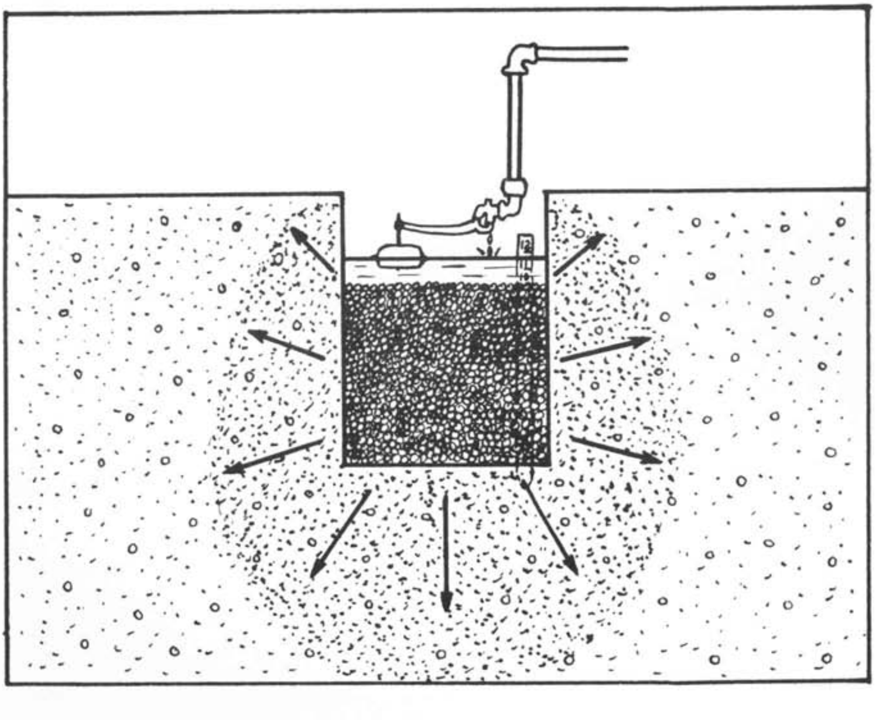
PERCOLATION TESTING FOR SEPTIC TANK DRAINAGE

David E. Hill

Principles of Water Flow and Site and Seasonal Variation



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INTRODUCTION

Field percolation tests have been used for nearly forty years to assess the capacity of soil for sewage effluent disposal. Today suburban expansion into the rural fringe beyond the sewer systems of the city has increased the use of septic tanks and drain fields and heightened our concern with evaluating soils for accepting the effluent from the drain fields.

The percolation test has the virtue of great simplicity. Essentially, a hole is dug in the soil. The soil is wetted for several hours and then the rate at which the water level in the hole falls is used as a measure of the capacity of the soil for accepting drainage. In our investigations we have determined how water travels away from the hole during this simple test, how the percolation rate varies with time during the test and with season, how much the percolation rate varies from one hole to another at the same site and at different sites within the same soil type, and whether we can predict percolation rates from standard soil survey maps.

SOILS AND METHODS

The Soils

Soil types were selected that represented broadly contrasting physical characteristics predominantly inherited from geological events common to New England in general and Connecticut in particular. Further, the three soil types that were studied occupy considerable acreage in Connecticut. Brief descriptions of these types are as follows:

1) Wethersfield silt loam: a reddish, well-drained soil developed on very firm compact glacial till derived principally from red Triassic sandstone and shale with some dark-colored basalt or trap rock present. The most noticeable characteristic is a fragipan or hardpan at depths less than 30 inches which restricts internal drainage.

2) Cheshire fine sandy loam: a reddish, well-drained soil developed on loose to firm glacial till derived principally from red Triassic conglomerates, sandstones, and shales. This medium-textured soil found on unsorted glacial deposits lacks a general fragipan within 30 inches of the surface.

3) Merrimac sandy loam: a yellowish brown, somewhat excessively drained soil developed on stratified sand and gravel terraces derived mainly from granite and schist. The coarse-textured stratified substratum is very porous with virtually no restrictions on internal drainage.

The Field Percolation Tests

In general, the percolation tests were performed according to standard procedures outlined in the *Manual of Septic Tank Practice* (23), but they were modified (8) (12) to facilitate hydraulic conductivity measurements. At each site three pairs of holes were dug with a tiling spade. The distance within each pair of holes was about 4 feet, and the distance between each pair was 50 to 100 feet. The holes were 10 inches in diameter. One of each pair was 18 inches deep, one was 36 inches deep. In the text, the three holes at each depth will be called observation triplets. As the holes were dug, bulk samples were collected at depths of 12, 24, and 36 inches in each 36-inch hole, and at 6 and 18 inches in each 18-inch hole. From these bulk samples the moisture content and texture of the soil were determined.

During digging of the hole, the wall may be smeared and sealed. And when water is added to the hole, the walls may be eroded and then sealed with suspended sediment. Therefore, measures were taken to prevent this sealing which causes an unwanted change in the percolation rate. After the hole had been dug, the sides and the bottom of the hole were scarified with a serrated knife. In wet Wethersfield soil, however, the scarification was not completely satisfactory.

To prevent erosion of the walls and bottom, 2 inches of "pea" gravel was added at the bottom of the hole to prevent scouring. Later we found that a gravel depth of 10½ inches was required to permit rapid filling of the hole with water and accurate marking of time zero, and to provide support of the wall against slumping.

The depth of the water in the hole was indicated by a ruler that stood in the gravel and extended above it. At time zero, water was added within 5 seconds or less to a depth or head of 12 inches in the hole. The time required for the head to drop from a depth of 12 to 11 inches was recorded as the percolation rate at time zero. Water was added to return the head to 12 inches and then a float valve, mounted on a steel probe, was inserted at the edge of the hole (Figure 1A). This valve, connected to a water source, maintained a constant head of water in the hole. When conductivity rates were rapid, two such valves were needed to maintain a constant head of water.

Ten minutes after time zero, the water supply was shut off by removing and locking the float valve. The time required for the head to drop 1 inch was recorded. The head was again increased to 12 inches and maintained with the float valve. This procedure was repeated at 100 minutes and at intervals after that according to the characteristics of the soil.

One thousand minutes after water had first been placed in the Wethersfield holes the conductivity observations were concluded and a conventional percolation test was made. After only 400 minutes, the more porous Cheshire and Merrimac soils had reached minimum conductivity rates; therefore, a conventional percolation test was made in the Cheshire and Merrimac soils after 400 minutes. First the water level was permitted to fall. Then 6 inches of gravel was removed from the hole and the water head was adjusted to 6 inches above the bottom of the hole. The fall of the head was then observed by means of a float (Figure 1B). The time required for this fall was recorded as the percolation rate of the pre-soaked soil.

Finally, the water content of the wetted soil was determined from samples taken from the pit wall at depths below the head level. To determine the moisture distribution pattern during the test, core samples were taken from some test holes at various distances from the pit wall and at various depths during the soaking. The samples were weighed, saturated with water, weighed again, and the water contents determined. The moisture content of the samples taken in the vicinity of the hole was expressed as a percentage of the moisture content of the saturated sample.

