AN APPROACH TOWARD A PHYSICAL INTERPRETATION OF INFILTRATION-CAPACITY[1]

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INFILTRATION-CAPACITY was first defined by the author as the maximum rate at which a given soil when in a given condition can absorb rain as it falls (6, 7).[3] Infiltration-capacity is usually designated by f, and since f varies with time, especially during the early part of rain, it is to be understood that the condition of the soil and hence the infiltration-capacity, vary with time, until a certain minimum infiltration-capacity f_c is reached.

It would be better to use the term "terrain" rather than the term "soil" in discussing infiltration-capacity, for the reason that infiltration-capacity is governed not only by soil in the ordinary sense—comminuted mineral matter, with more or less organic matter—but in the broader sense of the soil as involving not only its mineral composition, texture and micro-structure or ordinary crumb-structure but also its macro-structures, including root systems, root perforations, sun-checks, earthworm perforations and other biologic structures, and its vegetal cover.

Certain other factors, such as temperature of the air, and of rain and soil surface, rain intensity, initial soil-moisture, initial and residual rain occurring at intensities less than the infiltration-capacity, also require consideration.

In a previous paper the author showed that f has an initial value f_0 at the beginning of rain and that if rain is continued at an intensity $i > f$, the infiltration-capacity will decrease with rain duration in accordance with the equation (8)

$$f = f_c + (f_0 - f_c)\, e^{-K_f t} \quad . \qquad 1$$

This was originally given as an empirical equation. It can, however, be derived from the simple assumption that the processes involved in the reduction of f as rain continues are of the nature of exhaustion processes. These processes include rain-packing, in-washing, breaking down of the crumb-structure of the soil, the swelling of colloids and, in cases where they occur, the closing of sun-checks.

The graph of an inverse exponential equation can be represented over a considerable range by a hyperbola having the equation $f = \frac{a}{t^n}$. Such a hyperbolic equation or an equation for total infiltration derived therefrom by integration has sometimes been given (4). Hence it has seemed necessary to point out that such an equation, while it may quite accurately represent experimental data of an infiltration-capacity curve over a considerable range, violates the fundamental principle of curve fitting that the equation adopted should if possible fit not only the experimental data but give correct results for known conditions outside the experimental range. The above equation gives infinite initial infiltration-capacity for $t = 0$ and indicates that the infiltration-capacity approaches zero as a limit as the duration of rainfall increases, whereas, in fact, the infiltration-capacity almost invariably approaches a constant finite value, not zero.

A rational equation may be defined as one which can be derived directly from fundamental principles, which fits all the experimental data and which represents the physical conditions correctly throughout the entire range of their occurrence and hence is valid outside the range of experimental observations. Equation 1 above given has been found to fit hundreds of experimental infiltration-capacity curves obtained from different soils with different types of vegetal cover and in widely separated regions. This equation may therefore be accepted (a) as being at least semi-rational, in that it can be directly derived from fundamental principles, (b) as giving a complete picture of the infiltration characteristics of a given soil or terrain with its attendant conditions.

The factors affecting infiltration-capacity may be thrown into three classes, *viz.*, (a) soil and soil profile, (b) biologic and macro-structures within the soil, and (c) vegetal cover.

The infiltration-capacity—time equation above given contains three constants: f_0, the initial infiltration-capacity at the beginning of rain or at a chosen moment; f_c, the final constant infiltration-capacity, and K_f, a constant which governs the time required under given conditions for infiltration-capacity to change from its initial value f_0 to nearly its constant value f_c.

Physical processes which affect infiltration-capacity may not and in fact quite certainly do not affect

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[3]Figures in parenthesis refer to "Literature Cited", p. 417.

all these factors in the same way. Consequently little success has attended efforts to interpret infiltration-capacity curves as a whole in terms of different variables. Better success may be expected from consideration of the manner in which each different physical process operates on the different constants in the infiltration-capacity equation.

This paper largely centers around the meaning and interpretation of the three constants, f_0, f_c and K_f. Attention is also called to some of the outstanding problems in connection with infiltration-capacity.

The subject is treated throughout this paper from the viewpoint of physics and hydrodynamics, to which it most properly belongs. It is regretted that a large volume of experimental data studied by the author before undertaking the preparation of the paper have not yet been published and cannot be made available to the reader. Enough data have been published, and citations are given thereto, to afford an opportunity to check the various conclusions given.

RELATION OF INFILTRATION-CAPACITY TO LAND USE AND FLOOD CONTROL

The march of events during a shower which produces surface runoff is usually as shown by Fig. 1. At the start there is an interval t_1 of initial rain at intensity less than infiltration-capacity. During this

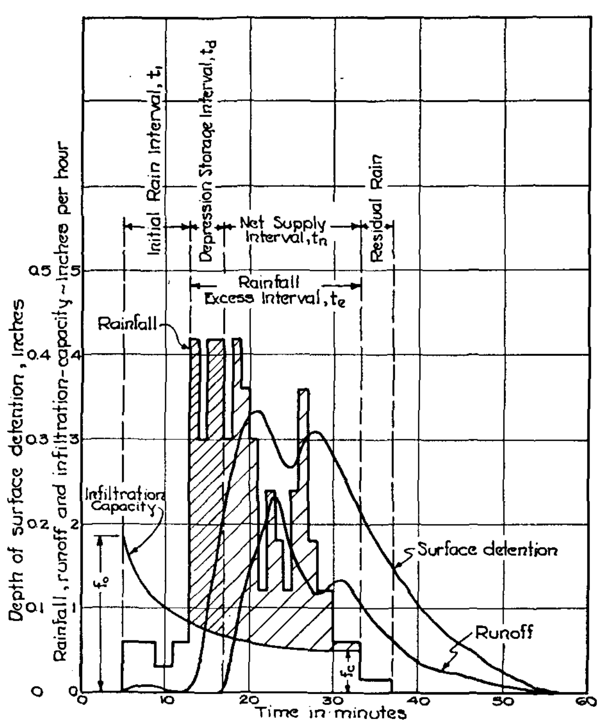

FIG. 1.—Relation of rainfall to surface runoff, Ewing and Washington block, St. Louis, Sept. 7, 1916.

