AGRICULTURAL DRAINAGE publication series

Soil Water Concepts

by Gary Sands

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*The **Agricultural Drainage** series covers topics including basic concepts; planning and design; surface intakes; economics; environmental impacts; wetlands; and legal issues.*

The growing use of artificial subsurface or "tile" drainage in Minnesota has sparked much debate about its impact on local hydrology and water quantity and quality. Discussions are typically focused on the following questions that have important policy implications for local and state decision makers.

- Does subsurface drainage lessen or worsen localized flooding?
- Are catastrophic floods more frequent because of subsurface drainage?
- Does subsurface drainage alter the quantity of flow in a river basin?
- Do subsurface-drained soils respond more like a "sponge" to excess rainfall, as compared to poorly drained soils?
- How do surface inlets (intakes) affect the quantity and quality of drainage flow?
- How do artificially drained lands impact water quality?

This publication presents concepts that are fundamental to understanding how subsurface drainage affects soil water and the water balance. It provides information about components of the water balance in the crop/soil system and their relationship to drainage. In addition, several commonly asked questions about drainage, soil water, and hydrology are addressed. Understanding these concepts is helpful in addressing broad issues and policy questions related to drainage and water management.

SUBSURFACE DRAINAGE

Artificial subsurface drainage continues to be a common practice in Minnesota, as well as in other states and countries around the world. Subsurface drainage is the practice of placing perforated pipe at a specified grade (slope) at some depth below the soil surface. Excess water from the crop root zone can enter the pipe through the perforations and flow away from the field to a ditch or other outlet. Subsurface drainage improves the productivity of poorly drained soils by lowering the water table, providing greater soil aeration, and enabling faster soil drying and warming in the spring. This may allow fields to be planted earlier and other field operations to take place in a timely fashion. It also provides a better environment for crop emergence and early growth, and can reduce soil compaction. Once a crop has been established, subsurface drainage greatly reduces the risk of crop water stress from ill-timed or excessive rainfall. For these reasons, subsurface-drained soils represent some or the most productive soils worldwide.[1]

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[1] Skaggs, R.W., Breve, M.A., and Gilliam, J.W. 1994. Hydrologic and water quality impacts of agricultural drainage. *Critical Reviews in Environmental Science and Technology.* 24(1):1-32.

SOIL WATER

To understand how drainage influences the water balance in the soil, we need to look at the forms of soil water. The soil bulk volume consists of both solids and pore space, as shown in **Figure 1**. The proportion of the soil volume that is pore space depends on soil texture and structure, but typically varies between 35 and 55 percent. Water is "held" in the soil pores by weaker capillary forces. Stronger adsorptive forces also hold water as "film" surrounding soil particles (see **Figure 2**). When a soil is sufficiently wet, its capillary forces can hold no more water and the soil is at "field capacity." The actual soil moisture content at field capacity varies with soil texture, typically ranging from 15 to 45 percent by volume. Plants can easily extract water from a soil when its moisture is at or near field capacity. As a soil begins to dry out, however, increasingly stronger forces hold the pore water until a point is reached when plants can no longer extract any water from the soil. This state of soil moisture is the "wilting point" of a soil. Soil moisture content at wilting point typically ranges from 5 to 25 percent by volume. Water in the soil between field capacity and wilting point is the "plant available water," and is illustrated in **Figure 3**.