FIGURE IA. CONSTANT HEAD APPARATUS

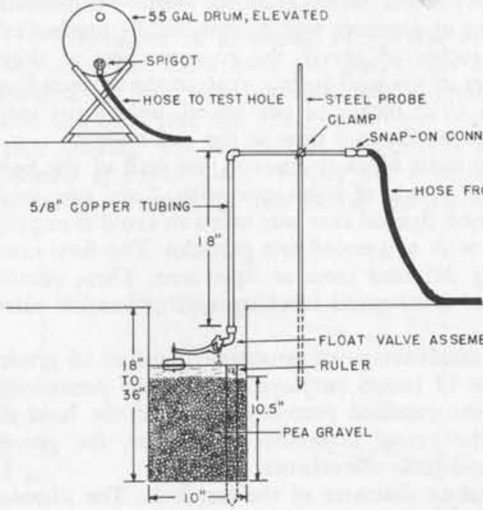
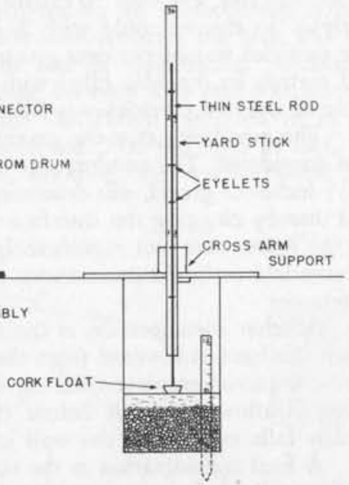


FIGURE IB. FALLING HEAD GAGE



HOW WATER FLOWS FROM THE HOLE

The Condition of the Wall

Fluctuations in the water level in the hole may affect the conductivity. Occasionally the head of water inadvertently fell below 11 inches or the hole drained completely because the water supply ran dry. When the water level was restored, the subsequent readings were considerably below those anticipated, attributed to the entrance of air into the soil pores of the wall. Further, periodic draining and refilling of the hole, advocated in the standard percolation test (23), causes scouring, agitation, and slumping in the hole. Suspended solids then clog the pores of the wall and decrease flow rates. Maintaining a constant head is especially important in soils with weakly developed structure such as found in most of Connecticut and the Northeast. Thus, a constant head was maintained in the holes whenever possible.

We made another modification of the percolation test by filling the hole with gravel to a depth of 10½ inches or only 1½ inches below the maximum head during soaking. The consequences of this must be examined. The deep gravel permitted the rapid filling of the hole at time zero, and a more accurate determination of the initial conductivity rate. With the standard 2 inches of gravel placed in the hole, rapid filling caused slumping and scouring at the sides of the hole. With 10½ inches of gravel in the hole, a smaller volume of water was required to fill to 12 inches, and slumping was minimized.

The reduced clogging of the sides of two test holes in Merrimac sandy loam containing 2 and 10½ inches of gravel was measured. After completion of the percolation tests, soil samples were taken at equal depths both by scraping the walls and by taking bulk samples 1 to 2 inches from the walls. The amount of silt and clay less than 50 microns in diameter was determined by mechanical analysis. In the test hole with 2 inches of gravel, the concentration of these fine particles was 24 per cent greater at the wall surface than in the surrounding soil matrix. In the hole filled with 10½ inches of pea gravel, only 5 per cent more of the fine particles was found in the wall than in the soil matrix.

The possibility that the gravel itself blocked pores in the wall of the hole was considered. The conductivity of a pair of holes, one with 2 and one with 10½ inches of gravel, was determined. Special care was taken to avoid slumping and thereby clogging the interface with suspended fine particles. The flow rates in the holes were not significantly different even at time zero. These results substantiate earlier considerations of mechanical blocking and infiltration rates (16).

Another consideration is the disadvantage of removing 6 inches of gravel when the head is lowered from the 12 inches employed during the presoaking to the 6 inches employed during the standard percolation test. If the head of water is allowed to fall before the gravel is removed, however, the gravel readily falls away from the wall and little disturbance occurs.

A final consideration is the size or diameter of the test hole. The *Manual of Septic Tank Practice* says "dig or bore a hole with horizontal dimensions of from 4 to 12 inches." To test whether or not the diameter would affect the observation, three holes 18 inches deep were dug in the Merrimac soil. Hole diameters were 10, 8, and 6 inches. At the end of 400 minutes the infiltration rates in volumes per unit time varied more than twofold. The percolation rates in inches per hour, however, varied only as follows: 66, 56, and 90. Since the infiltration rate in inches per hour depended less upon the size of hole than did the volumes per unit time, percolation rates in inches per hour have been employed throughout this Bulletin, in conformity with practice of some sanitary engineers and all soil scientists. Although the percolation rate in inches per hour did not vary regularly with the size of the hole, and varied little more with size of hole than from place to place, a 10-inch hole diameter was used for all investigations described in this Bulletin.

Condition of the Soil About the Hole

In discussing the pre-soaking procedure, the *Manual of Septic Tank Practice* says, "Saturation means that the void spaces between soil particles are full of water. This can be accomplished in a short period of time." Pre-soaking is also designed to permit the swelling of soil colloids, a slower process. A soil whose colloids have swelled and whose pores are saturated should simulate conditions which occur during wet seasons, and is also closely related to the actual conditions in an operating drain field. As we shall see, however, standard pre-soaking fails to saturate the soil. Even pre-soaking with the constant 12-inch head during our observation failed to saturate the soil. Whether the soil is saturated or not affects, fundamentally, the behavior of the test.

If the soil is saturated, water moves mostly in the large pores and primarily through the action of gravity. If, on the other hand, the soil is unsaturated during the percolation test the water will move primarily through the action of capillary forces from surface to surface or in the small pores in the presence of numerous water interfaces. Large pores — that would have readily passed water had the soil been saturated — are, in fact, largely filled with air. Since they form large ineffective capillaries, the large pores may actually be barriers as we shall see in the Merrimac soil.

The degree of saturation of the soil surrounding an 18-inch-deep hole in Merrimac fine sandy loam was determined 200 minutes after the hole was first flooded. At this time an essentially constant rate or equilibrium percolation rate had been reached. The rate did not change between 200 and 400 minutes after soaking was begun, and presumably the "saturation" referred to in the *Manual of Septic Tank Practice* had been observed. The soil was, in fact, unsaturated (Figure 2). Just before the initial flooding, the water content was only 13 per cent of saturation at 6 inches and 26 per cent at 36 inches depth. After 400 minutes of a 12-inch head of water in this 18-inch hole, the water content at 6 inches depth had increased to only 39 and 25 per cent of saturation at distances of 6 and 12 inches from the hole. At greater distances, the water content at the 6-inch depth, was roughly equivalent to the initial moisture content.