interval the rain is all absorbed by the soil, no surface runoff occurs and no surface detention accumulates. The infiltration-capacity is, however, reduced by this rain until, at the time t_1, it becomes less than the rain intensity. Then during a second interval t_d the excess rain above the amount absorbed by the soil goes to fill the surface depressions and no runoff occurs. When the surface depressions are filled, rainfall excess continuing produces, first, surface detention and, from this, surface runoff. On Fig. 1 the part of the rain which falls at intensities exceeding infiltration-capacity is designated rainfall excess and this is indicated by the cross-sectioned area. At the end of rainfall excess, t_n, previously accumulated surface detention still remains and is gradually disposed of by infiltration or by surface runoff. During the interval while surface detention is disappearing there may be and usually is rain at an intensity less than the then infiltration-capacity of the soil, and this residual rain goes in part into surface runoff, but the total surface runoff in most cases is sensibly equal to or at least not greatly different from the total rainfall excess. Hence if the infiltration-capacity of a given terrain is known, together with the rain intensity graph, the surface runoff can be immediately determined.

It will also be seen that for a given terrain, rain intensity and duration, together with infiltration-capacity, completely determine surface runoff both as to intensity and volume. While the effects of floods are most commonly observed in and adjacent to stream channels, floods always originate on the ground surface and are chiefly composed of direct surface runoff. Since the rainfall of a given region cannot be changed, efforts toward flood control outside stream channels, erosion control, and increase of crop production through improved land use practices or variation in vegetal cover, must necessarily be directed in a large measure toward increase of infiltration. This may be brought about either through increase of infiltration-capacity or through storage behind terraces or other structures, in such a manner as to prolong the opportunity for infiltration to take place.

INFILTRATION-CAPACITY AND INFILTRATION RATES

It is unfortunate that the terms "infiltration-capacity" and "infiltration rates" have sometimes been confused. Infiltration can take place at any rate from zero up to the capacity rate. If the rain intensity is less than the capacity, then the infiltration rate is not the capacity and should not be so referred to. On the other hand, if infiltration is taking place at capacity rate, it should be referred to as *capacity*, not merely as a *rate*. In other words, there may be an infinite variety of rates but there is only one capacity at a particular time for a particular soil. The situation is somewhat like that of flow of water through a pipe of a given length and size connecting two reservoirs. Such a pipe has only one capacity—that when it is flowing full—but water may flow through the pipe at an infinite variety of rates ranging from zero up to its capacity.

EQUATION OF INFILTRATION-CAPACITY

It has generally been found that during continuous rain the infiltration-capacity of a given terrain decreases, at first rapidly, then approaching an asymptotic line in such a manner as to give a constant or fixed infiltration-capacity after the lapse of a certain time interval, commonly ¼ hour to 3 hours but usually between ½ hour and 1½ hours.

Consider a soil surface which has become partially dried since the last rain. When another rain begins, the soil surface is directly exposed to the impact of the raindrops, as there is not yet any surface detention to protect it. Three effects commonly take place as follows:

1. Breaking down of the crumb structure of the soil surface, thereby decreasing the size of the soil pores and more or less filling the macro openings, such as sun-checks, insect and earthworm perforations with inwashed fine material.

2. An actual packing or puddling of the soil surface, thereby decreasing its porosity.

3. In soils containing colloids, swelling of the colloids takes place, also decreasing the pore space available for the flow of water into and escape of air from the soil.

All of these processes partake of the nature of exhaustion phenomena. For example, as rain packing proceeds to greater depths, the effect of impact of drops at the surface decreases. An exhaustion process may be defined as one in which the rate of performing work is proportional to the amount of work remaining to be performed. Such processes are common in Nature and follow an inverse exponential law. In case of a soil surface the work remaining to be performed at a given time t is that of changing the infiltration-capacity from its then value f to its ultimate constant value f_c. The rate of performing work is $\frac{df}{dt}$. In this case f is decreasing and $\frac{df}{dt}$ is negative. If this rate is proportional to the work remaining to be performed, $(f - f_c)$, then introducing a factor of proportionality K_f and equating gives

$$-\frac{df}{dt} = K_f (f - f_c)$$

or

$$-\frac{df}{f - f_c} = K_f \, dt.$$

But

$$\frac{df}{f - f_c} = d \ln (f - f_c).$$

Integrating and changing signs,

$$\ln (f - f_c) = - K_f t + \text{const.}$$

When $t = 0, f = f_0$. $\therefore$ const. $= \ln (f_0 - f_c)$ and

$$\ln \frac{f - f_c}{f_0 - f_c} = K_f t$$

or

$$\frac{f - f_c}{f_0 - f_c} = e^{-K_f t}$$

and

$$f = f_c + (f_0 - f_c) e^{-K_f t}. \qquad 1$$

Methods of derivation of the constants in this equation from infiltrometer experiments have been given elsewhere (8). By throwing the equation into the form

$$f - f_c = (f_0 - f_c) e^{-K_f t}$$

the experimental values of f can be platted as a straight line on semi-logarithmic paper in terms of t and the value of K_f determined from this line. This has the advantage that the line represents all the data and usually gives a more accurate value of K_f than would be derived from two selected points on a curve.