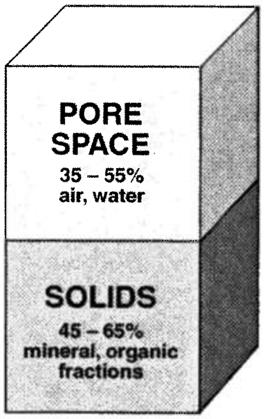

Fig. 1. Soil bulk volume

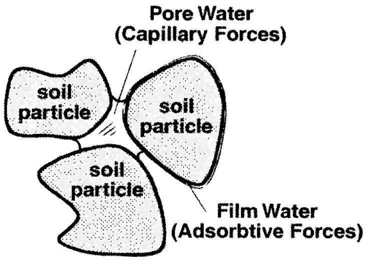

Fig. 2. Soil water held by capillary and adsorptive forces

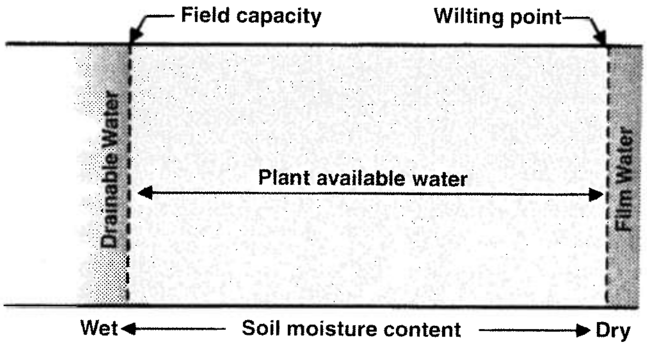

Fig. 3. Plant available water and drainable water in relation to field capacity and wilting point

Throughout this publication and in common practice, quantities of water are expressed in units of depth—inches or centimeters—as opposed to units of volume. (For example, "a soil holds three inches of plant available water," or "one inch of water was drained from the soil.") Expressing soil water in this way assumes that its depth applies to a unit area (i.e., a square foot or an acre) or some other area of interest. If one wanted to compute the volume of water resulting from this depth, it can be done easily by multiplying the depth of soil water by the area of interest, making sure to keep the units consistent. For example, 100 acres of soil that holds 3 inches of plant available water is: 100 acres x 3 inches = 300 acre-inches (1,089,000 cubic feet or 8,145,000 gallons) of plant available water.

While the agronomic terms field capacity and wilting point describe convenient agronomic reference points, soil moisture in the field is constantly changing with time and varies throughout the soil profile (the soil between the ground surface and a particular depth). If one could take a snapshot of soil moisture content after a rain, just as the water has stopped moving downward, it might look something like **Figure 4**. At some depth, the soil is saturated and a water table may be present. Soil closer to the water table is wetter than soil closer to the ground surface. This means that as you move up from the water table, the soil pores contain proportionately less water. If and where a water table forms depends in part on how well the soil drains. Poorly drained soils may have a water table form very near the soil surface, whereas soils that drain well usually don't have shallow water tables.

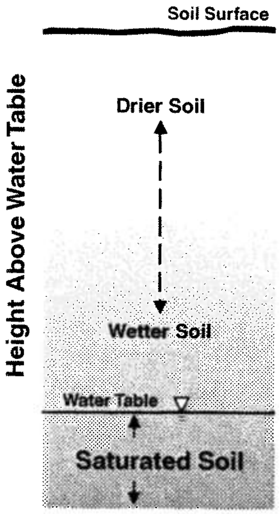

Fig. 4. Soil moisture variation between the water table

The change in proportion of air-filled and water-filled pores between the water table and the ground surface is illustrated by the curved line in **Figure 5**. If the water table is far enough below the ground surface, at some point above the water table the soil moisture will have drained to field capacity (shown as 28%, for example, in **Figure 5**). In the absence of additional rain, evapotranspiration (soil evaporation + plant transpiration) will begin to dry out the soil, further increasing the proportion of empty or air-filled pores. Poorly drained soils may have water tables at

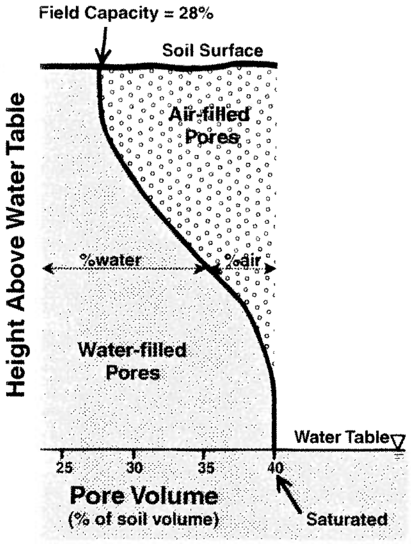

Fig. 5. Proportion of air- and water-filled pores between the water table and the soil surface after the downward flow of water ceases

or very near the soil surface for extended periods of time. Under these conditions, the proportion of air-filled pores in the soil profile is very small, so the soil lacks proper aeration to support plant growth.