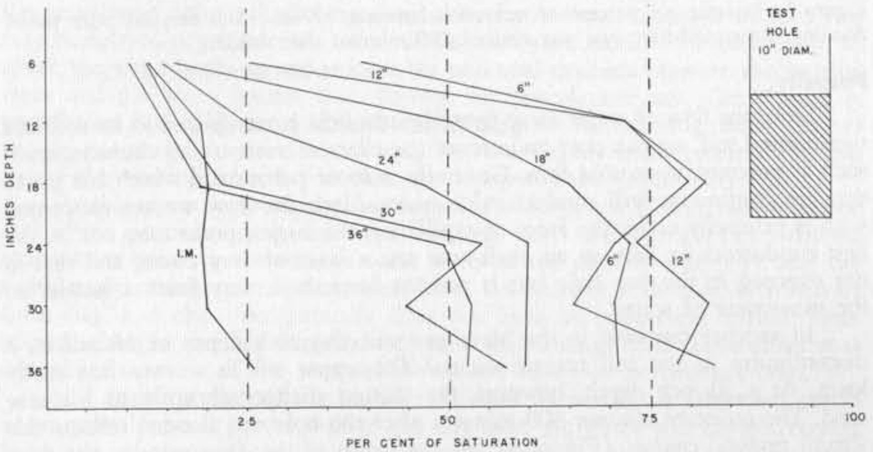


Figure 2. Water content 6, 12, . . . 36 inches laterally from Merrimac Test Hole 1 400 minutes after it was flooded to within 6 inches of the soil surface. Curve I.M. indicates water content before flooding. Water content expressed as percentage of the content of saturated cores. An equilibrium rate was attained 200 minutes after flooding.

On the other hand, near the bottom of the hole the soil was much wetter. Even in this wettest zone and even after an equilibrium rate had been attained, however, the soil was far from saturated.

The wetting of the soil between 200 and 400 minutes after the hole was first flooded is shown in Figure 3. The increase in moisture content within 12 inches of the hole occurred above and near the level of the water surface. At greater distances from the hole, the maximum wetting occurred below the water level. Even with these extended times, the soil was far from saturated. Thus it is safe to conclude that water flows away from the percolation test hole through unsaturated soil, and that the laws of capillarity will have more application to this test than will the laws of drainage in saturated soil. This explains the failure of an attempt (20) to apply the laws of saturated flow to the percolation test.

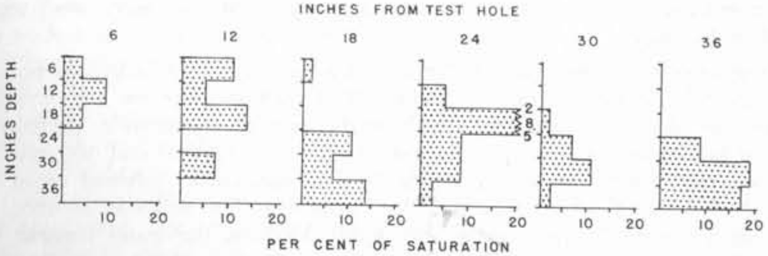


Figure 3. Increase in per cent of saturation between 200 and 400 minutes after initial flooding. An equilibrium rate was attained 200 minutes after flooding.

Porosity

Since the flow of water away from the test hole is recognized to be through unsaturated soil, we can now understand the effect of various soil characteristics, such as porosity, upon that flow. Generally, a more porous soil which has pores that are continuous will conduct more water. Since the flow we are concerned with is primarily under the force of capillarity, the largest pores may not be the best conductors. In fact, as we shall now see, a layer of very coarse soil that is not exposed in the test hole but is present beneath it, may form a barrier to the movement of water.

In another test hole in the Merrimac soil, dug to a depth of 18 inches, a discontinuity in the soil texture occurs. The upper soil is a very fine sandy loam. At a 30-inch depth, however, the texture changes abruptly to a coarse sand. The moisture content 300 minutes after the hole was flooded reflects this abrupt textural change (Figure 4). At the depth of the discontinuity, the finer soil has become very wet, reaching 90 per cent of saturation. Within the coarse soil at a depth of 36 inches, however, the soil has reached a maximum of only 45 per cent of saturation. The capillary conductivity of the overlying fine soil is greater than that of the underlying coarse material. Thus the large pores of the coarse material do not increase flow of water in the percolation test, as one would conclude from an erroneous application of the laws of saturated flow (20). In fact, these large pores actually impede flow in the unsaturated soil.

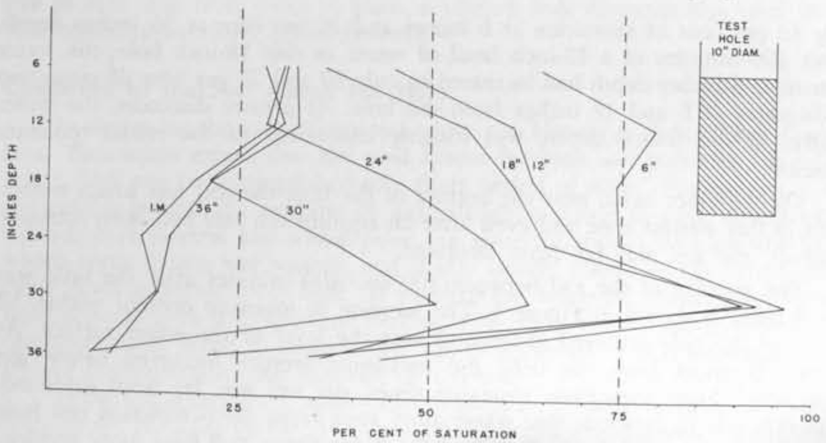


Figure 4. Water content 6, 12 . . . 36 inches laterally from Merrimac Test Hole 2 300 minutes after it was flooded to within 6 inches of the soil surface. Curve I.M. indicates water content before flooding. Water content expressed as percentage of the content of saturated cores. An equilibrium rate was attained 200 minutes after flooding.

In the Wethersfield soil a friable, medium-textured layer overlies a very compact layer, and this causes an easily understood restriction to the flow of water.

The effect of changes in pore size distribution within the soil profile due to stratification or geological variation will have a marked effect on the advance of the wetting front and percolation. This has been well studied by soil scientists (17). But for our purposes it suffices to say that a wetting front passing from the percolation hole and reaching a stratum of pronounced change in pore size may be delayed or temporarily halted if that new zone has a low conductivity. In effect, the water backs up and reduces the potential gradient between the wetting front and the water source, thus slowing the percolation rate. The change in percolation rate will occur almost immediately as the wetting front reaches the discontinuity, provided an air trap has not already accomplished this feat before the wetting front has reached the less permeable layer (26).

At this point it should be mentioned that some clays swell when wetted and affect permeability because the swelling clogs the pores (13). Volume changes are great in the soils of some parts of the country (2) (4) and can significantly change percolation rates. Most Connecticut soils contain relatively little clay, and clay that generally does not have an expanding lattice. Thus, volume changes are slight in Connecticut soils, although this slight effect may contribute to some of the seasonal differences noted in percolation rates.