TIME REQUIRED FOR INFILTRATION-CAPACITY TO BECOME SENSIBLY CONSTANT

The critical time t_c has been defined as the time from the beginning of rainfall excess, required for infiltration-capacity to become sensibly constant and equal to f_c (8). Since $f \longrightarrow f_c$ asymptotically, t_c has been more specifically defined as the time required for f to drop from its initial value f_0 to a value $1.01 f_c$ or 1% greater than its constant value.

The time t_c can be determined by the equation

$$t_c = \frac{1}{K_f} \ln \frac{100 (f_0 - f_c)}{f_c}. \qquad 2$$

Unfortunately this value of t_c is not constant for a given soil and cover, since it depends on the initial value f_0 of f, which in turn may have different values depending on the initial soil-moisture and initial rain before rainfall excess begins.

INFILTRATION-CAPACITY EQUATION IN TERMS OF f_1 AT BEGINNING OF RUNOFF

The infiltration-capacity—time equation has thus far been expressed in terms of f_0, the capacity at the beginning of rain. This has the advantage that f_0 can be approximately predicted from soil-moisture.

To determine total runoff during a given storm, it is also desirable to express f in terms of f_1, the infiltration-capacity at the beginning of runoff.

If t_1 = time from beginning of rain to beginning of runoff, and t_n = time measured from beginning of runoff, then

$$t = t_n + t_1.$$

From equation 1

$$f = f_c + (f_0 - f_c)\, e^{-K_f(t_1 + t_n)} \qquad 3$$

$$= f_c + (f_0 - f_c)\, e^{-K_f t_1} \cdot e^{-K_f t_n}.$$

When $t_n = 0$, $f = f_1$,

$$f_1 = f_c + (f_0 - f_c)\, e^{-K_f t_1}.$$

This gives

$$f_0 = \frac{(f_1 - f_c) + f_c\, e^{-K_f t_1}}{e^{-K_f t_1}}.$$

Substituting this value of f_0 in equation 3 gives:

$$f = f_c + (f_1 - f_c)\, e^{-K_f t_n}. \qquad 4$$

This shows that, starting at any point on an infiltration-capacity curve represented by the equation

$$f = f_c + (f_0 - f_c)\, e^{-K_f t}$$

and using the value of f at this point as f_0, and measuring time from this point on, equation 1 still applies. Hence f_0 may be given any assigned value and t measured from the time when this value occurs on the curve, without changing the form of the equation or the value of K_f. This fact makes it possible to determine the time required for f to drop from any assigned value to 1.01 f_c. For example, if f_0 is taken equal to 1.0, then, using the time at which this occurs as the origin, the f curves for different kinds of cover and treatment will start at the same point, and the differences between the curves will reflect treatment differences of soil and cover, with the same initial infiltration-capacity.

For $f_0 = 1.0$, a new critical time, which may be designated t_{c1}, will be the time required for f to drop from unity to 1.01 f_c and will be given by

$$1.01 f_c = f_c + (1 - f_c)\, e^{-K_f t_{c1}}$$

or

$$t_{c1} = \frac{1}{K_f} \ln \frac{100\,(1 - f_c)}{f_c}. \qquad 5$$

Another measure of critical time can be defined in terms of the time required for f_c to drop from an initial value n X f_c to 1.01 f_c. The value n = 10 or $f_0 = 10 f_c$ has been chosen for several reasons. This value may be called t_{10}. It is the time required for f to decrease through a range sensibly 10 times f_c and is given by

$$1.01 f_c = f_c + (10 f_c - f_c)\, e^{-K_f t_{10}}$$

from which

$$t_{10} = \frac{1}{K_f} \ln 900 = \frac{6.80}{K_f}. \qquad 6$$

It is to be remembered that t_{10} is not the time from the point at which f = 10 inches per hour but from the point at which $f = 10 f_c$. Values of $f = 10 f_c$ commonly come within the range of experimental determination. Also the value of the critical time t_{10} would be little affected by a considerable change in the value of n. For example, if n = 20 or $f_0 = 20 f_c$ instead of $10 f_c$, then

$$t_{20} = \frac{\ln 1900}{K_f} = \frac{7.54}{K_f} \qquad 7$$

or the critical time would be increased only 11% as compared with that obtained by using t_{10}.

DETERMINATION OF INFILTRATION-CAPACITY

The following named methods have been used for determining infiltration-capacity.

THE TANK METHOD

As in Neal's experiments, a tank is filled with soil and simulated rainfall applied (8). Obviously, micro-structures and biologic structures are eliminated, and such experiments show the effect of soil alone on infiltration-capacity. Similar tanks, artifically filled and exposed to rainfall under natural conditions, are also sometimes used.

THE RAINFALL SIMULATOR

In applying this method a metal frame is set up over a natural plat and rainfall simulated by a sprinkling apparatus is applied, and the runoff caught and measured in a tank. If a sufficiently large plat is used, preferably at least 6 × 12 feet or larger, this method gives infiltration-capacities under nearly natural conditions as to soil, soil profile, vegetal cover and soil structures, though not as to rainfall.