DRAINABLE SOIL WATER

Subsurface drainage provides a pathway for "excess" or "drainable" water to leave the soil. The drainable water is held by the weakest forces, at moisture contents between field capacity and complete saturation of the soil, as shown on the left side of **Figure 3**. A common household example may help to illustrate this concept. Suppose one watered a potted plant that had no holes in the bottom of the pot for water to escape. As water is added, the pot fills until water spills over the top. At this point the soil is saturated, with little or no air in the soil pores. If a hole was then made in the bottom of the pot, the "drainable" water would drain out and the soil would be left at field capacity. The soil in the pot is now artificially drained, yet no plant-available water (according to our previous definition) has been removed. When subsurface drainage is present, excess water drains—by the same process as the example above—from the soil profile through the drains, until the water table is lowered to the depth of the drain, below the ground surface.

A first step toward understanding the hydrology of drainage is understanding how much water can drain from the soil profile by subsurface drainage. The amount of drainable water in the soil depends on the amount of "drainable pore space" or "drainable porosity," P_d, of a soil. One way to express drainable porosity is the quantity of water drained for a given drop in the water table, "h" (see **Figure 6**), and described by the following relationship:

$$P_d(\%) = \frac{\text{drainable pore water (inches)} \times 100}{\text{h (inches)}}$$

or,

$$\text{drainable water} = \frac{P_d \times h}{100}$$

Figure 6 shows that drainage causes the water table to drop the distance "h" from its initial position at 1 to its final position at 2. The curves marked 1 and 2 are precisely the same curves as described in **Figure 5**, showing the proportions of air- and water-filled pores above the initial and final water tables, respectively.

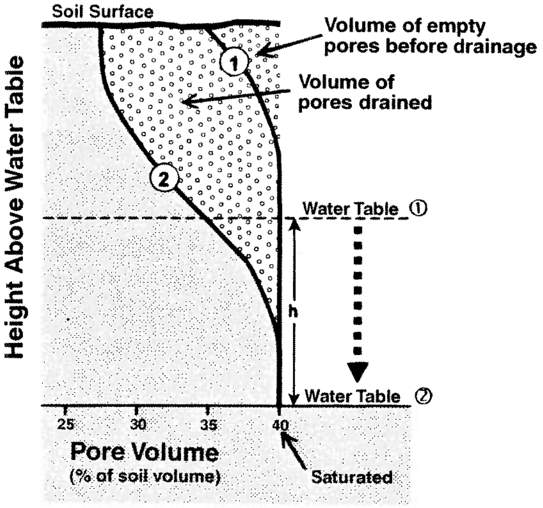

Fig. 6. Illustration of drainable porosity when a water table is lowered by drainage

The area between the curves illustrates the volume of pores that has been drained.

Another way to think of drainable porosity is the percentage of air-filled pores present when the soil has drained to field capacity. *(This is calculated as: soil porosity minus soil moisture content at field capacity.)* Drainable porosity is influenced by soil texture and structure, as shown in **Table 1**. Sands or coarser-textured soils have large drainable porosities, whereas clays or fine-textured soils have smaller drainable porosities. This means that for an equal amount of water drained, a sandier soil will show a smaller water table drop than a soil with higher clay content.