Soil structure also affects percolation rates. Obviously if structural cracks or worm holes occur in the wall of the test hole, the water will rapidly enter a large area. If these cracks or holes are at a distance from the hole, however, they may (like a coarse-textured material) be a barrier to capillary movement of water. In any event, Connecticut soils have weakly developed structure, and the effect of structure is minimal.

Water

As the water content of the entire soil that is being examined changes, both the capillary conductivity and the water gradient produced by the water in the hole will change. The change in soil water content, however, is the factor primarily responsible for the variation of percolation tests from season to season. Therefore, the effect of water will be investigated and discussed fully in the section entitled "Variability of percolation rates."

Changes in Percolation Rates with Time

Percolation rates decline from the moment that water is first added to the test hole. We now know that we are concerned with unsaturated soil. Soil scientists have described the declining rate in unsaturated soil by the following equation:

$$Q = At^B \qquad (1)$$

where Q is the cumulative percolation, t is time, and A and B are parameters to be fitted to the data (17). When the equation is differentiated, the following is obtained:

$$\log R = \log \frac{dQ}{dt} = \log AB + (B\text{-}1) \log t \qquad (2)$$

If the logarithm of the percolation rates is plotted against the logarithm of time, this equation predicts that a straight line will result. In plotting our data, the deviations from linearity were slight in two-thirds of the holes, suggesting that Equation 2 could be used reasonably well to predict the decline in the rate with time. The one-third of the holes where Equation 2 did not fit will be discussed later.

The values of parameter B calculated from our 100- and 300-minute observations will be compared to those observed by others. Values ranging from .50 to .95 have been proposed theoretically (9) (21) and observed in laboratory experiments (19) (24). Our observations of B (Table 1) for three-dimensional flow that occurs in the percolation test system are within the range of values observed by others.

The variation in B according to initial moisture content was observed in our field studies but not as clearly as has been seen in the laboratory (19) (24). At a depth of 18 inches, the values of B for dry, moist, and wet Merrimac soil were .67, .89, and .88; in Cheshire the values of B were .64, .76, and .78. When the soil was dry, B was considerably reduced, but when it was moist or wet, the B values were virtually the same. Assuming linearity, the percolation rates over a range of elapsed times in a moist or wet Merrimac soil can be predicted from a single observation and Equation 2 with B set at .89. When the soil is dry, a lower value of B is required. Similar rules can be stated for Cheshire.

What of the holes where Equation 2 did not fit because the values of B changed with time? It would be logical to assume that test holes in soils with horizons of sharply contrasting texture and structure would be most likely to have changing conductivity rates as the wetting front reaches the contrast. The logarithms of the percolation rates for Merrimac test hole 2 are related to the logarithm of time in Figure 5. This is a soil with the discontinuity at 30 inches which has already been shown in Figure 4. As Figure 5 shows, the rate nevertheless declines as predicted throughout the period except when the soil is dry. When the soil is dry, the rate declines in an erratic manner.

Since Wethersfield soils have impermeable fragipans or hardpans at depths of 18 to 30 inches, one would expect that their percolation rates would not follow the predictions of Equation 2. In fact, this happened in virtually all tests at one site. At the other two test sites, however, most of the percolation rates declined in the expected logarithmic fashion.

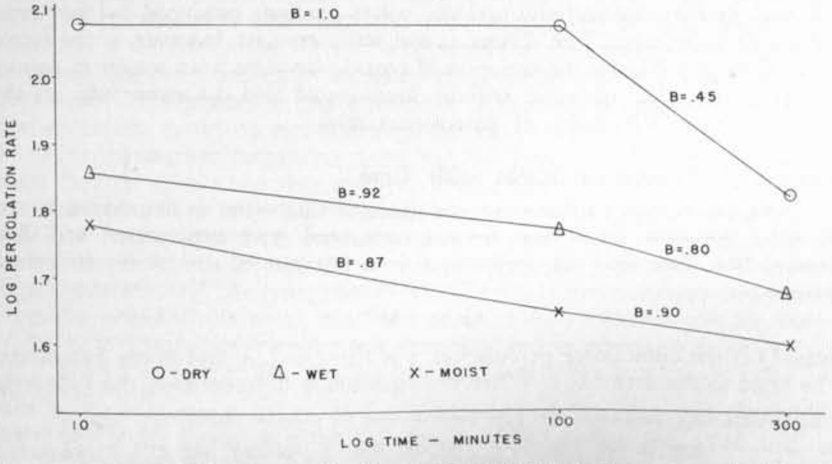


Figure 5. Linearity of parameter B with respect to initial moisture content in Merrimac Test Hole 2 at 18 inches depth.

Cheshire soils do not have strongly contrasting horizons and would not be expected to have incongruous changes in percolation rate with time. Nevertheless, some rates did not decline in the expected fashion.

If percolation rates had declined according to Equation 2, it would have been necessary to obtain one reading per test hole. In two-thirds of the holes this happened. Unfortunately, we could not predict from profile morphology where an exception would occur. Therefore, if the standard percolation test rate is to be placed somewhere in the initial decline of the rate, at least three observations in time are necessary.

THE PLACE OF THE STANDARD PERCOLATION TEST RATE IN THE TIME CHANGE IN PERCOLATION RATES

The percolation rate changes with time after initial wetting, and we naturally want to know where the percolation rate determined during the standard test lies in this change. To do this we must assume that percolation test rates are controlled by the same factors of water movement previously studied in the infiltration capacity of soils; i.e., water must pass through a surface interface and be influenced by an advancing wetting front.

If percolation rates are observed over a long period of time, the following sequence is seen. First, the rate declines for a day or two. Then it levels off at an apparent equilibrium rate, but later it rises again and then falls again slowly (1) (5). The initial decline occurs during a period of time that we might hope to observe in a practical test. The subsequent rise and decline that occur much later have to do with the dissolving of air in the water (5) and with microbial action (1). They seem to occur much too late to be observed by any practical field test. We are, therefore, concerned with locating the standard percolation test rate in the early decline and possibly estimating the equilibrium rate achieved after a day or two.

The *Manual of Septic Tank Practice* says ". . . to keep water in the hole for at least 4 hours, and preferably overnight. Determine the percolation rate 24 hours after water is first added to the hole." How much does the percolation rate change in about 4 hours and overnight?