It is subject to the objection that the artificial rain does not usually have the same drop sizes as natural rain, and the rain is applied at uniform intensity, whereas under natural rainfall conditions there is nearly always a period of low intensity at the beginning of a shower. As the result of the high initial rain intensity, greatly accentuated erosion may occur, with consequent effects on the infiltration-capacity.

At the present time two principal types of rainfall simulators are in use by the U. S. Soil Conservation Service. The type F simulator is designed for plat 6 × 12 feet or larger. This apparently gives results, when properly interpreted, comparable with those obtained from actual determination of infiltration-capacity under natural conditions from measured rainfall and runoff on small drainage basins. The North Fork or type FA infiltrometer (13) is similar to the preceding type but smaller, covering only a plat 12 × 30 inches. Data presently available indicate that it usually gives, on the same soil, much higher values of infiltration-capacity than those obtained from the type F or larger plats. While in many cases the type FA gives infiltration-capacity curves with values of f higher than those obtained from larger plats—other things equal—throughout the whole experiment, there are departures from this rule which make it difficult to establish a constant relationship or factor for reduction of the results obtained with type FA apparatus to those which would have been obtained with type F apparatus.

The higher values of infiltration-capacities obtained with the type FA apparatus are apparently due to two causes. First, disturbance and opening of the soil around the perimeter of the plat by the insertion of the boundary plates of the infiltrometer in the soil. This is especially likely to occur if the soil is stony and as a result there is a strip around the margin of the infiltrometer through which infiltration takes place much more rapidly and escape of air takes place more readily than over the interior of the plat. A similar effect takes place in the use of larger plats but is more nearly negligible in the result because of the smaller ratio of perimeter to area for the larger plats. For a plat 6 × 12 feet the ratio of perimeter to area is 36/72 = 1/2. For a type FA infiltrometer this ratio is 7/2.5 = 2.8. Hence the perimeter per unit of area for a type FA plat is 5.6 times as great as for a type F plat.

Suppose, for example, the infiltration-capacity is doubled in both cases for a strip 3 inches wide around the perimeter of the plat. Then a type F plat actually 6 × 12 feet would give the same total infiltration as an undisturbed plat 6.5 × 12.5 feet or 13% in excess of the true value computed on the basis of a 6 × 12-foot plat.

A type FA plat 1.0 × 2.5 feet would give the same total infiltration as an undisturbed plat 1.5 × 3.0 feet, or 80% in excess of the true value.

The second factor involved is the escape of air. Under natural conditions, where rain occurs over a wide terrain, air escapes through the soil surface and cannot spread laterally. In case of a sprinkled plat, only the soil on and closely adjacent to the plat is wetted and air can escape laterally below the depth of penetration, and the freedom of such lateral escape of air is about six times as great in case of a type FA as in case of a type F plat. It has sometimes been assumed that this condition is remedied by sprinkling a strip say 3 feet wide around the margin of the plat as over its surface. This does not provide a remedy for lateral escape of air although it prevents the lateral spreading of water around the margin of the plat. The latter is, however, quite certainly of much less importance than the lateral spreading of air.

THE TUBE METHOD

In applying this method a tube, usually 9 inches or more in diameter, is jacked down over a prism of soil to a depth of perhaps 3 or 4 feet. The soil surface within the tube is smoothed and water is applied by a burette and kept at a constant depth over the soil surface. The friction of the tube as it is jacked into the soil provides an excessive disturbance of the soil within the tube. There is also free lateral escape of air and water at the base of the tube. The experiment does not simulate natural conditions since the entire soil surface is smoothed and covered with water to a constant depth, a condition which does not exist in nature. Compared with experiments with type F plat infiltrometers, results obtained by the tube method are often three to five or seven times greater for the same soil.

It has sometimes been assumed that results obtained by the tube method could be used as indexes of infiltration or that they show correctly the relative infiltration-capacities of different soils.

Suppose that the true infiltration-capacities of the soil on two different plats are f_1 and f_2 but that as a result of disturbance of the soil around the perimeter of the tube and the lateral escape of air below the tube, an additional quantity of water q_1 passes through the first, and a quantity q_2 through the second infiltrometer. The ratio of the true infiltration-capacities will be $\frac{f_1}{f_2}$. The apparent ratio of the infiltration-capacities as derived from the tube experiments will be $\frac{f_1 + q_1}{f_2 + q_2}$. The quantities q_1 and q_2 do not necessarily bear any definite relation to the true infiltration-capacities of the soils but are governed largely by the accidental occurrence of stone in the soil and the personal equation of the operator in jacking the tube into the soil. Hence there is no reason for assuming that the ratio $\frac{f_1 + q_1}{f_2 + q_2}$ bears any constant or definite relation to $\frac{f_1}{f_2}$ or that the experiments give true relative infiltration-capacities.

AREAL INFILTRATION-CAPACITY DETERMINATION

Given a good record of surface runoff, together with adequate recording rain gage and other rainfall data, it is possible to determine the average areal infiltration-capacity over a given drainage basin with considerable accuracy. Details of the method of procedure are given elsewhere (9, 10). This method gives results under natural conditions in all respects but unfortunately it is difficult to find drainage basins on which the terrain, including both soil and cover conditions, is sufficiently uniform so that the results will represent those corresponding to a single soil and cover type alone. In order to compare infiltration-capacities for different soils and cover types it is therefore desirable to supplement areal determinations of infiltration-capacity by determinations under more fully controlled conditions, as, for example, those obtained with the type F infiltrometer, or from small plats with given cover conditions and natural rainfall. There are, however, significant differences between the results obtained by areal determinations of infiltration-capacity and those obtained by the infiltrometer method as follows:

(a) Under natural conditions and for areal determinations there is usually an interval of initial rain at intensity less than infiltration-capacity.