Table 1. The variability of drainable porosity with soil texture and structure

Soil Texture	Field Capacity (% by vol.)	Wilting Point (% by vol.)	Drainable Porosity (% by vol.)
clays, clay loams, silty clays	30–50%	15–24%	3–11%
well structured loams	20–30%	8–17%	10–15 %
sandy	10–30%	3–10%	18–35 %

A P_d of 10 percent, for example, means that draining one inch of water lowers the water table 10 inches. Stated another way, lowering the water table 10 inches means an inch of water has been drained from the soil profile. As an example, consider a soil with an average drainable porosity of 8 percent, with a high water table at 6 inches below the soil surface. To lower the water table to a depth of 48 inches below the soil surface, 3.36 inches of water must be drained from the soil profile (the 42-inch water table drop x 8% ÷ 100 = 3.36).

DRAINAGE AND THE WATER BALANCE

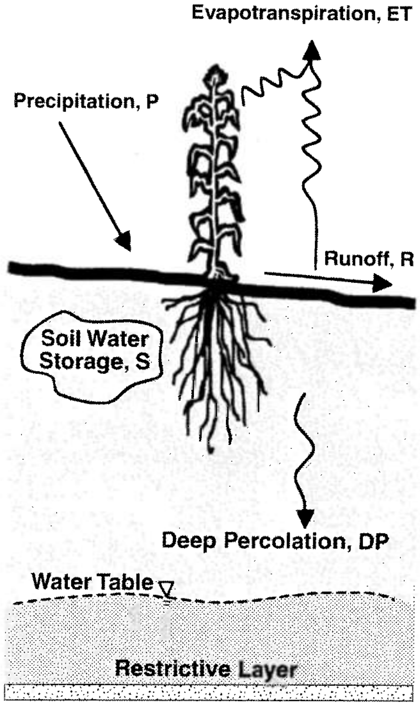

Fig. 7. Components of the soil water balance with good natural drainage

The term water balance, when applied to a crop/soil system, describes the fate of precipitation and the various components of water flow in and around the soil profile. Because drainage affects soil water, other components of the water balance are also affected. With an understanding of soil water and drainable porosity, we can now consider these effects. Consider first a simple water balance on a soil profile with good natural drainage, as pictured in **Figure 7**. In the typical case, precipitation (P)—rainfall, snowmelt, irrigation (if practiced)—is the major water input to the crop/soil system, affecting surface runoff water (R), crop evapotranspiration (ET), deep percolation (DP), and changes in soil water storage (S). In **Figure 7**, we assume that no water enters the soil from adjacent areas by horizontal flow (an assumption that is not true in some cases). Mathematically, the water balance can be written as:

$$P = R + ET + DP + S$$

When the water table is relatively deep as shown in **Figure 7** (3 to 15 feet), deep percolation recharges it. If deep percolation continues, there is an opportunity for the water table to rise. The water balance demonstrates that the amount of deep percolation depends on the extent to which the precipitation input to the soil is reduced by R, ET, and S.

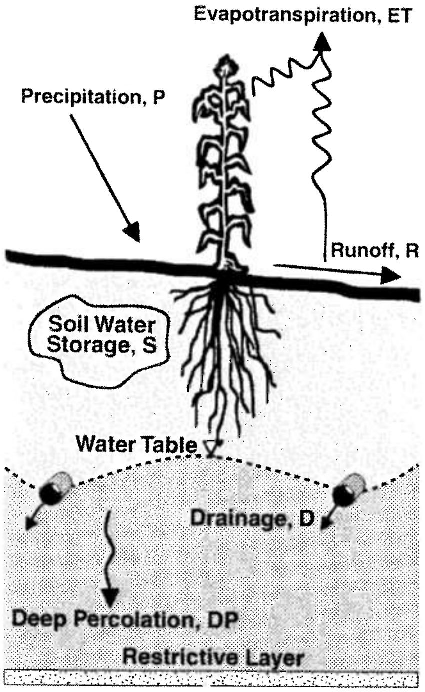

Fig. 8. Illustration of the soil water balance with artificial drainage

The same water balance relationship holds true in an artificially drained soil profile, as depicted in **Figure 8**. Now, however, drainage flow (D) becomes a major component of the water leaving the system. As before, the amount of drainage is dependent on how much precipitation is lost to R, ET, and S. Simply put, the quantity of drainage flow is driven by precipitation and the relative proportion of the other components of the water balance. This means that the impact of drainage will vary on an annual basis and from region to region. This is certainly true in Minnesota, which has a 13- to 15- inch variation in annual rainfall across the state. The water balance equation can now be written as:

