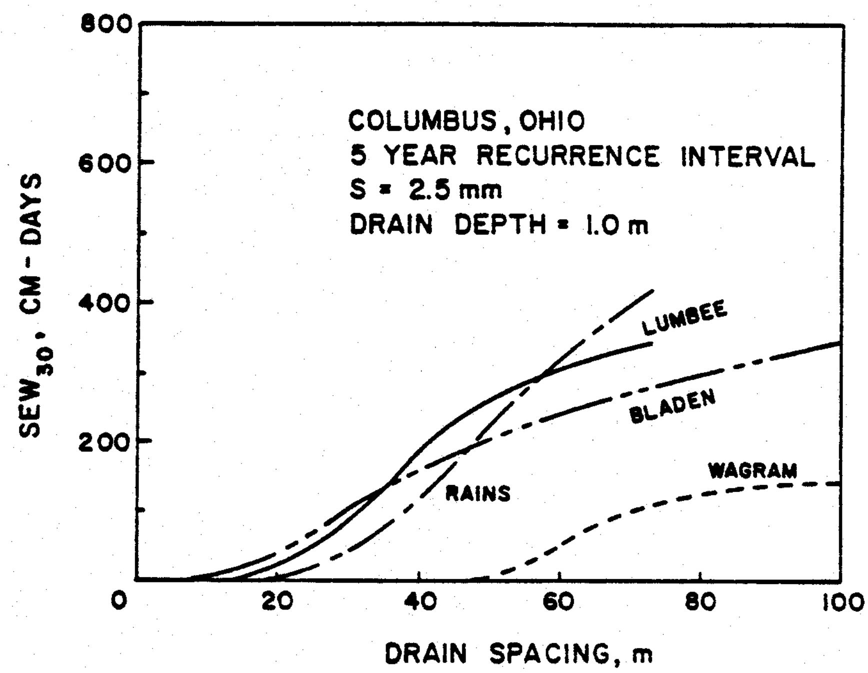

Figure 6-8. The effect of drain spacing on SEW-30 values for good surface drainage on four soils at Columbus, Ohio.

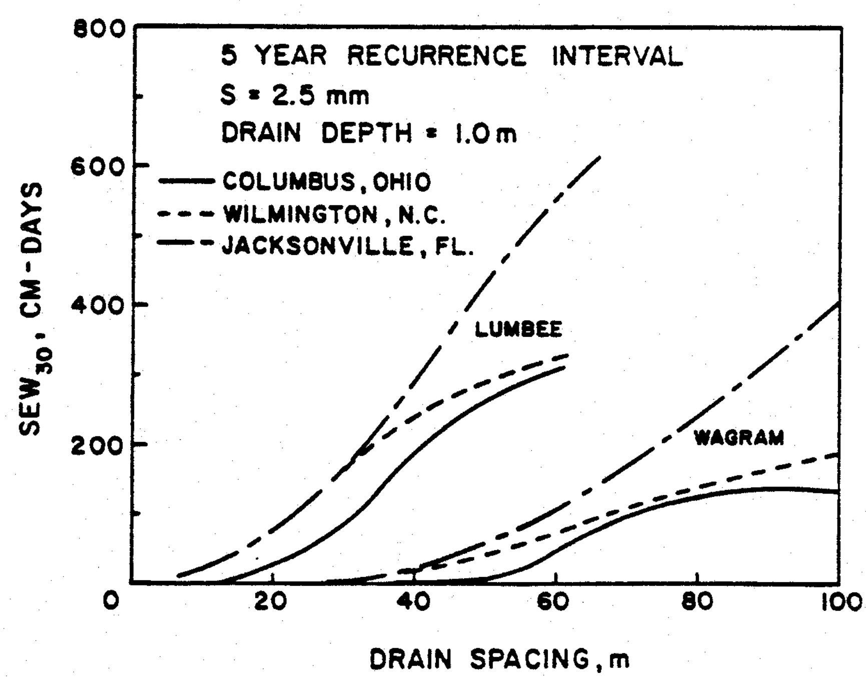

Figure 6-9. SEW-30 versus drain spacing for Lumbee and Wagram soils at all three locations.

Example Set 2 - Subirrigation and Controlled Drainage

The soils considered in Example 1 are relatively flat so water table control via subirrigation or controlled drainage should be considered. Outlet conditions for drainage, controlled drainage and subirrigation are shown schematically in Figure 6-10. When subirrigation is used, a weir is placed in the drainage outlet and water is pumped into the outlet as required to maintain a constant water level. For controlled drainage a weir

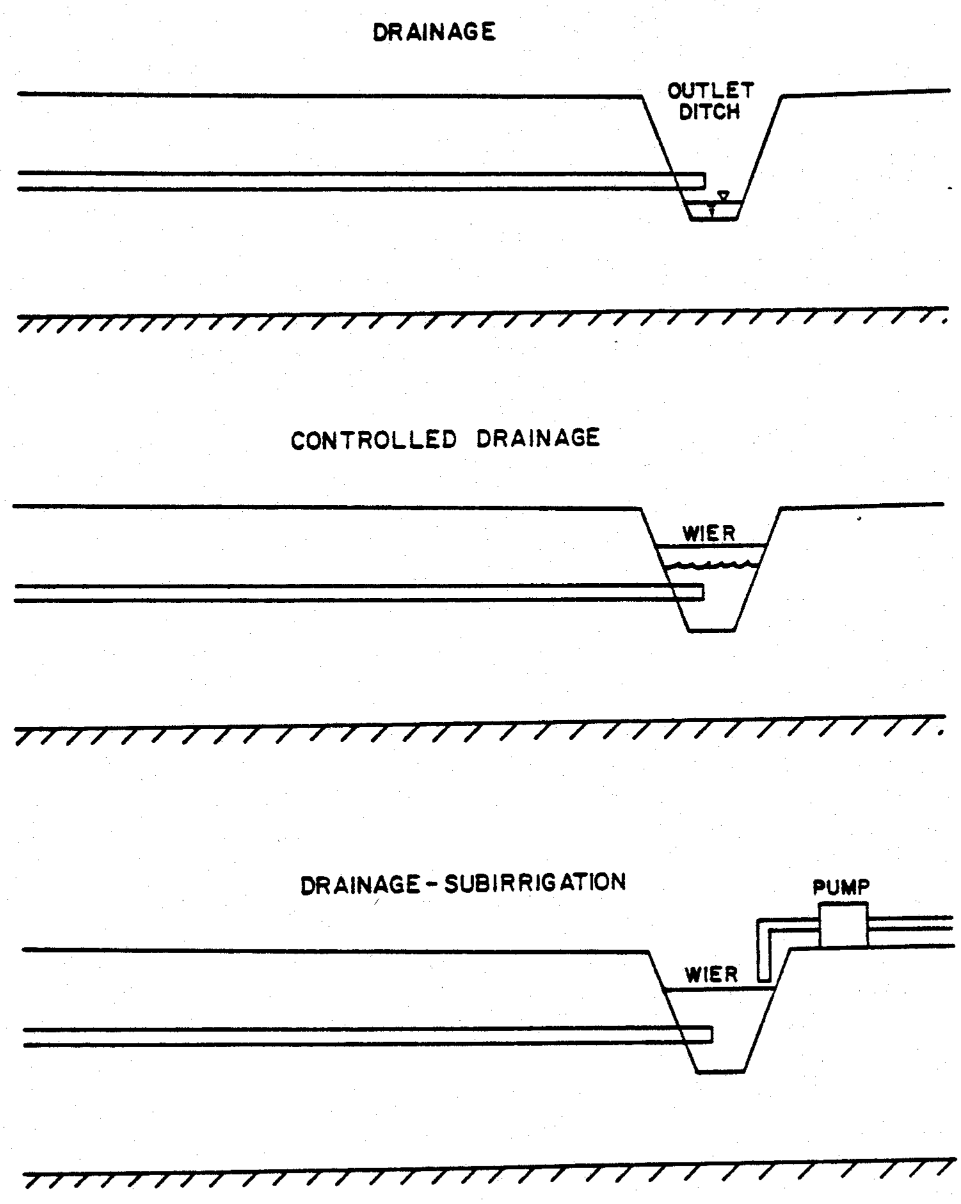

Figure 6-10. Schematic of three possible modes of operation for a subsurface drainage system.

is also placed in the drainage outlet, but no water is pumped in. This reduces the drainage rate and allows plant use of some runoff and drainage water that would be lost from the system under conventional drainage practices. In the analysis of controlled drainage systems, it is assumed that water in the outlet comes only from the field being drained and not an upstream source. Therefore, controlled drainage is not expected to provide assistance during dry years when drainage water is not available.

Simulations were conducted for subirrigation and controlled drainage on the Bladen and Wagram soils analyzed above for drainage and on a Portsmouth sandy loam. The input soil properties for Portsmouth are given in Tables 6-1 and 10-5 and Figures 5-4 and 5-6. Analyses were conducted for only the North Carolina site with the crop being continuous corn as discussed above. A drain depth of 1.0 m was used for all soils. Additional simulations were made for a drain depth of 1.5 m on the Portsmouth soil.