(b) The rain intensity under natural conditions is usually less than that applied by rainfall simulators, and the rain intensity under natural conditions is more or less variable, sometimes highly variable, while in the use of the rainfall simulator a constant rain intensity is generally applied.

(c) Drop sizes and distribution of drops of different sizes are generally not the same for simulated rainfall as for natural rainfall.

In applying the results of determination of infiltration-capacity obtained by the use of rainfall simulators it is desirable to take into account the effect of these variations from natural conditions. This matter will be discussed in a subsequent paragraph.

RELATION OF INFILTRATION-CAPACITY IN INITIAL AND WET RUNS

Two extreme viewpoints have developed in connection with the interpretation of the results of infiltrometer experiments as follows:

1. That infiltration-capacity is governed solely by the soil mass, in the ordinary sense, and hence is largely independent of surface conditions or microstructures at or close to the soil surface. In accordance with this viewpoint the only thing which changes during an infiltration experiment is the moisture content of the soil down to the depth of penetration. Consequently the observed change of infiltration-capacity during an experiment is credited solely to the moisture conditions within the soil mass.

2. The second viewpoint is that infiltration-capacity is, except under the abnormal condition of saturation to the surface, governed solely or at least chiefly by conditions at and close to the soil surface, including, however, macro-structures, such as sun-checks, insect, earthworm and root perforations (3).

If capillary pull at the moist front within the soil was the only factor involved in the change of infiltration-capacity with time during rain, then differences in surface cover and surface treatment should have little effect in cases where, as is often true, the depth of moisture penetration is below the depth of surface treatment. Numerous experimental data show that even in such cases there is a marked variation of infiltration-capacity for the same soil with the same depth of penetration with different types of cover and different surface treatments.

The usual procedure in infiltrometer experiments is to make an initial run with the soil in a natural condition as to moisture at the start, and continue the application of water until f has become and remains constant. This is called the dry (or better, initial) run. The apparatus is left in place and later, usually the following day, a second or so-called wet run is made, in which water is applied at the same intensity and for about the same interval. Unless the soil surface has been heavily eroded and in some other exceptional cases, such pairs of successive runs, made in widely separated regions on different types of soils and different kinds of soil cover, almost invariably show differences between the initial and wet runs similar to those shown on Fig. 2.

The wet run starts off with a value of f of the same order of magnitude as in the initial run, sometimes greater, sometimes less. The value of f drops off, however, much more rapidly in the wet run than in

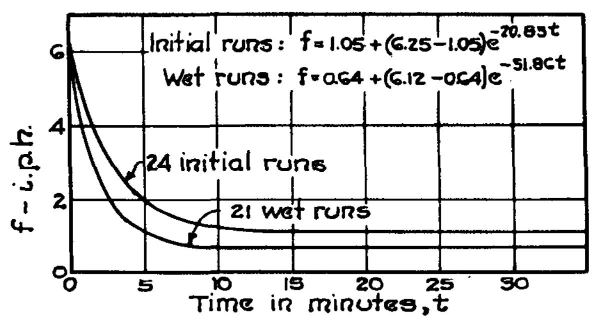

FIG. 2.—Infiltration-capacity curves, initial and wet runs, Arizona soils (2).

the initial run and attains a constant value f_c sometimes about the same but often considerably lower than the value of f_c attained in the initial run.

Taking first, for purposes of discussion, the viewpoint that infiltration-capacity is controlled wholly by the soil mass *per se* and not by the soil structure or surface condition, then the difference in values of f_c in successive runs may apparently be readily explained on the basis of greater depth of moisture penetration, with consequent reduced capillary gradient and infiltration-capacity, in the wet than in the initial run. This viewpoint is negatived, however, by various facts as follows:

1. The initial values of f are of the same order in the initial and wet runs although the depth of the moist front or depth of penetration is much greater in the wet than in the initial run.

2. Numerous experiments show that the infiltration-capacity does become constant or f_c attains an actual constant value in the initial run and again in the wet run. On the basis of the hypothesis that infiltration-capacity is controlled by the soil mass or more directly by the depth of penetration of the moist front, the infiltration-capacity should not attain a constant value in either the wet or initial run but should continue to decrease in each. It does not do so.

3. In accordance with that hypothesis the infiltration-capacity should decrease less rapidly in the wet than in the initial run, since in accordance with that hypothesis the infiltration-capacity varies inversely as the depth of moisture penetration.

For illustration, suppose that after an interval t from the beginning, the depth of penetration in the initial run is 4 inches, and after the same time interval in the wet run it is 8 inches. Then in accordance with the hypothesis of capillary pull, the infiltration-capacity should decrease at one-half as great a rate in the wet as in the initial run. Actually it usually decreases at more nearly twice as great a rate in the wet as in the initial run.

Finally, bearing in mind that the soil is not, as a rule, fully saturated during infiltration under natural rainfall conditions, it is difficult to see how capillary pull at the moist front can be transmitted effectively to the soil surface so as to in any way affect or increase the infiltration-capacity in the presence of capillary surfaces exposed to air within the soil. The situation is like that of attempting to apply a suction pump under conditions where there is an air leak in the suction pipe. It does not work. This feature of the situation has been clearly stated by Baver (1): ". . . . The capillary conductivity of a soil is practically zero at moisture contents lower than that of the wetting front, since there is no continuity of moisture films. As Moore has pointed out, these facts show that the magnitude of the potential gradient from a dry soil to the wetting front has little or no influence on the rate of movement of this front."