$$P = R + ET + DP + S + \mathbf{D}$$

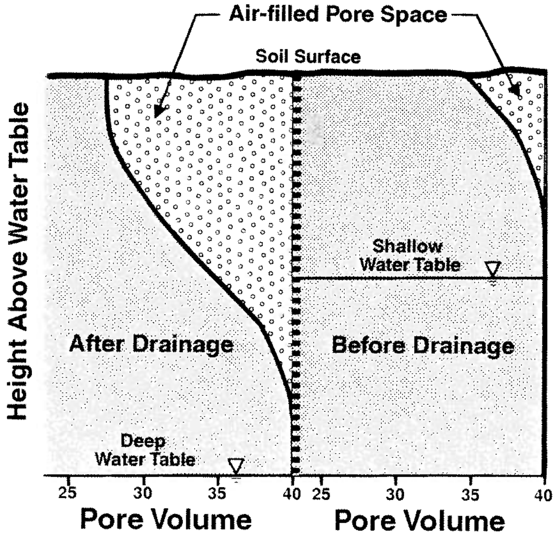

Fig. 9. Illustration of drainable porosity when the water table is lowered by drainage

Let's compare the water balance of a poorly drained soil with a high water table with the same soil after it's drained, without considering the influence of a growing crop. **Figure 9** shows the distribution of water- and air-filled pores above a shallow water table in the poorly drained soil (right portion), and above a deep water table in the same soil profile after drainage has occurred (left portion). After draining, the soil has more pore volume available for water infiltration during the next rain because of the larger volume of empty pores. Consequently, *more infiltration* and *less runoff* may occur with an artificially drained soil compared to a poorly drained soil, depending on the nature and timing of the next rain (a very intense rain may not produce much infiltration in either case). How much more infiltration could occur on the drained versus the undrained soil? This depends on many factors, but the amount will be greater when (1) the difference between the shallow and deep water table levels is greater (i.e., very high initial water table drained to a greater depth), (2) the poorly drained water table is closer to the soil surface, and (3) soil textures are coarser.

A WATER BALANCE EXAMPLE

Consider two soils, each with a drainable porosity of3 percent. The undrained soil has a water table 6 inches below the surface, and the drained soil has a water table at 48 inches, the depth of the drain. The undrained soil has a total of **0.18 inches** (6 inches x 3% ÷ 100) of available pore space between the water table and the surface; the drained soil has a total of **1.44 inches** (48 x 3% ÷ 100). The drained soil has **1.26 inches** (1.44 – 0.18) more available (empty) pore space than the undrained soil. If a low-intensity 1.5-inch rain occurred, our simple water balance would lead us to expect 0.06 inches of runoff from the drained soil (the soil can hold 1.44 inches) and 1.32 inches of surface runoff from the undrained soil (the soil can hold 0.18 inches). Following the rain, both soils are saturated to the soil surface. Additionally, we would expect 1.44 inches of drainage from the drained soil over the following 24 to 48 hours to bring the water table back to the 48-inch depth.