The Connecticut data above on the change of percolation rate with time concerns a 12-inch rather than the 6-inch head of the standard procedure. We assume that the relation between percolation rates at any time interval is the same for either a 12- or a 6-inch head. Equation 2 and the parameters B of Table 1 are a summary of the time change in the percolation rate as time passes. These are used to obtain the ratios of percolation rates at different times that are tabulated in Table 2. In two of the soils, Merrimac and Cheshire,

Table 1. Average values of parameter B for Merrimac, Cheshire, and Wethersfield soils

Soil	Depth		Average
	18″	36″	
Merrimac	.83	.88	.86
Cheshire	.75	.84	.80
Wethersfield	.70	.75	.72

Table 2. The ratios of percolation rates, R_i/R_4, at times i and 4 hours calculated from the parameters B of Table 1 and Equation 2

	Merrimac	Cheshire	Wethersfield
R_2/R_4	1.10	1.15	1.21
R_3/R_4	1.04	1.06	1.08
R_6/R_4	.94	.92	.89
R_{16}/R_4	.82	.76	.68

it would make little difference whether the percolation rates were observed at 3, 4, or 6 hours. Two hours is probably too soon compared with 4 hours. In the Wethersfield soil, of course, which has a discontinuity in its profile, the percolation rate changes more rapidly, and the rate observed will clearly depend upon the time of observation.

The question remains of the relation between percolation rates after 16 hours or overnight and at the end of 4 hours in Merrimac and Cheshire soil. If Equation 2, which is the foundation of Table 2, applies to fully 16 hours, then the rates observed the following day will be 18 to 24 per cent less than those observed at the end of 4 hours. Observations at three holes in Merrimac, however, show that the decrease over these long periods of time is not as great as Equation 2 indicates. Percolation rates were observed in two 18-inch and one 36-inch hole in Merrimac. The observations were made at 400 minutes and at 1400 minutes. Compared to the rate at 400 minutes, the rates at 1400 minutes were 100, 104, and 94 per cent. Thus, in Merrimac, the percolation rate observed 16 hours or overnight after the hole is first wetted will be no more than 18 per cent less than the 4-hour rate (Table 2) and may be very nearly equal to the 4-hour rate (above observations).

In addition to locating the standard percolation rate in the initial decline, we would like to know the rate that the soil permits during the equilibrium before the late increase and decrease. Ludwig *et al.* (10) (11) (12) have concerned themselves with this problem. They found that the following equation fit not only the initial decline of the percolation rate but the leveling off at the equilibrium rate. They wrote their equation in terms of the reciprocal percolation rate, and we have chosen to rewrite it for our convenience in terms of percolation rates R in inches per minute. The equation is:

$$R = \frac{b + kt}{t} \qquad (3)$$

where b has the dimension inches; k is the minimum rate attained at equilibrium and has the dimensions inches per minute; and t is time and greater than zero.

As Ludwig *et al.* have shown, the product "rate × elapsed time" or Rt is linearly related to elapsed time. The intercept is b and the slope k is the minimum rate attained after a long period of time. We have analyzed our data in this fashion.

Percolation rates for three sites in each of three soils are given in Table 3. Percolation rates pertain to a 12-inch head of water in an 18-inch hole. The first column beneath each soil refers to the rate observed in inches per hour at 4 hours. The second column refers to the equilibrium rate k calculated according to Equation 3. In all three soils, the 4-hour and equilibrium rate for the same site are closer together than are the 4-hour rates at the different sites within the same soil type. Further, the 4-hour and equilibrium rates are very close indeed for Merrimac and Cheshire. In two of the Wethersfield holes the infiltrating water reached a discontinuity in the profile. This caused a changing rate. This, of course, has already been seen in the low value of parameter B for Wethersfield in Table 1. In these instances, the percolation rate at 4 hours is considerably different from the percolation rate at equilibrium. The conclusion from Table 3 is that, in many soils, the 4-hour percolation rate obtained according to standard methods will be very close to the equilibrium rate. In soils with discontinuities in texture and structure, the rate will decrease for some time before equilibrium is reached. The same conclusion has already been reached concerning the difference between the standard percolation test taken after 4 hours and at 16 hours.

Table 3. Percolation rates, inches per hour, at 4 hours and at equilibrium (as estimated from Equation 3) using a 12-inch head of water in a hole 18 inches deep

Hole	Merrimac		Cheshire		Wethersfield	
	4 hrs	Equil.	4 hrs	Equil.	4 hrs	Equil.
1	41.0	40.0	26.0	28.0	19.0	15.0
2	26.0	25.0	20.0	20.0	6.0	3.5
3	9.2	9.4	24.0	24.0	4.6	3.0

This concludes the examination of the process of the percolation test and the factors that influence its value. We turn to the variability of the standard percolation test from place to place and with season.

VARIABILITY OF PERCOLATION RATES

Percolation rate variation over a period of a day can be coped with, as we have seen in the last section. We must now face the other sorts of variability that beset percolation rate measurement; variability from place to place and season to season. When variability is encountered in a measurement, a common procedure is to refine the method or more commonly to take a considerable number of measurements and average them. In the percolation test, variation is a characteristic of the soil and not the fault of the method. Further, the variability of the soil is a characteristic with which the engineer must contend, as surely as he must contend with the mean percolation rate. Averaging for a site or a region, or over seasons provides a less variable measurement but obscures the problem that the engineer must face. We have, therefore, examined the variability.

Examples from Elsewhere

In a relatively homogeneous silt loam, the percolation rate variation among several holes, determined on the same site on the same day, was greater than the variation between holes of different size and between wet and dry soils. Variation observed at 2-week intervals, however, exceeded the variation in percolation rates among holes at the same site on the same date (3).

To assess site variation, percolation rates were observed in 24 holes spaced uniformly in a 300- by 30-foot area. The rates varied from 4 inches to 0.1 inch per hour. Although these variations were extreme, the rates less than 1 inch per hour were localized in distinct areas within the test site (28).

Although the variations within sites are considerable, those between sites were even greater. The hydraulic conductivity varies two to three times as much between sites as within sites (14). Even among sites within the same soil series, variability is greater than within a single site (18). The variation between sites is apparently due to soil rather than vegetation differences (6).

General View of Variability in Connecticut Soils

The three soils studied — Merrimac, Wethersfield, and Cheshire — were chosen because they had contrasting physical properties. An examination of the range in percolation rates (Figure 6) for 18- and 36-inch depths, at all sites and in all seasons, reveals that soil properties which control percolation rates differ more at 36-inch than at 18-inch depths. The development of a solum or weathered zone has equalized, to some extent, percolation rates among the three soils, but their sharply contrasting substrata have percolation rates that are widely divergent. The variability within each soil, however, is not the same; the Merrimac soil is less variable at 18 than at 36 inches while the Wethersfield is variable at 18 inches but is uniformly impermeable at 36-inch depths.

Another general characteristic of the variability is its relation to the mean. The mean and standard deviation of each of the 22 triplets of observations at each site, depth, and season was calculated. Figure 7 shows an obvious relation between the standard deviation and the mean, therefore the percolation rates were transformed into log percolation rates and reanalyzed. No obvious correlation existed between standard deviation and mean of the logarithms. The standard deviations of most of the triplets were about 0.20. Three triplets at 18 inches and one at 36 inches in Wethersfield soil, however, had much larger standard deviations, fully 0.85. Since these four triplets were significantly more variable than the main body of the observations, they are excluded from the following analyses of variance and are discussed individually in a subsequent section.