Consideration will next be given to the hypothesis that infiltration-capacity is determined not by the soil mass itself but by the soil surface and macro-structures, chiefly at or close to the soil surface, with reference to explanation of the following observed facts or differences between initial and wet runs:

1. The initial values of f or the values of f_0 are of the same order and often nearly identical.

2. The infiltration-capacity becomes constant and equal to some value of f_c during each of the two runs but f_c has different values and usually a lower value in the wet than in the initial run.

3. The value of f drops off much more rapidly in the wet than in the initial run.

On the basis of the hypothesis of surface control of infiltration-capacity the reduction of f from its initial value f_0 to its constant value f_c in a given run is chiefly due to surface effects induced by the energy or impact of the falling rain, and comprising surface packing, puddling, breaking down of soil-structure and inwashing of fine material to macro-openings.

It has been pointed out that these processes are of the nature of exhaustion processes. It may be noted, however, that rain-packing tends to restrict the operation of the other processes, particularly breaking down of the soil-structure. On the basis of this hypothesis the constant value of f_c in the initial run results from the fact that these processes have gone as far as they can go in the initial run. If, however, the soil is allowed to dry for a day, then a change takes place in but only in the soil at or close to the surface. There is no appreciable change in the interior of the soil. As a result the surficial soil-structure is partially restored, the effects of rain-packing partially eliminated, and, if water is again applied, a second increment of reduction of infiltration-capacity, which goes farther than the first increment, can take place. This again soon reaches its limiting value as the result of rain-packing, etc. but before it does so, the infiltration-capacity is reduced to a constant value, but lower in this case than in the initial run.

Furthermore, because of the fact that the soil at and close to the surface has been wetted and its resistivity to breaking down thereby decreased, the reduction in value of f from its initial value f_0 to its constant value f_c takes place much more rapidly in the wet than in the initial run, although the range between f_0 and f_c may be even greater than in the initial run.

The hypothesis that infiltration-capacity is controlled chiefly at the soil surface therefore affords a simple and apparently complete explanation of the observed differences between infiltration characteristics in initial and wet runs.

The preceding explanation of the constancy of f_c in individual experiments and the change of f_c in wet runs is offered as a hypothesis rather than a confirmed theory. This hypothesis explains the observed experimental facts but the physical basis for it has not yet been fully worked out and there is much yet to be learned about the changes which take place in the soil surface as a result of the effect of the energy of falling rain, especially in case of successive storms or showers. It will be noted that this hypothesis neither eliminates nor precludes the effect of swelling of colloids in reducing infiltration-capacity but, on the other hand, includes this effect as one of the factors but on the basis that it is at least as great at and close to the soil surface as deep within the soil mass.

There are probably cases to which the explanation of the changes of infiltration-capacity on the basis of conditions at and close to the soil surface does not apply, as, for example, a fat clay soil in which the principal change as a result of partial drying is the formation of deep and numerous sun-checks. In such cases, aside from the possible puddling of the soil surface by the energy of falling rain, the principal factor involved in the variation of infiltration-capacity is the area of exposed surface of sun-checks and this unquestionably varies with the degree of swelling of the colloids within the soil adjacent to the walls of the sun-checks.

Another case is that of a pure sand which contains no colloids, does not rain-pack and has no crumb structure. There is experimental evidence that such soils, sometimes at least, show decrease of infiltration-capacity with duration of rain.

The two cases above cited are at the extreme ends of the scale of soil texture. For the intermediate portion of this scale, which includes most arable soils, the explanation above given appears the best at present available to account for observed characteristics of infiltration-capacity curves.

EFFECT OF DROP SIZE AND RAIN INTENSITY ON INFILTRATION-CAPACITY

The work of Lenard, Defant, Bentley, and others has brought out certain facts in relation to drop sizes and their distribution in showers, as follows:

1. Drop size is closely related to rain intensity and, in general, the largest drop sizes occur in the most intense rains. Since rain intensity is generally greater in summer than in winter, drop sizes are generally larger in summer than in winter. Rain intensity in storms of the thunderstorm type in particular is usually highest during the first half of the storm, the maximum intensity commonly occurring rather early in the storm, frequently within 5 to 15 minutes from the beginning of rain and usually at about the ⅓ point of the storm duration. A similar relation has been found with reference to drop sizes, the largest drop sizes occurring in the first half of storms, particularly of the thunderstorm type. Usually the drop sizes are larger at the beginning than at the end of rain. Drop sizes are generally larger in thunderstorms than in other storms.

2. Drops of all sizes do not usually occur, particularly in case of larger drops. Larger drops are often concentrated in certain sizes, with gaps between. This is shown in Table 1, giving the results of some of Lenard's experiments. From these and other data Defant suggested that drop diameters are multiples of a certain minimum or base size in each particular storm. Defant's hypothesis is not, however, accurately confirmed by data thus far available.