With this simple example, we estimate that we lose about 1.32 inches of water as surface runoff from the undrained soil, compared to 1.44 inches of water over the next 24 to 48 hours as drainage from the drained soil. The real difference between the two, in terms of water loss, is one of timing. The 1.32 inches of surface runoff from the undrained soil will occur relatively rapidly (perhaps in a few hours) compared to the 1.44 inches of water outflow from the drained soil. The drained soil's water must first pass through the soil before it reaches the drainage system. Thus, the resultant flow at the drainage outlet will typically occur over a longer period of time, and with a lower peak flow, than surface runoff from the undrained soil. Consequently, the total runoff ***rate*** (surface runoff + drainage flow) of the drained soil is typically reduced. For a given soil, the magnitude of this reduction depends on the depth and intensity of the rain. Smaller rains of low intensity will reduce the total runoff rate more dramatically because proportionally more water will have an opportunity to infiltrate and pass through the drainage system. In addition, smaller rains may cause surface runoff on the undrained soil and no surface runoff at all on the drained soil. However, if one or more rains occur before the drained soil has had time to drain adequately, water balance differences between the two soils will be diminished.

Based on this analysis—without the influence of a growing crop—we see that drainage can, to some degree, enhance the soil profile's ability to store water and alter runoff rates and volumes. This is known to some as the "sponge effect" of subsurface drainage. The reader should bear in mind that these simple calculations are volume balances only and do not take into account the dynamic nature of rainfall and other factors associated with the rainfall-runoff process. Nevertheless, the calculations are useful in understanding the potential influence of drainage on the water balance of a soil and how this may affect hydrology.

SEASONAL WATER BALANCE

Finally, we must consider the influence of a growing crop on the water balance. We previously included crop ET in the water balance but have not yet explored the changes in the soil profile that take place over the growing season in response to drainage.

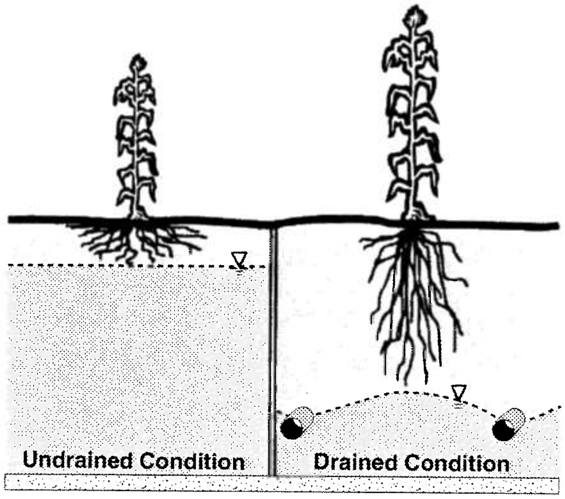

Fig. 10. Comparison of water table and root development in drained and undrained conditions

The undrained condition shown in **Figure 10** is characterized by a shallow water table. This condition almost always exists in poorly drained soils in the spring, and may extend into or recur later in the growing season, depending on seasonal precipitation patterns. Due to saturated conditions near the soil surface, the depth of crop root development may be severely restricted, even effectively eliminated (in the most poorly drained soils). In such conditions, the effective root zone depth will be a fraction of what it could potentially be in a well-drained or artificially-drained soil. The deep root structure in the "drained condition" section of **Figure 10** plays an important role in the water balance and the health and production of the crop. Drainage may even be advantageous in unseasonably dry years. And when dry summer conditions follow a wet spring, the crop may have an increased resistance to drought because plant roots can access water in deeper—and moister—soil.

The presence of a vigorously growing crop increases the "sponge effect" in a drained soil in the following way. As the growing season progresses and crop ET increases, crop water uptake will further dry the root zone, causing an upward flow of water from below. By drying out the soil in and below the root zone, the crop creates yet more empty (air-filled) pore space compared to drained soil with no crop. This drying effect can be illustrated by the change in the soil air/water percentage curve shown in **Figure 11** (the curve shifts to the left). The shaded area between the curves represents the additional empty pore space created by crop-induced drying of the root zone and the upward flow of water to that zone. The deeper and healthier the root system is, the larger this effect will be, for a given crop, with the maximum effect occurring later in the growing season as the crop and its root system matures. The shifted curve in **Figure 11** represents the extreme case where the soil moisture in the root zone has been depleted to the wilting point.