Variation Within and Between Sites

Soil moisture, as we shall see, has a great effect upon percolation rates; therefore, the observations were segregated into categories of wet, moist, and dry soil before the other sources of variability were examined. Since percolation rates have been determined at all sites for moist soil, observations made in moist soils can be used in assessing both site and depth variation without introducing the effect of moisture. In Table 4, the percolation rates in moist soils at five sites and two depths are tabulated. Analysis of variance (Table 5) of the log of the percolation rates in Table 4 shows that the variability between sites that are in different series is greater than the variability between sites within the same series; although the difference is not statistically significant, there is little doubt that it is real. The variability between sites within the same series is, in turn, significantly greater than the variability within a site. This is particularly evident in the Wethersfield soil.

Table 4. Percolation rates, inches per hour, in moist soils

Depth	Cheshire 1	Cheshire 2	Merrimac	Wethersfield 1	Wethersfield 2
18"	28	10	33	.44	7.1
	9	7	18	.19	2.9
	10	11	10	.81	20.0
36"	33	5	33	.06	0.9
	16	6	60	.09	0.8
	18	6	143	.06	1.9

Depth

The effect of depth upon the mean percolation rate is a pertinent subject because depths from 24 to 36 inches have been recommended for the holes used in percolation tests (7). In the analysis of variance (Table 5) the mean square for depth is not significantly greater than the mean square for the interaction of depth by site. That is, the effect of depth upon the mean rate is not significant or consistent over the sites that we have sampled. Variability is, however, more important here than the means.

Table 5. Analysis of variance of percolation rates tabulated in Table 4

Source of variation	Degrees of freedom	Mean square	"F" ratio
Site			
Between series	2	7.26	120**
Within series	2	2.48	41**
Depth	1	.36	6*
Depth × Site	4	.54	9**
Within site (at the same depth)	20	.06	

**Significant at the 1 per cent level
*Significant at the 5 per cent level

Earlier the (page 16) observations of Figure 6 showed that the range in percolation rates was greater at 36 inches than at 18 inches. Now, if we calculate the mean square for the variation among sites at 18 inches and at 36 inches, we find that the variation, the mean square, at 36 inches is three times as great than

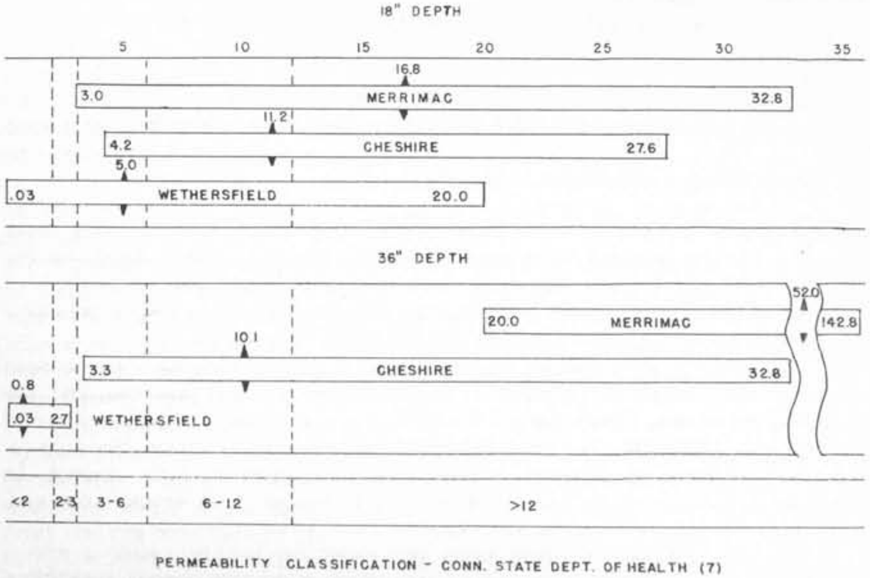


Figure 6. Range in percolation rates, inches per hour, for all tests in Merrimac, Cheshire, and Wethersfield soils. Triangular symbol indicates mean rate for all observations.

the mean square among sites at 18 inches. This is a significant difference and confirms the casual observation that percolation rates at 36 inches are indeed more variable than those at 18 inches.

Water and Season

The obvious difference between spring, summer, and fall is the water content of the soil. We here define the wet soils as those observed in early spring following the spring thaw, the moist soils as those observed later, and the dry soils as those observed during early autumn. Agriculturists would say that the wet soils are at "field capacity" and the dry soils are at "the wilting point." The moist soils fall somewhere between the two.

The effect of soil moisture upon percolation rates can be seen in the data of Table 6. The numbers in Table 6 are mean percolation rates; the averages of triplets or observations at three holes at the same site and at the same time. The data for the wet and moist condition at the 18- and 36-inch depths in the two Cheshire and the one Merrimac sites were orthogonal, and an analysis of variance could be performed. This analysis revealed that the effect of moisture was significant and similar for both depths at all three sites.

Table 6. Mean percolation rates, inches per hour, in wet, moist, and dry soils. Means of three holes.

Soil	Initial moisture		
	Wet	Moist	Dry
		18" depth	
Merrimac	13.3	20.4	20.6
Cheshire 1	12.5	15.7	10.7
Cheshire 2	7.5	9.5	......[1]
Wethersfield 1	.26[3]	.31[3]	.17[3]
		36" depth	
Merrimac	25.5	78.5	......[2]
Cheshire 1	7.3	22.2	11.6
Cheshire 2	3.9	5.5	......[1]
Wethersfield 1	Water table	.07	......[2]

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[1] Rates in dry soil not measured because plot area became inaccessible.

[2] Rates in dry soil not measured because soil did not dry sufficiently to contrast with moist soil.

[3] Average of duplicate observations.

This characteristic change in percolation with soil moisture can be seen at the 36-inch depth in Cheshire 1. In the spring the soil was wet, and the percolation rate was 7.3 inches per hour. As the soil dried, the percolation rate increased to 22.2 inches per hour. Although the evidence is scanty, the percolation rate appeared to decrease as the soil dried further in early autumn. In Cheshire 1, the percolation rate fell from 22.2 inches per hour in the moist soil, to 11.6 inches per hour in the dry soil.