Results - Subirrigation and Controlled Drainage

The effect of drainage, controlled drainage, and subirrigation on the number of dry days during the growing season is shown in Figure 6-11 for the Wagram loamy sand. The relationship plotted for drainage shows clearly that drainage systems should not be over designed. For example, a drain spacing of 40 m would give, on the average, 35 or more dry days in one year out of five. Closer spacings, which are not required for trafficability (Figure 6-1) nor for crop protection (Figure 6-6) could increase the number of dry days and have detrimental effects on crop growth.* Recall that a dry day does not mean that there is no water available to growing plants, but that ET is limited by soil water conditions. The relationships plotted in Figure 6-11 were derived for good surface drainage (s = 0.25 cm). Surface drainage had little effect on the number of dry days and similar relationships were obtained for the other surface drainage treatments.

When subirrigation is used, water is pumped into the drainage outlet such that the water level is held constant at a depth of 60 cm below the soil surface during the growing season. The water table depth directly over the drain tubes during subirrigation will be approximately equal to that in the drainage outlet, but will increase with distance away from the drain during dry periods because of ET (Fox, et al, 1956). The 60 cm depth was chosen so that the water table would not be too close to the surface directly over the drain tubes. Williamson and Kirz (1970) reported that a 60 cm steady water table depth caused a 15 percent reduction in yield from the optimum depth of 76 cm for a loam soil. Yield reduction for the area directly over the drains is expected to be less for the lighter Wagram loamy sand. Results plotted in Figure 6-11 for subirrigation show that a drain

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* Note that it was assumed that the effective root depth depends on time alone, although it clearly is also dependent on soil water conditions during the growing season. Thus, good drainage, early in the season, may allow a better developed, deeper root system, which may counteract the over drainage effects shown in Figure 6-11.

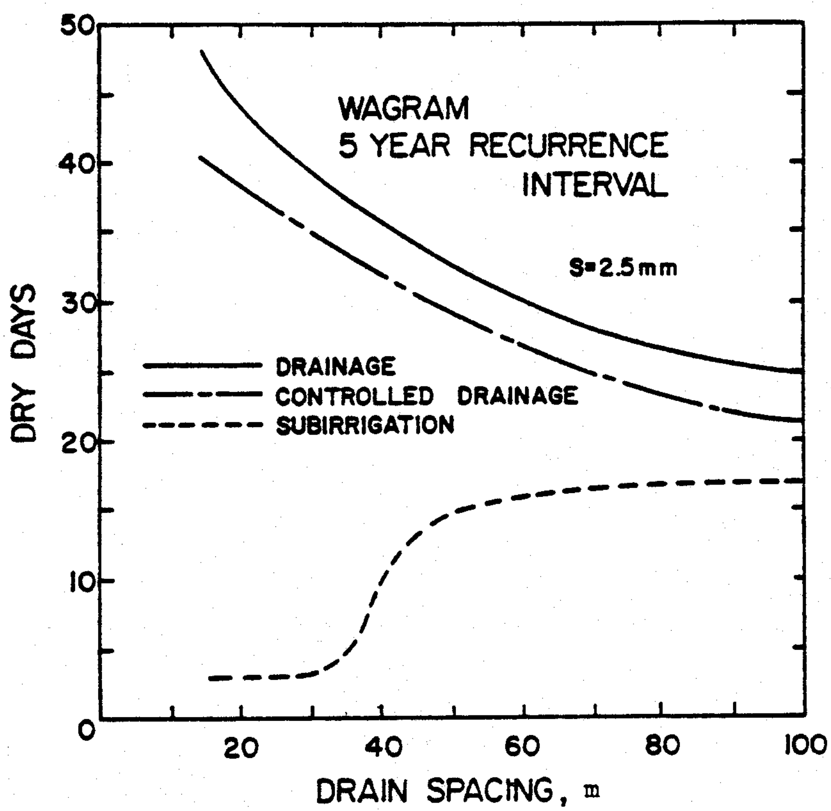

Figure 6-11. Dry days, during the growing season, as a function of drain spacing for three water management methods on Wagram soil.

spacing of 30 m or less will provide sufficient water table control to allow only 3 dry days on a 5 YRI basis. For spacings between 30 and 60 m, the number of dry days increases to 16. Further examination of the results of simulations show that, for L = 30 m, the three dry days occurred immediately after planting when rooting depths were negligible and subirrigation had just been initiated. Under these conditions, three dry days appeared to be acceptable and a drain spacing of 30 m sufficient for subirrigation on the loamy sand. These results are subject to the assumption that the water level is held constant in the drains at the 60 cm depth. This level may fall due to equipment failure or operator error. Therefore, the time required to raise the water table back to its steady state position may be critical and should be checked using the procedures given in Chapter 8.

One of the major concerns in using subirrigation in humid regions is that a high water table reduces storage available for infiltrating rainfall and may result in frequent conditions of excessive soil water. The effect of subirrigation on SEW-30 values is shown in Figure 6-12. These results show the importance of good surface drainage if subirrigation is to be used. A 30 m drain spacing gives a SEW-30 value of 210 cm days for poor surface drainage (s = 25 mm). Additional simulations showed that a SEW-30 value of less than 100 cm days can be obtained with only moderate surface drainage (s = 7.5 mm). When a 30 m spacing is used with good surface drainage (s = 2.5 mm), the 5 YRI SEW-30 value exceeded 100 cm days only once, in 20 years, and that value was only 114 cm days.

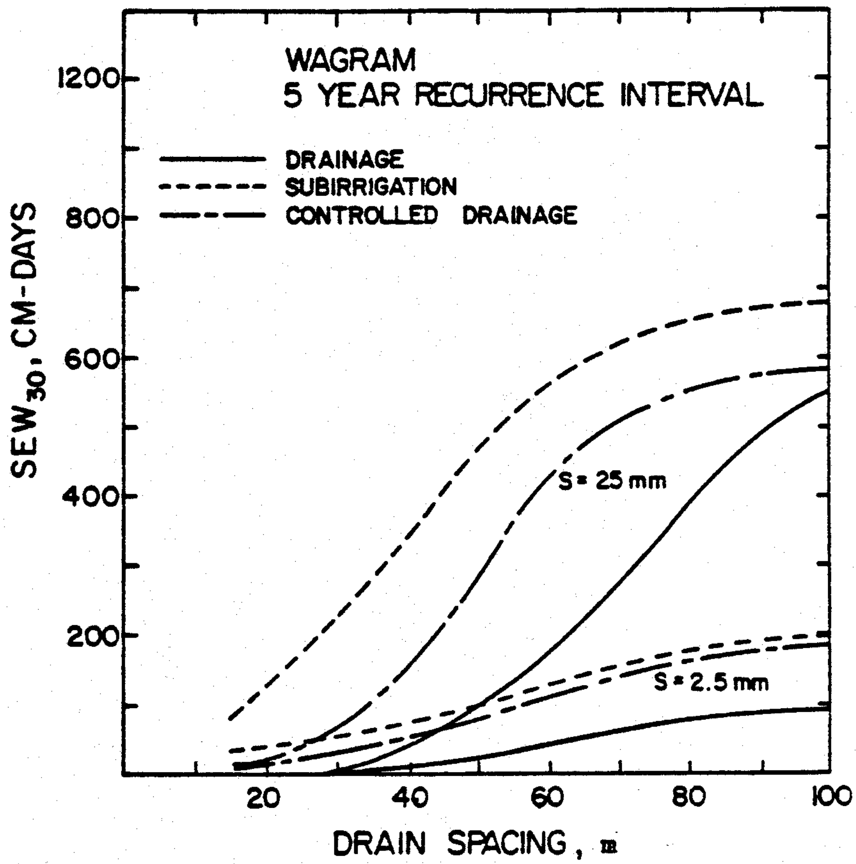

Figure 6-12. SEW-30, as a function of drain spacing for conventional drainage, subirrigation, and controlled drainage on Wagram soil. Results are plotted for two levels of surface drainage.

The results presented for Wagram loamy sand indicate that, if subirrigation is used, a drain spacing of 30 m with good surface drainage will satisfy both drainage and irrigation requirements. If subirrigation is not used, a drain spacing of 40 m will satisfy drainage requirements for both trafficability and plant growth, regardless of surface drainage. However, unless irrigation water is applied through other means, we can expect at least 35 dry days during the growing season on an average frequency of once every 5 years. The number of dry days can be reduced somewhat by using controlled drainage. Simulations were conducted for controlled drainage by assuming a weir is placed in the drainage outlet at a depth of 60 cm below the soil surface. From Figure 6-11, we see that this practice reduced the number of dry days on a 5 YRI basis by only 4, from 35 to 31. Obviously, this provides very little assistance for dry years and cannot replace an irrigation system. However, for wetter years, controlled drainage did provide some assistance. For example, a 40 m drain spacing gave fewer than 10 dry days in a growing season in 16 of 20 years of simulation when controlled drainage was used, versus only 7 of the 20 years when it was not used. When good surface drainage is provided, controlled drainage will not cause a problem with inadequate drainage during wet years, as shown in Figure 6-12.