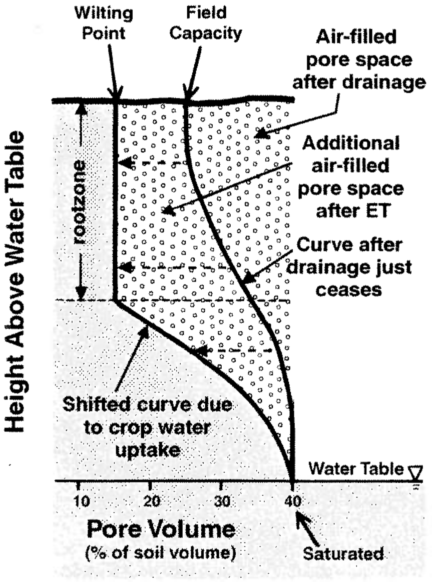

Fig. 11. **Crop-induced increase in empty (air-filled) pore space in a drained soil**

AN ILLUSTRATION WITH FIELD DATA

The graph in **Figure 12** provides an illustration of how water balance dynamics can change over the growing season due to subsurface drainage and crop growth. The figure shows the daily subsurface drainage flow and precipitation over the 1998 growing season for corn on a Webster clay loam soil. Precipitation for the season was 36.4 inches, of which 26.4 inches occurred between February 22nd and November 1st (the period shown in **Figure 12**). The data were collected by Dr. Gyles Randall at the University of Minnesota Southern Research and Outreach Center at Waseca, Minnesota. The highest drainage flow corresponds to the period just following soil thaw, in late March and early April. From this point on, the peak subsurface flows decreased throughout the growing season. After mid-July, no more subsurface flow occurred, despite rains as large or larger than those that occurred earlier in the season (note the rains of nearly 1 inch and 1.7 inches in September and October).

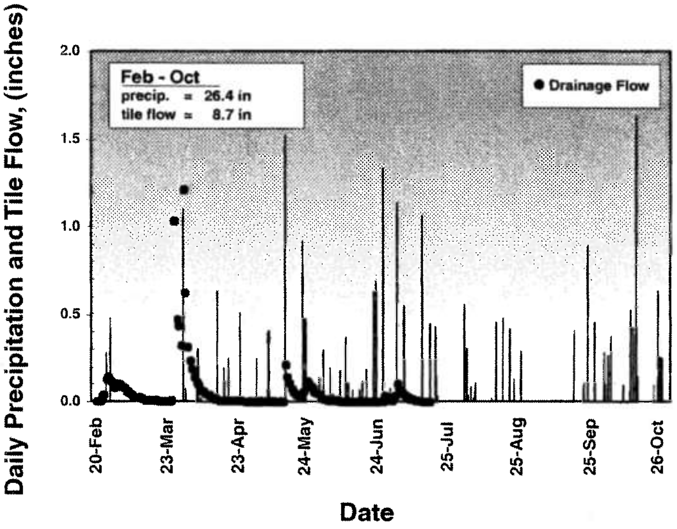

Fig. 12. **1998 daily precipitation and drainage flow for corn on a Webster clay loam soil at Waseca, MN**

Without surface runoff data, there are two possible explanations for the absence of subsurface flow later in the growing season. Either (1) all the late-season rains were of very high intensity, generating mostly surface runoff and little infiltration; or (2) the combination of subsurface drainage and crop growth produced a drier soil profile and more available pore space for absorbing the rainfall. While it is likely that some of the late-season rains were of high intensity, it is equally likely that many were not. What is not evident from the above data are the proportions of the drainage and crop effects, relative to one another. These data illustrate, however, that subsurface drainage and crop growth together create a buffering capacity or sponge effect as the growing season progresses. It is hoped that results from current drainage research in Minnesota will strengthen our understanding of drainage and the water balance for this region of the U.S.

COMMONLY ASKED QUESTIONS & ANSWERS

How does subsurface drainage promote better plant growth on poorly drained soils?