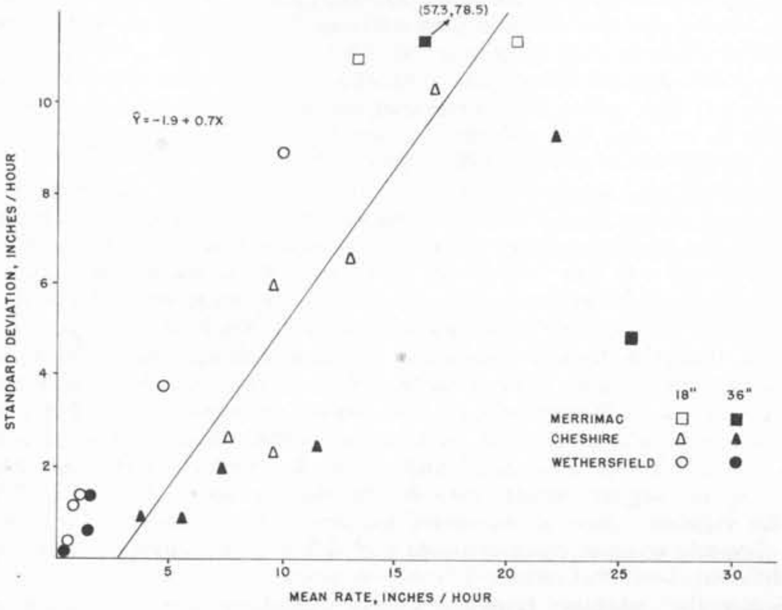

Figure 7. Relationship between standard deviation and mean percolation rate for all observation triplets in Merrimac, Cheshire, and Wethersfield soils.

The effect of soil moisture upon the variability within a site is also a significant matter. Since moist soils have more rapid percolation rates than either wet or dry soils, and since the variation of the percolation rates is proportional to the rates (Figure 7), we predicted that variability would increase in moist soils. The standard deviations of the percolation rates for wet and moist Cheshire and Merrimac soils are tabulated in Table 7. These are the data that were earlier subjected to an analysis of variance. The mean square for moist soils, within sites, is 18 times as great as that for wet soils. Certainly, this is a significant difference. In dry soil, the rates are slower than in the moist soils, and as Figure 7 demonstrates, the rates are less variable. Therefore, the percolation rates obtained from tests in moist soil in late spring and early summer are most rapid and most variable within a site, while those obtained in the wet soils of early spring or possibly the dry soil of early autumn are slower and less variable.

We turn now to investigation of the effect of observed variability upon the decisions that must be made after the percolation rate is observed.

Table 7. Standard deviations of percolation rates, inches per hour, in wet and moist Cheshire and Merrimac soils

Depth		Cheshire 1	Cheshire 2	Merrimac
18"	Wet	6.5	2.6	11.0
	Moist	10.3	2.4	11.4
36"	Wet	1.9	0.8	4.8
	Moist	9.3	0.8	57.3

Decisions

In Connecticut, decisions concerning the suitability and design of septic tank drain fields are made according to which Connecticut Department of Health permeability class the rate falls within (7). In Figure 6 these classes are separated by vertical dashed lines, and they are identified in the figure and in the text by their limits in inches per hour.

The practical question is whether or not the variability naturally encountered in a given soil type, within or between sites, will cause a percolation rate to lie sometimes in one class and sometimes in another, causing important practical decisions to depend on chance variability.

The within-site standard deviation at 18 inches in moist Merrimac soil is about 11 inches per hour (Table 7). This variability will cause the individual percolation rate to lie somewhere between the boundary of class 3-6 and 6-12 on one hand and well into >12 on the other hand. At 36 inches, the standard deviation for moist Merrimac is even greater, but the entire range lies within class >12 and will cause no confusion in decisions (Figure 6).

In Cheshire, the standard deviation at 18 inches within a site, is sufficiently great to cause observations to lie in classes 3-6, 6-12, or >12. This is also true at 36-inch depths. In Wethersfield soil, the standard deviation at 18-inch depths within a site is sufficiently great to cause individual observations to lie in classes <2, 2-3, 3-6, or 6-12. At 36-inch depths, the percolation rates are uniformly low. The decision would clearly be that the rate lay in class <2 or 2-3. Thus, the variability encountered among percolation rates obtained at a single site is obviously going to make decisions very difficult, for individual rates may lie in different classes that require different decisions.

Finally, the variability from site to site must be examined in terms of permeability classes and decisions. Table 5 showed that the mean square for the within-site variability was only one-fortieth as great as the variability between sites. The difficulty of making decisions concerning one site, in Wethersfield for example, from percolation rates on another site is extremely great.

The variation from wet, to moist, to dry soil or from spring, to summer, to autumn conditions (Table 6) must be examined in terms of Connecticut Department of Health permeability classes and decisions. In many soils the mean percolation rate (Table 6) whose seasonal variations are significant, vary within the empirical permeability class. In these soils, decisions are not dependent upon the season in which they are measured. Some soils did not share this good fortune and the Cheshire 1 soil at 36-inch depths provides a good example. When the soil is wet, the mean percolation rate is 7.3 inches per hour which places it in class 6-12; when the soil is moist, the percolation rate is 22.2 inches per hour which puts it is class >12; when the soil is dry, the percolation rate is 11.6 inches per hour which puts it in class 6-12 again. Thus, the percolation tests performed when the soils are moist provide an optimistic answer concerning septic tank leaching field performance. To obtain rates that occur when water transmission conditions are poorest, it is necessary to perform the test when the soils are either excessively wet or dry. Percolation testing in wet soil has, of course, two advantages. First, it provides a conservative estimate of soil capability to transmit effluent; secondly, the slow rates are less variable and the difficulty of locating the rate within a single class is made easier. That is, the mean percolation rate can be estimated with a smaller standard deviation with equal sample numbers or with an equal standard deviation with fewer samples in a wet than in a moist soil.

At this point, it is important to recall that pre-soaking to saturate the soil and eliminate seasonal or initial moisture effects (8) (10) (23) was shown in an earlier section to fail to perform this function. Pre-soaking of the holes does provide an equilibrium rate, a short-term constant, but the soil is not saturated and the short-term equilibrium rates do vary from season to season.

The final question to be examined is whether the variability observed in the field permits soil surveys to be employed in predicting percolation rates and septic tank leaching field performance.

PREDICTING PERCOLATION RATES FROM SOIL SURVEYS

Soil surveys are being used more and more by those concerned with urban expansion. The most satisfactory use of the soil surveys has been for making preliminary estimates of suitability for effluent disposal and for planning detailed field investigations.

The use of soil surveys for predicting septic tank leaching field performance was pioneered in Fairfax County, Virginia (22); Montgomery County Maryland (15); and Hartford County, Connecticut (25). Soil series were rated individually in Hartford County according to their estimated disposal capacity; in Fairfax and Montgomery counties, mapping units with similar soil properties were collected into suitability groups. More recently, mapping units have been collected into groups with slight, moderate, and severe limitations for leaching fields. The soil properties considered are permeability, texture, structure, slope, depth to water table or bedrock, and frequency of surface flooding. We now examine the predictability of the State of Connecticut percolation rate class from the soil series name.

The 74 percolation rates for all the observation holes in the three soils at the two depths were translated into permeability classes according to the Connecticut Department of Health criteria. The percentage in each class is tabulated in Table 8 according to soil series and depth. There are obvious differences in predictability.