The effect of the various water management alternatives on the number of dry days is plotted in Figure 6-13 for the Bladen soil. The relationships given in Figure 6-13 were obtained for good surface drainage, s = 2.5 mm, but the quality of surface drainage had little effect on the number of dry days. Subsurface drainage had only a small effect on number of dry days, as shown by the fact that the number of dry days decreased from 50 to only 40 when the drain spacing is increased from 7.5 to 60 m. The number of dry days during the growing season for drainage seems high, even on the basis of a 5 YRI. This may be due to assuming a root zone depth which is too shallow. Spot checks using a 75, rather than 60 percent curve in Figure 2-22 for the root zone depth, showed a reduction in the number of dry days for a 30 m spacing to about 30.

The relatively high number of dry days is consistent with the reputation that Bladen soils have for being droughty. This is caused by the low hydraulic conductivity which decreases rapidly with water content for unsaturated conditions so that the rate of upward water movement from wetter regions is slow (Figure 5-6). Thus, plants must obtain their water from a relatively shallow zone which extends only a small distance below the root zone. These soils have severe water shortages during dry years, as indicated by Figure 6-13 and it is not uncommon to experience large reductions in yield every three or four years, if irrigation is not used.

The relationship given for subirrigation if Figure 6-13 was obtained for a water level in the drainage outlet of 60 cm below the surface. In order to use subirrigation on this soil, the drains would have to be spaced about 5 m apart to provide (on a 5 YRI basis), less than 10 dry days during

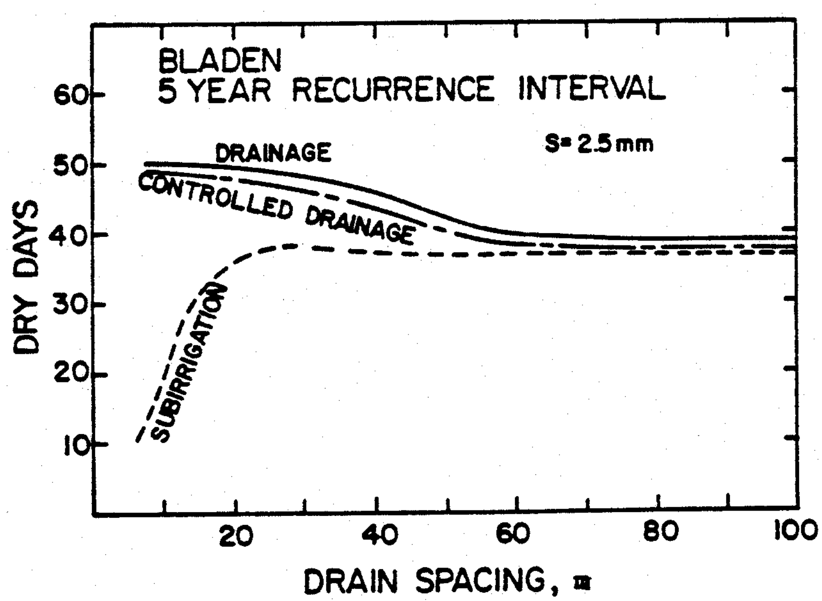

Figure 6-13. Dry days, during the growing season, for three water management methods on Bladen soil.

the growing season. Furthermore, it would be necessary to have good surface drainage in order to insure that the soil is adequately drained during wet periods (Figure 6-14). Such close drain spacings are not economically feasible and other methods of applying irrigation water should be used on this soil. For example, a drain spacing of 5 m rather than the 20 m necessary to meet trafficability (Figure 6-3) and crop requirements for conventional drainage would require 2,000 m/ha of tubing, as compared to 500 m/ha for conventional drainage. At an assumed cost of $2.50/m (installed), the tubing cost alone would be $5,000/ha ($2,000/ac) for subirrigation versus $1,250/ha ($500/ac) for conventional drainage. One possibility of increasing the drain spacing for subirrigation is to hold the water level in the drainage outlet closer to the surface. A water table depth at the drain of 40, rather than 60 cm was tried, but could not be used because of high SEW-30 values during wet years. In order to meet both subirrigation and drainage requirements, it was still necessary to have drain spacings of about 5-7 m.

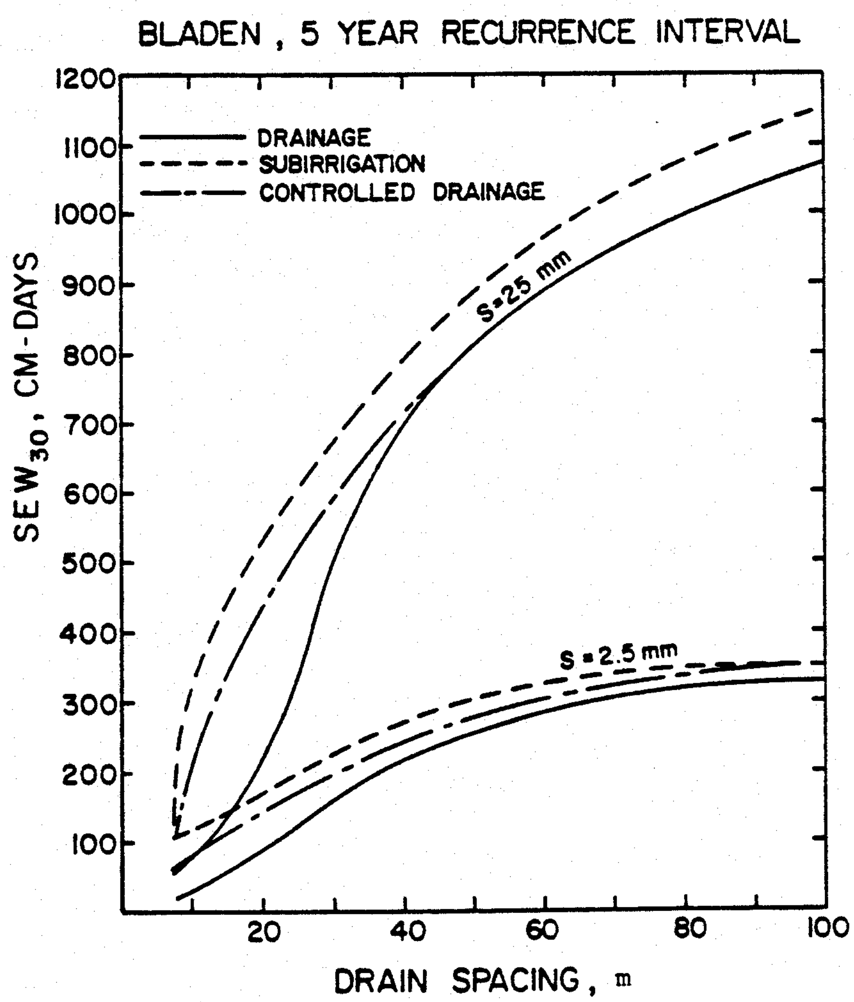

Figure 6-14. SEW-30, as a function of drain spacing for conventional drainage, subirrigation, and controlled drainage on Bladen soil. Results are plotted for two levels of surface drainage.

Controlled drainage is not attractive for this soil either. Use of controlled drainage reduced the number of dry days by only 2 on a 5 YRI basis (Figure 6-13). Thus, neither subirrigation nor controlled drainage appear feasible for the Bladen soil.

The above examples considered a soil (Wagram) with a relatively high K where subirrigation is feasible and a tight soil (Bladen) where subirrigation is impractical. A third soil, Portsmouth sandy loam with intermediate conductivity of K = 3 cm/hr, is analyzed in the following example. This same soil is also used in examples in Chapter 8 to demonstrate methods for predicting the time necessary to raise the water table at the beginning of the subirrigation process. The position of the water table during subirrigation with steady state ET conditions is also considered in Chapter 8.

A subirrigation system is to be designed for a Portsmouth sandy loam soil located near Wilson, North Carolina. Corn is to be grown on a continuous basis. The soil is flat, but good surface drainage can be provided by filling potholes in the field and smoothing the surface. Some of the soil properties and site parameters are given in Table 6-1. The soil water characteristic is given in Table 10-5 and the drainage volume and upward flux relationships in Figures 5-4 and 5-6, respectively. Example calculations in Chapter 8 showed that a steady ET rate of 0.5 cm/day could be supplied by either of the following combinations of drain spacing and drain water elevations:

1. L = 25 m with water level at drain = 30 cm deep

2. L = 17 m with water level at drain = 50 cm deep

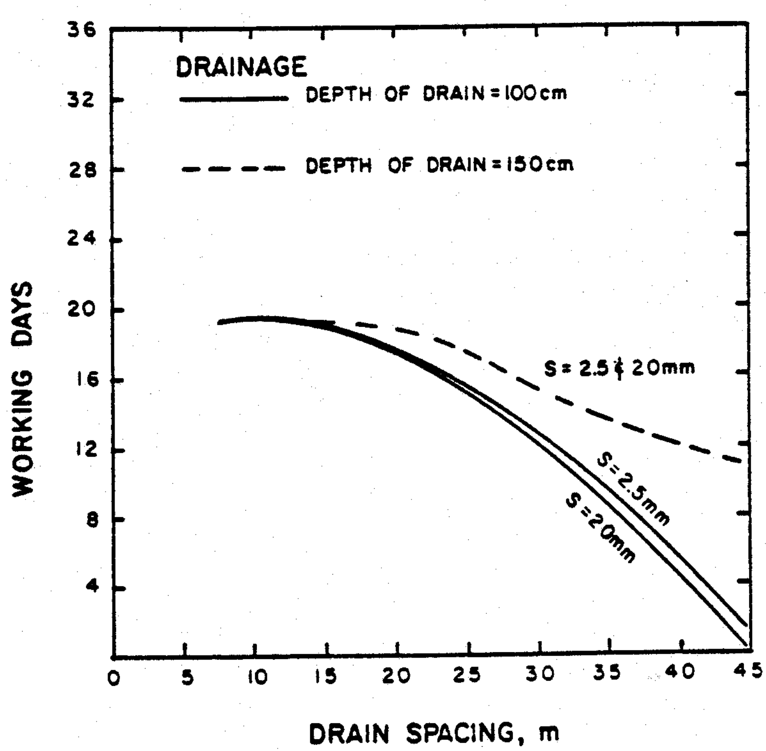

Figure 6-15. Working days on a Portsmouth s.l., as affected by drain spacing and depth and by surface drainage. Results are plotted for a 5 year recurrence interval.