Subsurface or "tile" drainage removes excess water from the soil—water that prevents air and oxygen from getting to plant roots. Without artificial drainage, plants have difficulty establishing a healthy root system on poorly drained soils. Subsurface drainage provides the mechanism for these soils to drain to field capacity in a reasonably short period of time so that plant growth is not significantly impaired. In addition, drainage often permits spring field operations (e.g., tillage, planting) to take place in a more efficient and timely way. Depending on seasonal rainfall, this can have the effect of adding days, to a week or more, to the length of the growing season, providing another source of potential crop yield improvement.

Does subsurface drainage remove plant-available water from the soil?

No, drainage does not increase or decrease plant-available water in the soil profile. Drainage removes "drainable" water from the soil the same way a potted plant with a hole in the bottom of the pot drains after watering. Upward flow can occur in soil with tile drains, however, from the water table to the root zone, providing an important source of moisture for crop growth. On lighter (coarser) soils, placing drains too deep can limit this source of moisture.

Is groundwater or rainfall the source of subsurface drainage water?

In most situations, flow from drainage systems is shallow groundwater that is replenished by rainfall—the less rainfall there is, the less drainage flow there can be. In some cases, however, drainage systems are designed to intercept lateral flow.

Does subsurface drainage cause more water to leave the field compared to undrained conditions?

While not true for all cases and locations, in general, subsurface drainage may cause 10 to 15 percent more water to leave the field than agricultural land with surface drainage only. This number is based on drainage simulation models because variations this small are difficult to measure in the field due to high seasonal variability.

How does drainage influence surface runoff and flooding?

Rainfall provides water for surface runoff and infiltrating the soil. The route that water takes as it flows through the landscape plays a very important role in the amount and rate of total runoff, and this is affected greatly by land use. When natural vegetation is disturbed or converted into field crops and pasture, peak runoff rates at the field edge can increase dramatically. Often these conversions are accompanied by some surface drainage practices. In general, subsurface drainage tends to decrease surface runoff (sometimes one- to three-fold) and decrease peak surface runoff rates when compared to surface-drained or undrained land. The decrease occurs because water flows more slowly through the soil to reach the drainage system (and eventually the outlet) than it would as surface runoff. The later arrival of drainage flow may cause the overall peak outflow (surface + drainage) to decrease. Moreover, when the amount of runoff is reduced, the speed of its flow may also decrease. While these processes are well understood and documented at field and farm scales—flooding is a watershed-scale phenomenon. As we look at larger and larger landscapes, the increasing complexity of watershed hydrology makes it more difficult to make statements about drainage that hold true for all watersheds, at all scales and at all times. It can be said, however, that the potential for subsurface drainage to reduce peak flow rates at the field scale does not support the notion that subsurface drainage exacerbates flooding at larger scales. It should also be noted that most researchers agree that large-scale, basin-wide floods, such as those of 1993 and 1997 in Minnesota, are largely attributable to catastrophic precipitation, not the presence of subsurface or surface drainage systems.

What is meant by the "sponge effect" of subsurface drainage?

The combined effect of subsurface drainage and water removal by a healthy, deep-rooted crop provides for an increased storage capacity for water infiltration into the soil, compared to an undrained, high-water table soil. Depending on the timing, depth, and intensity of rainfall, more water has a chance to infiltrate a drained soil compared to a poorly drained soil. This increased storage capacity is often referred to as the "sponge effect." The extent to which the effect is realized depends on soil type, crop, time of year, and both rainfall and soil moisture characteristics prior to and during precipitation. In poorly drained, high water table soils, subsurface drainage lowers the water table and increases the empty (air-filled) pore space available for infiltrating water. The deeper, healthier plant root structure that is promoted by drainage further enhances this effect by removing still more water from the soil profile, which creates more empty pore space. The combined effect of subsurface drainage and crop growth is most apparent from middle to late growing season.

Send your additional questions to:

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