Table 8. The per cent of percolation rates observed in the five permeability classes established by the Connecticut Department of Health (7). The boundaries of these classes are shown in Figure 6

Soil	Depth inches	Mean perc. rate falls in class	Probability of perc. rate falling in class					No. of observations
			>12	6-12	3-6	2-3	<2	
Merrimac	18	>12	80	10	10	0	0	8
	36	>12	100	0	0	0	0	6
Cheshire	18	6-12	30	50	20	0	0	16
	36	6-12	40	20	40	0	0	17
Wethersfield	18	3-6	10	20	0	20	50	15
	36	<2	0	0	0	10	90	12

At a depth of 36 inches, the predictability in some soils is high. For example, in a tract of land with a map symbol for Merrimac or Wethersfield, the probability that the percolation rate at any time of the year will fall within class >12 for Merrimac and class <2 for Wethersfield is greater than 90 per cent. In Cheshire, on the other hand, the predictability is less. The rates are distributed between classes 3-6, 6-12 and >12. The user should also beware, because up to 15 per cent of the area within a map unit may, by definition, be another soil series.

The ability to predict percolation rate classes at 18 inches is less than at 36 inches, in spite of the fact that the 18-inch rates are less variable. The scattering of the rates through the different classes in Table 8 is as much a manifestation of the location of the class limits as of the variability of the rates.

Soil survey maps have been suggested (18) as a substitute for percolation tests. For some soils, such as Merrimac or Wethersfield at 36 inches, this is a distinct possibility. For other soils, such as Cheshire, there seems little hope for the substitution. The soil classification system, of course, causes some of the predictability and unpredictability. The soils that are predictable are those that are so good or so bad, from a leaching field point of view, that the percolation rates lie wholly above the lower limit of the good or below the upper limit of the bad. This is shown in figure 6. The variability of a very bad soil lies wholly within a single permeability class, whereas intermediate soils fluctuate between classes. Thus, a simple permeability classification system, for interpretative use with descriptive terms such as satisfactory, variable, and unsatisfactory might be predicted from soil survey maps. The use of a five-class system, such as is used by the State Health Department, seems unpredictable, especially the intermediate classes.

Another problem in prediction is that soils do not all conform to the concept of the series. In this study, holes were selected where the soils exhibited morphological characteristics ascribed to that series. In the statistical analysis, however, four observation triplets in the Wethersfield soil had standard deviations of log percolation rates significantly greater than all of the other observation triplets. The cause of this variability was profile morphology that deviated from the Wethersfield concept in the direction of Cheshire soils. In evaluating soils for effluent disposal, the mean rate for that series obviously pertains only to the soils near the ideal and not to the deviates.

If it is necessary to assign a rate for interpretative purposes, the most useful satistics to represent the soil series can be illustrated by the Wethersfield rates. At 18 inches, half the rates fall in the slow class <2 (Table 8) which would seem to correspond to the Wethersfield concept. But observations lie in most of the other classes too. The average rate falls in class 3-6, where, in fact, there were no observations. The average seems, therefore, a poor rate to assign to the areas called Wethersfield on a soil map. Two alternate assignments can be suggested. First, the intergrades in Table 8 can be discarded and the rates of class <2 of the Wethersfield concept assigned (i.e. the mode). Or, more realistically, the user can be told that the Wethersfield soil at 18-inch depths had variable rates but tended to be in class <2.

In addition to the problems of prediction already mentioned, there is a further problem. This is the use of the saturated conductivity rates obtained from undisturbed core samples (27) in predicting the unsaturated conductivity reflected in the percolation rates obtained from test holes. In the laboratory, the confined core samples are saturated, and water under a 1-inch head is forced through the core. This saturated conductivity is greatly increased by the presence of large pores in the soil, whereas, the percolation rate from a test hole may be decreased by the presence of large pores. Therefore, it is not surprising that the average field percolation rate is not proportional to the average laboratory permeability rate (Table 9). Great care must be taken in predicting percolation rates for soil series names using saturated permeability rates obtained from soil cores.

In conclusion, a survey of soil series can be the basis of predicting satisfactory, variable, and unsatisfactory percolation rates. This is the consequence of the variability from place to place within a site and between sites of the percolation rates themselves.

Table 9. Comparison between average percolation rates from field tests and average permeabilities from laboratory determination

Soil	Depth	Average field percolation rate inches/hour	Average laboratory permeability rate inches/hour	R_f/R_l
Merrimac	18″	13.3	8.7	1.5
	36″	25.5	16.4	1.5
Cheshire	18″	8.1	2.1	3.9
Wethersfield	18″	1.0	0.6	1.7

SUMMARY

1. Water flows from a percolation test hole through unsaturated soil, and its movement is governed more by capillary forces than by gravity. Saturated flow occurs only in the presence of a water table.

2. Percolation rates decline with time from the moment that water is added to the hole. Temporary equilibrium rates were established in about 4 hours in most soils examined. In a soil with a compact substratum, the equilibrium rate was not attained until 16 hours had passed.

3. In two-thirds of the observations, the percolation rate initially declined in proportion to $(\text{time})^B$ where B varied from 0.7 to 0.9. In the remaining third, the decline differed from this pattern in a manner not explained by profile morphology. The equilibrium rate in soils without a compact layer could be calculated as the slope of the linear relation between "rate × elapsed time" and elapsed time.

4. Because variations between sites within the same soil type are greater than variations within sites, several sites rather than several holes within one site must be examined before a rate or range of rates is assigned to a soil type.

5. Percolation rates are more variable at 36-inch depths than at 18-inch depths.

6. Percolation rates are significantly affected by moisture content. They are low in the wet soil of early spring, increase as the soil dries during late spring and summer, and decrease again if the soil dries excessively in late summer and early fall.

7. In some Connecticut soils, the seasonal variation in percolation rates lie wholly within a State Health Department permeability class while others may lie in different classes at different times of the year. Those that lie within a permeability class are either very fast or very slow transmitters of effluent.

8. Soil surveys can be used effectively to estimate leaching field capacity when the soil conforms to the ideal or modal concept of the soil type. Because soils vary, assigning precise, narrow ranges of rates to soil types is misleading; instead the simple categories of "satisfactory," "variable," and "unsatisfactory" would seem wiser.

9. Predicting percolation rates from saturated conductivities of soil cores in the laboratory is dangerous. The conductivities do not reflect changes in texture and structure above and below the region from which the core was taken, whereas, these changes would influence percolation rates. Further, water flows from the test hole through unsaturated soil.

10. Suggested modifications of the standard percolation test arise from the following observations:

a. A constant head of water in the test hole prevents air from entering the pores in the wall of the hole and slowing the rate.

b. Structural support of the hole wall is necessary in soils with weak structure to minimize slumping and scouring. Filling the hole with gravel was found satisfactory.

c. Percolation testing in early spring conservatively indicates the capacity of the soil to transmit effluent. Also, percolation rates are less variable at this time and high water tables, if present, can be observed.

d. If a constant head of water is maintained in a hole in the nonswelling soils which predominate in Connecticut, percolation rates have essentially reached equilibrium at the end of 4 hours. In soils with compact substrata, equilibrium rates are reached more slowly.

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