Both combinations assumed a constant midpoint water table depth of 76 cm. With the 17 m drain spacing, the water table could be raised to a subirrigation position in 2.3 days (c.f. example in Chapter 8), but an excessive length of time (10 days) was required for the 25 m spacing. Therefore, a drain spacing of about 17 m is expected to do the job so far as meeting the irrigation requirement. DRAINMOD was used to determine if both irrigation and drainage requirements can be met by this on other alternative system designs.

Simulations were conducted for two drain depths (100 and 150 cm) at drain spacings of 7.5, 15, 22.5, 30, and 45 m. After planting (about April 15), the water level was raised in the drain to within 30 cm of the surface where it was held for the growing season. Simulations were also conducted for the drain water level 50 cm from the surface during the growing season.

Working days during the month prior to planting (March 15 to April 15), are plotted versus drain spacing in Figure 6-15. These relationships would be the same whether the system is used for subirrigation or for conventional drainage. Based on these results, 10 working days could be provided on a 5 YRI with a drain spacing of 32 m for a depth of 100 cm or a spacing of 45 m for a 150 cm drain depth. As in previous examples, surface drainage had a small effect on working days. SEW-30 for drainage without subirrigation is plotted in Figure 6-16. These results show that a threshold value of 100 cm days on a 5 YRI basis can be maintained with a spacing of about 35 m if the surface drainage is good (s = 2.5 mm). For poor surface drainage (s = 20 mm) drain spacings of 17 and 22 m would be required for depths of 100 and 150 cm, respectively.

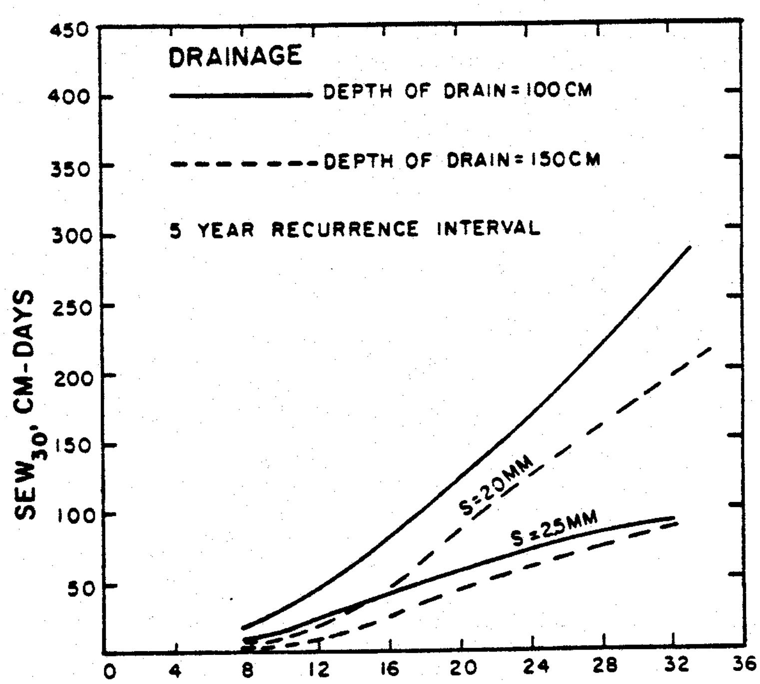

Figure 6-16. SEW-30, as a function of drain spacing for two surface drainage treatments and two drain depths on Portsmouth s.l. The system is used for conventional drainage without subirrigation, in this case.

The number of dry days on a 5 YRI basis are plotted in Figure 6-17. For conventional drainage, about 40 to 50 dry days can be expected in one year out of five. When subirrigation is used, the number of dry days depends on the drain spacing and the depth that water is held in the drains (weir depth). For a drain spacing of 15 m, about 4 dry days (5 YRI) would result for a weir depth of 30 cm and 10 dry days for a weir depth of 50 cm. However, a 30 cm weir depth and L = 15 m would result in SEW-30 values in excess of 300 (5 YRI) during the growing season (Figure 6-18). A 50 cm weir depth would have 5 YRI SEW-30 values of about 140 cm days for good surface drainage. There is no advantage in placing the drains at a depth of 150, rather than 100 cm, if subirrigation is used. At a spacing of 15 m, the 100 cm drain depth is sufficient to provide trafficable conditions for seedbed preparation (Figure 6-15), as well as protection for crop growth (Figures 6-16 and 6-18). Close inspection of the simulation for subirrigation with L = 15 m showed that most of the 10 dry days occurred during start-up immediately after planting, as observed earlier for the Wagram soil. This number can be reduced to 4 or 5 days by raising the weir to within 30 cm of the surface during start-up and then lowering to a 50 cm depth for the remainder of the growing season.

A summary of results for the Portsmouth soil shows that drainage and irrigation requirements could be provided with the alternatives given in Table 6-4. It is interesting that the factor limiting the drain spacing for a combination drainage-subirrigation system on this soil is the drainage requirement. For example, the irrigation requirement could be satisfied with a drain spacing of 25 m and a weir depth of 30 cm (Figure 6-17). However, this would give an unacceptable SEW-30 value of 450 cm days (Figure 6-18).

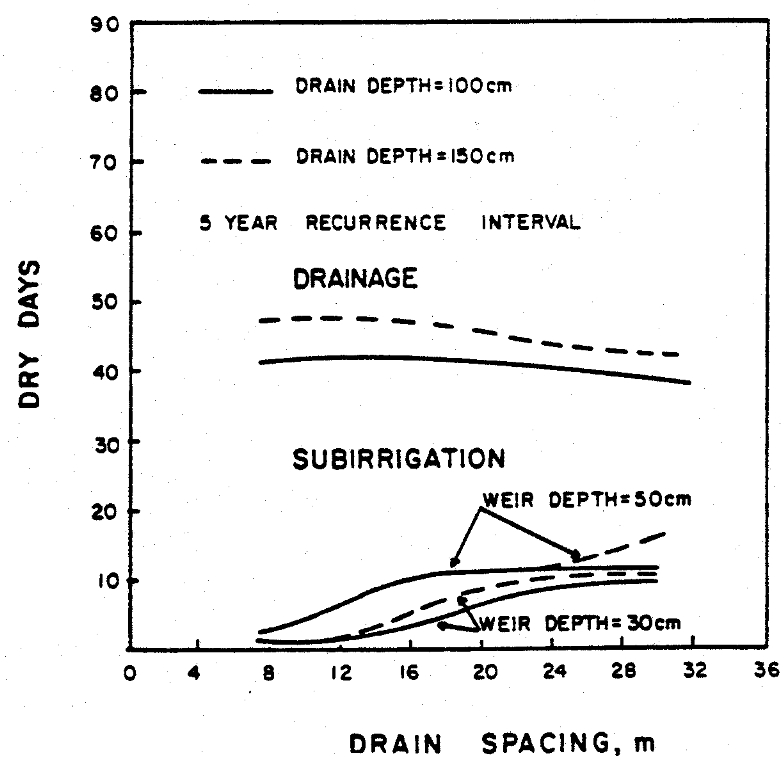

Figure 6-17. Dry days, as affected by drain spacing for conventional drainage and for subirrigation with weir depths during the growing season of 30 and 50 cm. Drain depths of both 100 and 150 cm are considered.