3. From physical considerations, drops larger than 5.5 mm or 0.216 inch, or a little over 1/5 inch in diameter, are unstable and will break in falling. Hence this is theoretically the maximum limit of drop size. Actually, larger drops do occur, up to ¼ or ⅜ inch diameter. The author recently observed such large drops but also noticed that these large drops contained, and perhaps always contain, a skeleton of ice which holds them together. In the case

TABLE 1.—*Number of raindrops of various sizes in nine showers.**

Drops			No. of drops per m.² per second†								Mean	
Diameter		Volume										
Mm	Inches	Mm³	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
0.5	0.019	0.066	1,000	1,600	129	60	0	100	514	679	7	454.3
1.0	0.039	0.523	200	120	100	280	50	1,300	423	524	233	358.9
1.5	0.059	1.77	140	60	73	160	50	500	359	347	113	200.2
2.0	0.079	4.19	140	200	100	20	150	200	138	295	46	143.2
2.5	0.098	8.19	0	0	29	20	0	0	156	205	7	46.3
3.0	0.118	14.2	0	0	57	0	200	0	138	81	0	52.9
3.5	0.138	22.5	0	0	0	0	0	0	0	28	32	6.7
4.0	0.157	33.5	0	0	0	0	50	0	0	20	39	12.1
4.5	0.177	47.8	0	0	0	0	0	200	101	0	0	33.4
5.0	0.196	65.5	0	0	0	0	0	0	0	0	25	2.8
Total number...............			1,480	1,980	486	540	500	2,300	1,840	2,190	500	1,312.9
Rate of rainfall (mm/min.)...			0.09	0.06	0.11	0.05	0.32	0.72	0.57	0.34	0.26	0.28

*After P. Lenard. Meteorological Glossary, page 335.
†Nos. 1, 2, and 3—Ordinary rains; Nos. 4, 5, and 6—convectional and thunderstorm types; Nos. 7, 8, and 9—heaviest, medium, and terminal periods in a rain of cloudburst intensity.

of observations made by the writer, the large drops had evidently originated as hail, the ice had nearly all melted in falling but enough remained to hold the drops together at a size exceeding the theoretical limit.

An ascending air current having a velocity of about 8 m per second or 26.3 feet per second will sustain a drop of 5.5 mm diameter. Hence rain cannot fall in an ascending air current having higher velocities. As the velocity of the ascending air current decreases, only drops exceeding the critical diameter for the given velocity can fall. This would seem to indicate that, since rain is produced by ascending air currents, it should often be free of very small drops. Actually this is not generally the case. The explanation has been suggested that a drop breaks up not into two drops but usually into five or seven. The breaking up of a large drop into five or seven—usually seven—smaller drops can easily be observed under various other conditions, as where a colored drop falls from air into a denser fluid.

On the basis of the meager data at present available, two theories have been suggested regarding raindrops and their size distribution—the first that the larger drops are formed by coalescence with smaller drops either in ascending or falling, the second that all or nearly all rain originates as snow and that larger drops are formed by successive accretion through successive vertical circulations above the condensation level, in the same manner in which hailstones are formed. As suggested by Bentley, it seems certain that both processes are involved, and the net result is that in the majority of storms the greater part of the total rainfall is concentrated in the larger drops, although the number of these may be relatively small compared with the number of small drops.

In sprinkled plat experiments it has not thus far been found practicable to use either as great a variety of drop sizes or the specific drop sizes which ordinarily occur in storms, nor to distribute drop sizes in terms of duration of rain in the same manner in which they are distributed in natural storms.

The question naturally arises, to what extent does this variation of simulated rainfall from natural rainfall affect the determination of infiltration-capacity. Apparently there is an effect and it takes place in at least two distinct ways as follows:

1. Drop size unquestionably profoundly affects the rate of rain-packing and breaking down of soil structure, this rate increasing as drop size increases.

2. With sufficiently numerous small drops the entire soil surface will be continually absorbing water at its maximum infiltration-capacity with a lower rain intensity than is required for complete absorption over the whole surface with large drops. Both these effects, however, disappear wholly or mainly soon after runoff begins, since then the surface is wholly or mainly covered with a layer of surface detention. Drops falling into this layer have little further effect in rain-packing and related processes, on the one hand, and, on the other hand, the entire soil surface is covered and absorbing water at its maximum infiltration-capacity whether the drops are small or large.

Reverting to the question of effect of size of drops on rain-packing and related processes, the maximum or terminal velocities of drops of different sizes can easily be calculated by means of the Stokes equation.[4] In this way the total kinetic energy released to act on the soil surface, in rain of a given intensity, with drops of different sizes, can readily be computed. The kinetic energy of 1 inch of rain, in foot-pounds per square foot, for different drop sizes, is as follows:

Drop diameter, mm	Velocity, ft. per sec.	Kinetic energy, ft. lbs.
1	14.4	16.8
2	19.4	30.2
3	25.0	50.4
4	25.6	53.0
5	26.3	56.0

Except for larger drops (4 mm or over in diameter) the kinetic energy per inch of rain is nearly in direct proportion to the drop diameter. From this it will be seen that kinetic energy available to perform work on the soil surface per inch of rain is about 3½ times as great for drops 3 mm in diameter as for drops 1 mm in diameter.

This, however, does not tell the whole story. As regards rain-packing and related phenomena, the effect of small and large drops is probably more nearly comparable to the difference in effect which would be produced on a lump of hard-packed soil by giving it a million light taps with a pencil, or, on the other hand, giving it a few smart blows with a hammer, the total kinetic energy being the same in both cases. The light taps with the pencil correspond to the effect of very small drops and this effect may be wholly negligible, whereas the few smart hammer blows would more or less completely break down the soil mass.

The differences in kinetic energy per drop between small and large drops are relatively large, as shown by Table 2.

It will be seen from the last column of Table 2 that a drop 5 mm in diameter has 430 times as much kinetic energy as a drop 1 mm in diameter.