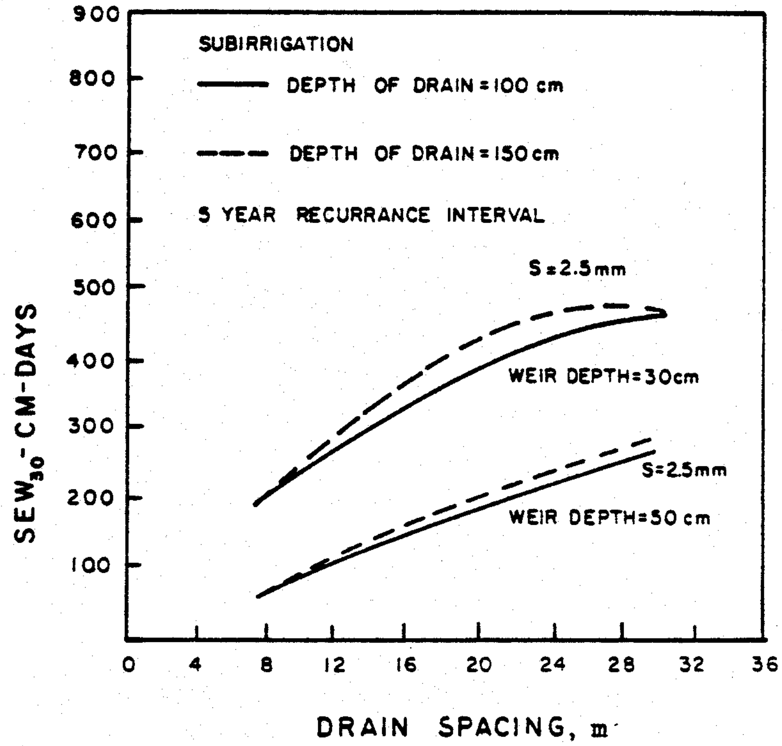

Figure 6-18. Effect of drain spacing on SEW-30 during the growing season for subirrigation with weir depths of 30 and 50 cm.

Table 6-4. Drain spacings required to meet drainage* and irrigation** requirements for a Portsmouth sandy loam near Wilson, North Carolina.

Drain Depth	Surface Drainage Good (s = 2.5 mm)	Surface Drainage Poor (s = 20 mm)
	DRAINAGE ALONE	
100 cm	34 m	17 m
150 cm	36 m	21 m
Weir Depth	DRAINAGE AND SUBIRRIGATION	
30 cm	05 m	05 m
50 cm	15 m	7 m

* The drainage requirement is assumed to be at least 10 working days during the month prior to planting and SEW-30 values less than 100 cm days.

** The irrigation requirement is assumed to be 10 or fewer dry days during the growing season.

Example Set 3 - Waste Water Application on Drained Lands

Land application of agricultural, municipal, processing, or industrial waste water, with appropriate pretreatment, is an economically and technically feasible alternative to conventional waste disposal methods for many situations. A major step in designing a land application system is determining the permissible loading rate for a given site. In some cases, the loading rate is limited by the pollutants in the waste water. In others, the application rate is limited hydraulically by drainage conditions of the site. In the latter cases, it may be feasible to provide subsurface drainage to increase the amount of waste water that can be applied to a given site and reduce the land area required. Since the costs of land and irrigation systems to apply waste water are relatively high, increasing the application rate by the use of artificial drainage could significantly lower the costs of a land disposal system.

In this example, we consider waste water application to the Wagram loamy sand discussed in example sets 1 and 2 above. The hypothetical site is located near Wilson, North Carolina. Fescue is grown year around and waste water from a processing plant pretreatment lagoon is to be applied (sprinkler irrigation) onto the surface. Consideration of the nutrient levels in the water limit the application rate to 25 mm/week in this example. The water may be applied at any irrigation frequency, but the average must not exceed 25 mm/week. Higher loading rates of 50 mm/week and 100 mm/week will be considered in another example. As discussed in example set 1, the soil surface is flat and a restrictive layer exists at a depth of 1.8 m so that drainage under natural conditions is slow. Outlet conditions limit the depth of the drain tube to 1.25 m, which is considered deep enough to prevent short-circuiting of the waste water directly into the drain.

The objective in this example is to determine the effect of surface and subsurface drainage on the amount of water that can be applied without causing surface runoff. The effect of application frequency (e.g. one irrigation per week of 25 mm versus one application of 50 mm every 2 weeks), on the total permissible annual application will also be considered. Simulations were conducted for good surface drainage, s = 2.5 mm, poor surface drainage, s = 25 mm, and very poor surface drainage, s = 150 mm. The very poor surface drainage was considered because it may be desirable in some cases to construct dikes or otherwise artificially shape the surface to prevent runoff during high rainfall intensities. This would prevent pollutants deposited on the surface, grass cover, etc., from washing off the site with runoff water. Simulations were conducted for five drain spacings and for 3 application strategies as follows: (1) 10.5 mm every 3 days; (2) 25 mm every 7 days; (3) 50 mm every 14 days. All 3 strategies would give an average application rate of 25 mm/week. As discussed in Chapter 3, waste water application is simulated by DRAINMOD on the application interval, INTDAY, if the drained volume (air volume) in the profile is greater than a given amount, REQDAR, and if rainfall occurring on the scheduled day is less than AMTRN. Parameter values used to determine whether an application will be skipped or postponed are listed in Table 6-5 for the cases considered in this example. In all cases, the required drained volume, REQDAR, was 10 mm greater than the amount of water to be irrigated.

Table 6-5. Application parameter values used in Example 3.

Application interval, INTDAY	3 days	7 days	14 days
Irrigation amount	10.5 mm	25 mm	50 mm
Time irrigation starts	1000	1000	1000
Time irrigation ends	1200	1200	1200
Drained (air) volume required in the profile, REQDAR	20.5 mm	35 mm	60 mm
Amount of rain to postpone irrigation, AMTRN	10 mm	10 mm	10 mm

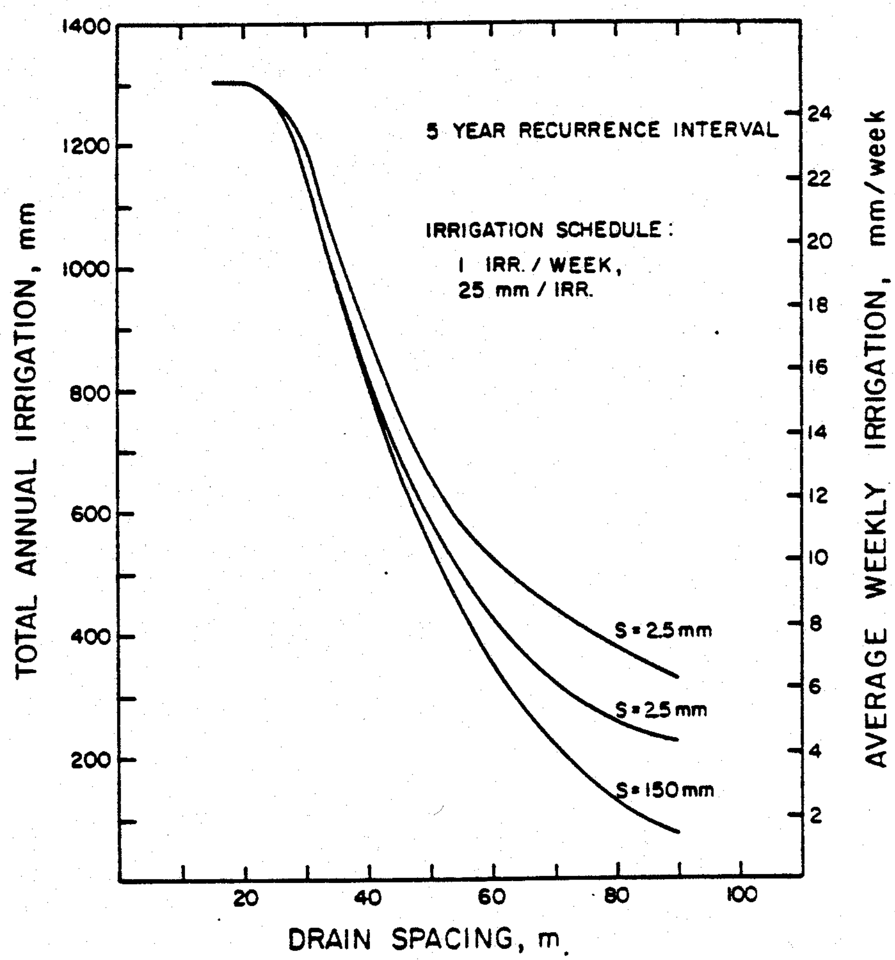

Figure 6-19. Effects of drain spacing and surface storage on amount of waste water treated annually for irrigation scheduled once per week, 25 mm per application.

All simulations were conducted a 25-year period and the results analyzed to determine the total annual irrigation on a 5-year recurrence interval basis. The results are plotted in Figure 6-19 for the 7-day application frequency and all three surface drainage treatments. The results show that, for drain spacings of 25 m or less, water could be applied at every scheduled application for a total of 1300 mm (52 weeks x 25 mm/week) on a 5 YRI basis. In some weeks, waste water application may have to be postponed for one or more days due to rainfall, but the scheduled amount could be applied in all cases. For larger drain spacings, many of the scheduled irrigations could not be applied because there was insufficient water-free (drained) volume in the profile. When this happened, application was canceled for that period and conditions were checked on the next scheduled day. For example, only 770 mm could be applied (5 YRI basis) for a drain spacing of 45 m and good surface drainage. Closer inspection of the simulation results showed that most of the cancellations due to wet conditions occurred in the winter and early spring when ET is low. The results plotted in Figure 6-19 show that the amount of water that can be applied is more dependent on subsurface drainage, as indicated by the drain spacing, than on surface drainage. However, when subsurface drainage is poor (large drain spacings), the amount of waste water that can be treated is heavily dependent on surface drainage. When surface drainage is poor, water may be stored on the surface after periods of high rainfall and can be removed only by evaporation or subsurface drainage. Time required for removal of this surface water may cause the next scheduled waste water application to be canceled due to wet soil conditions.

The effect of the application interval on annual amount applied is shown in Figure 6-20. Recall that the intervals and amounts to be applied were selected so that the average application rate was 25 mm/week for all three combinations simulated. This is obvious for good subsurface drainage where 1300 cm could be treated for all three irrigation frequencies. For slower subsurface drainage (i.e., drain spacings greater than 25 m), the results in Figure 6-20 indicate that more water can be treated by applying smaller amounts on a more frequent basis. For example, if drains are spaced 45 m apart, 950 mm of water could be treated (on a 5 YRI basis) by applying 10.6 mm every 3 days, while only 650 mm could be treated by scheduling 50 mm every 14 days. The reason for the difference is that, due to random occurrence of rainfall, it is more difficult to get the required water free (drained) volume for larger, less frequent irrigations. For the 14-day application interval, a water-free pore volume of 60 mm was required in order to apply waste water at the scheduled time. This volume may be available on the 12th day, but rainfall on the 13th day could cause conditions to be too wet for application at the scheduled time on day 14. For the 3-day interval, on the other hand, the same rainfall conditions would cause cancellation of only one or perhaps none of the 4 scheduled smaller waste water applications during the same period.

The results discussed above assumed that a given amount of waste water is applied at a schedule time providing that soil water and rainfall conditions are not limiting. For a given drainage system, soil water conditions are more likely to be limiting in the winter and early spring because of lower ET rates, as mentioned above. However, it may also be

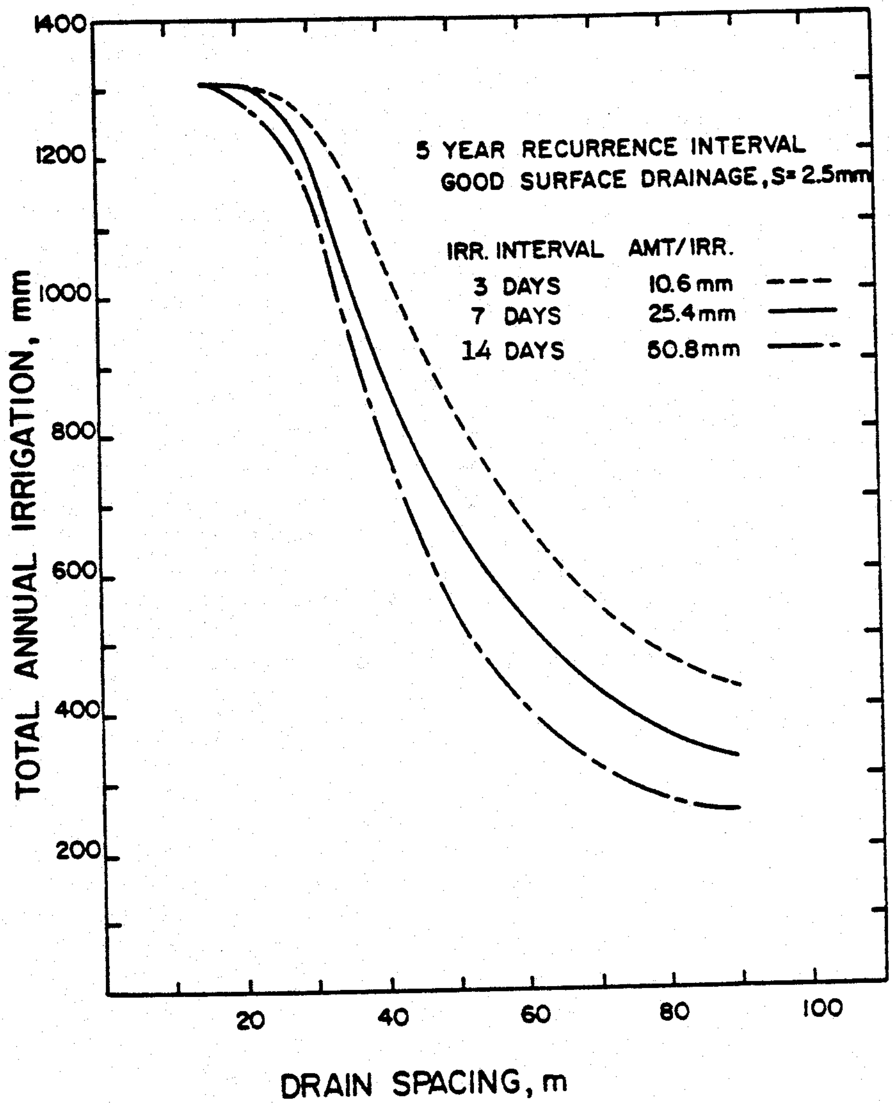

Figure 6-20. Effect of drain spacing and application frequency on total annual waste water treated for a Wagram loamy sand.

possible to increase the amount applied during the late spring and summer months because of the relatively high ET rates during this season. Thus, it would be possible to increase the annual application over that shown in Figures 6-19 and 6-20 by storing the water in a reservoir during periods when irrigation is not possible and increasing the application rate during the summer. In this case, it is important to determine the amount of storage that would be required for a given drainage system and application strategy. Storage required for the alternative systems considered here is shown in Figure 6-21 for drain spacings up to 45 m. The values given represent the storage required (5 YRI basis) to permit land treatment of an

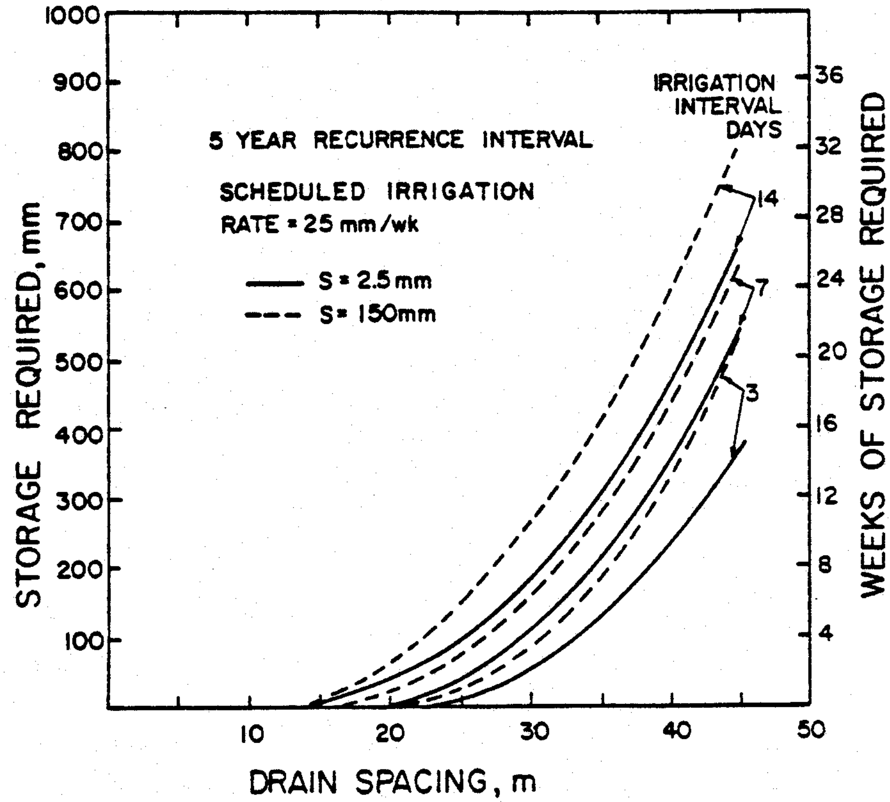

Figure 6-21. Effect of drain spacing, surface drainage, and application frequency on storage volume required for application of an average of 25 mm/week on a Wagram loamy sand.

average of 25 mm per week for 52 weeks per year. For example, a drain spacing of 45 m, with good surface drainage, would require storage capacity for 350 mm of waste water. This amounts to 13 weeks of irrigation at 25 mm per week.

The results of this example show that DRAINMOD can be used to determine the amount of waste water than can be applied to drained soils. The storage volume required because application is not possible during wet periods can also be assessed. Since simulations are made with actual weather data, designs can be made on a probabilistic basis. By considering alternative systems, DRAINMOD can be used to select the most economical system that will meet the design requirements for a given situation.

In many cases, concentrations of potential pollutants in waste waters are very low and the amount of water than can be applied to a disposal site depends on hydraulic limitations only. The following hypothetical example considers the effect of drainage system design and loading rates on the total amount of water than can be applied to the same Wagram soil discussed above.

A processing plant needs to treat above 11,000 m^3 (3,000,000 gallons) of waste water per week during the 8-month period from March 15 to November 15. The waste has a low concentration of pollutants and could be applied to the soil at rates up to 10 cm/week as far as the pollutant load is concerned. What size land disposal site will be required and how is the size dependent on the drainage system design?

The size of the land area required will obviously depend on the loading rate. If 2.5 cm of water can be applied every week, an area of 44 ha (110 acres) will be required. For loading rates of 5 and 10 cm/week, areas of 22 ha (55 acres) and 11 ha (27 acres) would be needed respectively. However, land application of the waste water would be limited during some weeks because of natural rainfall. Application may also be frequently restricted by wet soil conditions if the soil is not adequately drained. Simulations were conducted for planned loading rates of 2.5, 5, and 10 cm/week. A 3-day application interval was used in all cases with the amount

Table 6-6. Irrigation parameter values for three different loading rates on Wagram l.s.

Loading rate*			2.5 cm/week	5.0 cm/week	10.0 cm/week
Application interval (INTDAY)			3 days	3 days	3 days
Irrigation amount* (per application)			1.07 cm	2.14 cm	4.28 cm
Time irrigation starts (IHRST)			10	10	10
Time irrigation ends (IHREND)			12	12	12
Intervals when no irrigation is applied:					
	Interval 1	NOIRR1	1 (Jan 1)	1	1
		NOIRR2	74 (Mar 15)	74	74
	Interval 2	NOIRR3	314 (Nov 15)	314	314
		NOIRR4	365 (Dec 31)	366	366
Drained (air) volume required in profile, REQDAR			2.07 cm	3.14 cm	5.28 cm
Amount rain to postpone irrigation, AMTRN			1 cm	1 cm	1 cm
Irrigation rate**			0.53 cm/hr	1.07 cm/hr	2.14 cm/hr

* Not a direct input to this model.

** Constant for all months in which waste water is to be applied.

of water at each application adjusted to give the required weekly loading. The irrigation parameter values used in this example are given in Table 6-6. As in the previous example, subsurface drainage is provided by 4-inch drains placed at a depth of 1.25 m in the Wagram soil. Also, the required drainage volume was set at 10 mm greater than the amount of waste water to be applied. However, in this example, it is assumed that good surface drainage (s = 2.5 mm) will be provided for all cases. A good stand of fescue, with an effective rooting depth of 30 cm, will be grown on the site.

All simulations were run for a 25-year period and the results analyzed to determine the annual waste water applied on a 5 YRI basis. The results are plotted in Figure 6-21 for all three loading rates. In this case, the 5 YRI means that the total waste water application, taken from Figure 6-22 could be applied four years out of five on the average.

Results given in Figure 6-22 show that, for narrow drain spacings, the amount of waste water than can be applied during the 8-month season is directly dependent on the planned loading rate. For example, a 15 m drain spacing would permit an irrigation total of 85 cm, 170 cm, and 325 cm for planned loading rates of 2.5, 5, and 10 cm/week, respectively. For wider drain spacings, the drainage rate limits the application of irrigation water and there is much less difference in the amount of water that can be applied at the different loading rates. At a 30 m drain spacing, both 5 and 10 cm/week loading rates will apply a total of 140 cm of water while the 2.5 cm/week rate will still result in a total application of 85 cm. Clearly, the drainage system should be designed to fit the loading rate desired. For example, if the loading rate is restricted to 2.5 cm/week, the total amount of water applied cannot be increased by placing the drains closer together than 30 m. Likewise, a 10 m spacing would allow the maximum amount of irrigation to be applied if a 10 cm/week loading rate is used.

The relationship plotted in Figure 6-22 can be used to determine the optimum drain spacing and size of the land disposal site for a given application rate. Assuming a land cost of \$3,000/ha (\$1,200/ac), irrigation system (pipe, sprinkler, installation, etc.) costs of \$2,000/ha (\$800/ac) and drainage system costs (installed) of \$2.50/m (\$0.78/ft), the initial cost of a land disposal system can be calculated, as follows, for a planned application rate of 5. cm/week.

An average waste load of 11,000 m^3/week gives a total of 477,400 m^3 to be applied over the 8-month period. For an application rate of 5 cm/wk and a 10 m drain spacing, 170 cm of water can be applied (Figure 6-21). Then, the area required is:

$$\text{Area} = \frac{377{,}300\ m^3}{1.7\ m} \times \frac{1\ ha}{10{,}000\ m^2} = 22.2\ ha$$

The total drain length = 22.2 ha x 10,000 m^2/ha/10 m = 22,200 m. Then, the total land cost is 22.2 ha x \$3,000/ha = \$66,600; the irrigation system cost is 22.2 ha x 2,000/ha = \$44,400 and the drain cost is 22,200 m x 2.50/m = \$55,500. Initial costs for land, irrigation, and drainage systems are tabulated in Table 6-7 for drain spacings of 10, 20, and 30 m.

Table 6-7. Initial costs for a land disposal system with subsurface drainage to treat 11,000 m^3 (3,000,000 gallons) per week. These calculations are based on a planned application rate of 5 cm/week.

Drain spacing	10 m	20 m	30 m
Total seasonal loading (Figure 6-21)	170 cm	167 cm	144 cm
Land area required	22.2 ha	22.6 ha	26.2 ha
Total drain length	22,200 m	11,300 m	8,700 m
Land cost*	$66,600	$67,800	$78,600
Irrigation system cost**	$44,400	$45,200	$52,400
Drain cost	$55,500	$28,200	$21,800
Total cost	$166,500	$141,200	$152,800

* Land cost calculated at $3,000/ha ($1,200/ac)

** Irrigation system costs assumed to be $2,000/ha ($800/ac)

*** Drainage cost (installed) calculated at $2.50/m ($0.78/ft)

The initial cost of land, irrigation, and drainage system considered above are plotted in Figure 6-23 for all three loading rates. These results show that the minimum cost will be obtained by using the loading rate of 10 cm/week and a drain spacing of 15 m. If the loading rates are restricted, due to pollutant concentration or for other reasons to 5 or 2.5 cm/week, initial costs can be minimized by using drain spacings of 23 m and 30 m, respectively. Pumping, maintenance, and other operational costs have not been considered and the analysis is therefore incomplete. However, this example demonstrates the use of the model in optimizing the design of an under-drained land disposal system.

<u>Example Set 4 - Effect of Root Depth on the Number and Frequency of Dry Days</u>

Root depths are limited in many North Carolina soils due to the physical barriers caused by hard pans or layering and by chemical barriers, such as a low pH below a given depth. In other cases, root depths are limited by high water table conditions which frequently prune back deeper roots. Some varieties of a given crop have more shallow rooting depths than others. Thus, increasing the rooting depth for a given crop may be a matter of variety selection, providing good drainage, or removing physical and chemical barriers to root growth. Because increasing the rooting depth

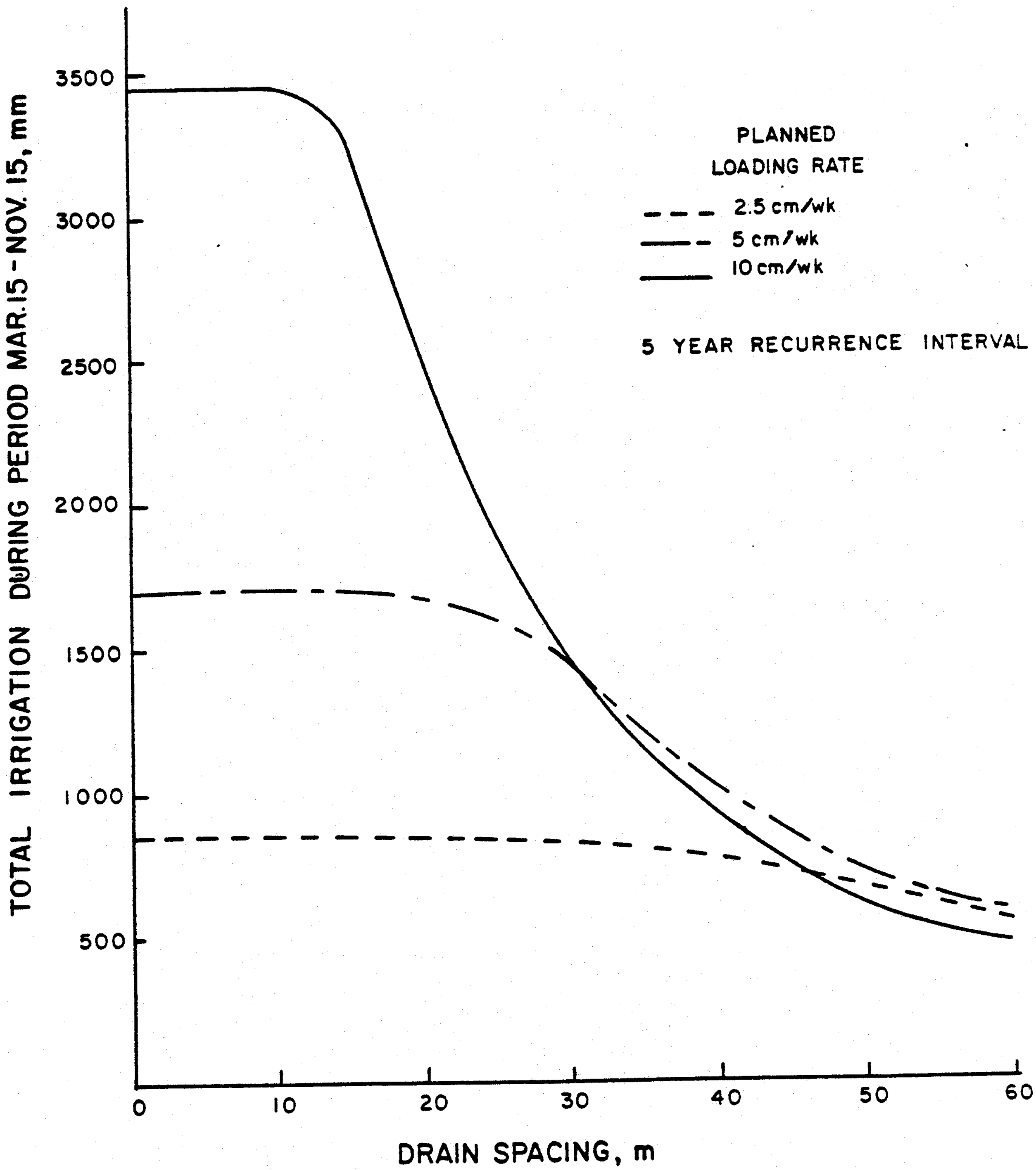

Figure 6-22. Effect of drain spacing and planned loading rate on total volume of water that can be treated on a Wagram l.s. soil near Wilson, North Carolina.

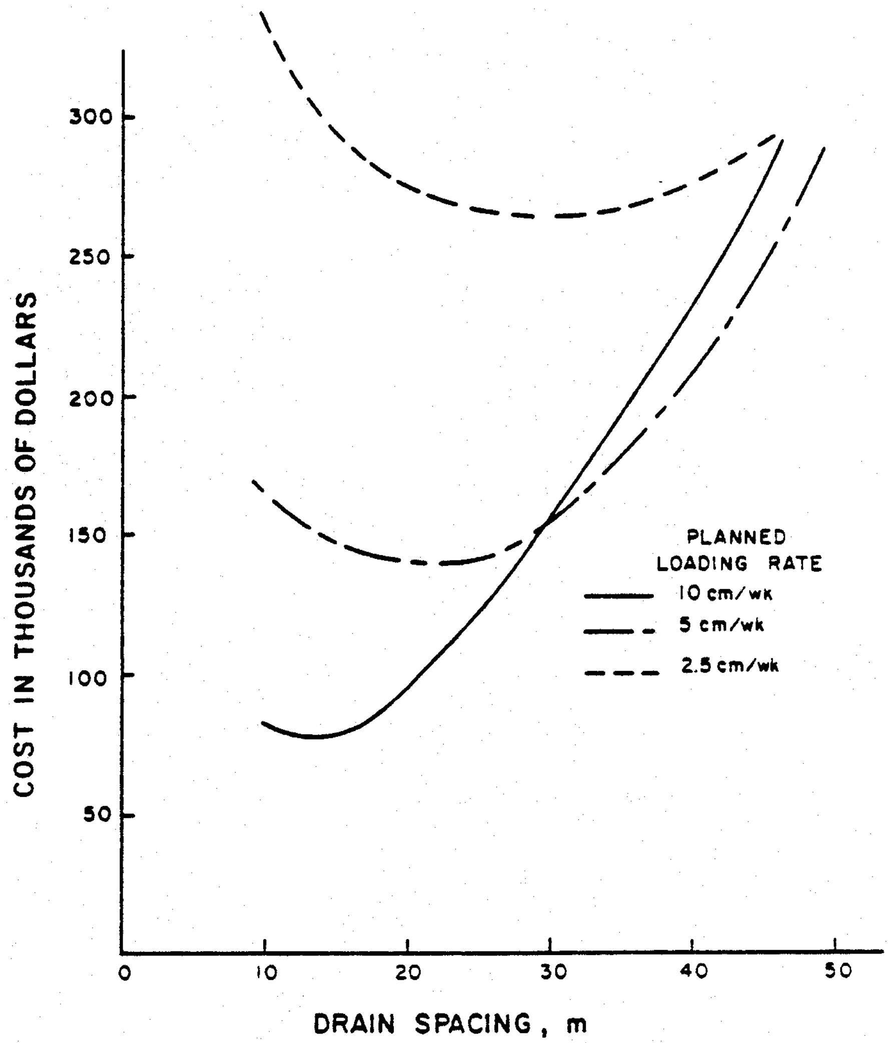

Figure 6-23. Initial costs (sum of land, irrigation equipment, and subsurface drainage costs) versus drain spacing for three loading rates.

directly increases the water available for plant use, there has been much interest in removing barriers to root growth and in developing plant varieties with deeper rooting systems. The purpose of this example is to examine the effect of root depth on the number of days that the plant is under stress due to dry conditions. A day when plants are under stress due to dry conditions is assumed here to be a dry day and is defined in Chapter 3 as a day in which ET is limited by soil water conditions.

The soils, Bladen loam and Wagram loamy sand, and drainage systems considered here were used in previous examples (Example Sets 1 and 2). The drainage system for the Bladen soil is composed of parallel drains buried 1 m deep and placed 20 m apart with good surface drainage (s = 2.5 mm). For the Wagram soil, the drain spacing is 43 m with poor surface drainage (s = 25 mm). Conventional drainage is assumed without controlled drainage or subirrigation. Simulations were conducted for 20 years of climatological data for Greenville, North Carolina. It was assumed that corn was to be grown on a continuous basis and the maximum effective rooting depth was varied from 0.1 m to 0.6 m to determine the effects on number of dry days. The basic relationship for rooting depth versus time was the same as used in the previous examples and is given by the 60 percent curve in Figure 2-22, which has a maximum depth of 0.3 m. When the value given in Figure 2-22 was greater than the maximum rooting depth chosen, the rooting depth was set equal to the maximum. For maximum rooting depths greater than 0.3 m, the values given by the 60 percent curve in Figure 2-22 were increased by the ratio M/.30 where M is the maximum depth.

The results of the simulations are plotted in Figure 6-24 for 5-year and 2-year recurrence intervals for both Bladen and Wagram soils. An example interpretation of these results yields the following for a Wagram soil with a limiting root depth of 0.15 m. On a 5 YRI basis, we should expect to have 38 or more dry days during the growing season in one year out of 5 when the root depth is limited to 0.15 m. However, if the barrier to root growth is removed and the maximum effective depth reaches 0.3 m, the expected dry days (once in 5 years) would be 23. From another point of view, we can say that 23 or fewer dry days would be expected in 4 years out of 5 when the maximum effective root depth is 0.3 m. If the effective maximum root depth could be further increased to 60 cm, the expected number of dry days in 4 years out of 5 would be 7 or fewer.

Use of the model, as in this example allows an evaluation of the potential benefit of operations to increase rooting depths, such as chisel plowing to break hardpans or deep incorporation of lime to raise subsoil pH. Potential benefits of research to develop varieties with deeper rooting systems could also be evaluated.

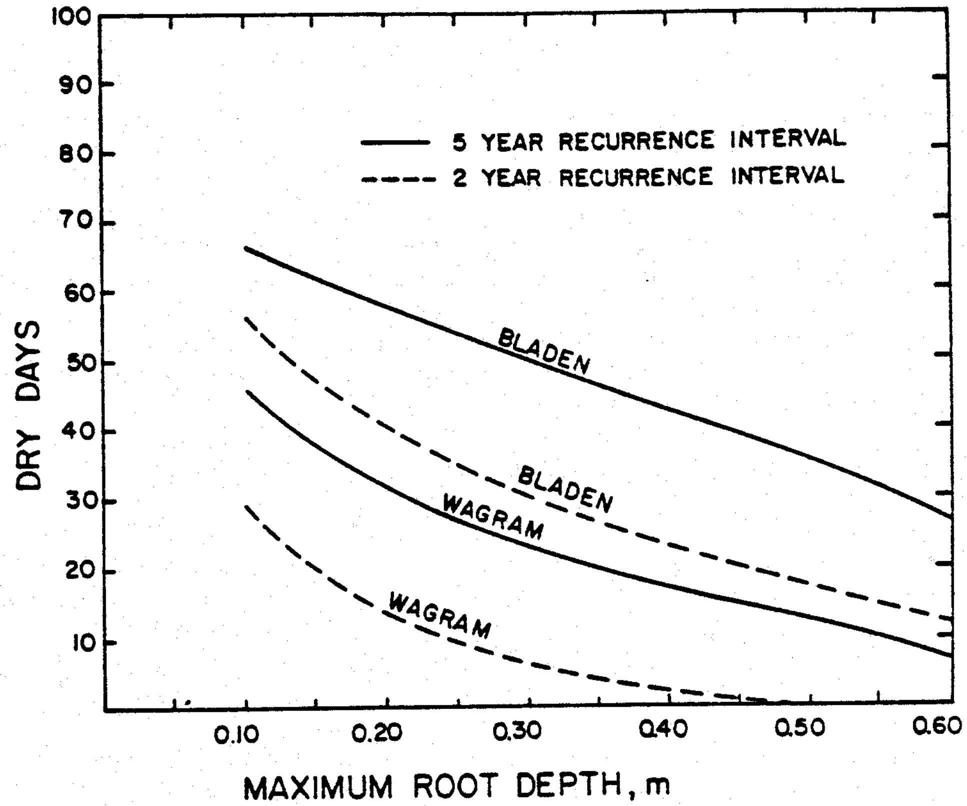

Figure 6-24. Effect of maximum root depth on number of dry days, 2 and 5 years recurrence intervals.