While the point is not yet determined and needs further investigation, present indications are that there is a limit to the depth to which the effect of rain-packing and related surface phenomena extend below the soil surface. When the soil structure is completely broken down, soil colloids swollen to their maximum limit and rain-packing has extended to its maximum depth, additional showers have no further effect in reducing the surface infiltration-capacity. On the other hand, the time during which rain-packing effect occurs, especially in sprinkled plat experiments, starting off with a constant rain intensity, is relatively slight, being chiefly confined to the interval before runoff begins, since it ceases on any part of the area on which there is an appreciable depth of surface detention, and in a dry run only a partial effect may be produced. The wet run the following day may complete the rain-packing effect.

The question has often been asked in connection with infiltrometer experiments with a given drop size and rain intensity, whether the resulting infiltration-capacity curve would be the same if the drop size and rain intensity had been changed.

As regards drop sizes the answer, as far as it can be given at the present time, seems to be that you would apparently get the same initial infiltration-capacity in both cases, since that is determined by antecedent conditions, and if the conditions were such that the surface effects were complete in both cases, then you would get the same final constant infiltration-capacity.

TABLE 2.—*Relative kinetic energy of raindrops of different sizes.*

Diameter, inches	Diameter, mm	Relative weight	Maximum velocity, m.p.s.	v^2	Relative kinetic energy	Relative to 1 mm drop
(1)	(2)	(3)	(4)	(5)	(6)	(7)
0.01	¼	1/5.2	6.5	42	0.0821	0.0004
0.02	½	1/8	10.4	108	0.135	0.067
0.04	1	1	14.4	208	208	1.000
0.08	2	8	19.4	374	2,992	15.000
0.12	3	27	25.0	623	16,821	84.000
0.158	4	64	25.6	655	41,920	200.000
0.200	5	125	26.3	692	86,500	430.000
0.236	6	216	Unstable	...	......	......
	7	343	Unstable	...	......	......

[4]Recent experiments by Laws (12) show terminal velocities of falling raindrops somewhat higher than those given by Stokes' equation or derived from previous experiments. The velocities here used, as derived from Stokes' equation and Lenard's experiments, serve sufficiently well for purposes of illustration.

It is probable, however, that in the case of larger drop sizes, rain-packing and related effects would take place more rapidly, the infiltration-capacity would drop off more rapidly at the start of the experiment, and the value of the factor K_f would be larger for large than for smaller drops.

As to the effect of difference of rain intensity, assuming the drops to be the same size in both cases, the infiltration-capacity would drop off more rapidly in case of the higher intensity. If the degree of surface effect due to packing and breaking down of surface structure was the same, then the same final constant value of f_c would be attained in both cases. For a soil surface in the same condition in both cases, however, if the rain intensity is sufficient so that the soil surface is all or substantially all covered with and absorbing water at its maximum rate, then the rain intensity will have no appreciable effect on the infiltration-capacity.

Proof of this is afforded by experiments by Neal, using, with the same plat and soil, rain intensities of 0.90, 1.50, 2.1, 3.0, and 4.0 inches per hour. With other conditions the same, the infiltration-capacity showed no significant differences for different rain intensities above 1½ inches per hour.

With rain intensities less than 1½ inches per hour there is some evidence of increase of infiltration-capacity with rain intensity. This may have been partly because the initial infiltration-capacity exceeded the rain intensity in some of these experiments, but there is also another explanation.

Table 3 shows the number of raindrops of different diameters, in inches, falling on 1 square inch per second, which are required to make up 1 inch of rain per hour.

TABLE 3.—*Number of raindrops of different diameters required to make up 1 inch of rain per hour when falling on 1 square inch per second.*

Diameter, inches	Volume per 1,000,000, cu. in.	Number per cu. in.	Number per sq. in. per sec. per in. per hour
(1)	(2)	(3)	(4)
0.01	0.524	1,908,397	528.00
0.02	4.192	238,450	66.2
0.03	14.148	70,670	19.6
0.04	33.536	29,815	8.3
0.05	65.500	15,267	4.24
0.06	113.1	8,842	2.46
0.07	179.73	5,565	1.55
0.08	268.29	3,727	1.04
0.09	381.90	2,618	0.73
0.10	524.00	1,908	0.53
0.12	905.000	1,105	0.307
0.14	1,437	696	0.193
0.16	2,145	466	0.129
0.18	3,054	327	0.091
0.20	4,189	239	0.066

It will be noted that it requires 528 drops 0.01 inch in diameter per second, 1 drop 0.08 inch in diameter per second, and only 1 drop in about 16 seconds if the drops are of approximately maximum size, 0.2 inch in diameter, to produce a rain intensity of 1 inch per hour.

While the behavior of a drop striking the soil surface depends much on the character and dryness of the soil surface and also on its slope, in general a drop striking the soil surface spreads instantly to a diameter commonly two or three times the drop diameter, having an area four to nine times the cross-section of the drop. On this area absorption takes place at maximum capacity as long as water from the drop still remains on the surface. Commonly it takes a few seconds—frequently two or three seconds, sometimes longer—for a drop to be absorbed.

It is evident from the preceding that for drops of 0.01 inch diameter, with a rain intensity of 1 inch per hour, the entire soil surface would be continually absorbing water at maximum rate, whereas with drops 0.2 inch in diameter and the same rain intensity, only a fraction of the soil surface would be absorbing water at its maximum rate or at its infiltration-capacity. It would therefore require a higher rain intensity with drops of maximum size to bring about absorption at capacity rate than with drops of very small sizes with the same rain intensity.

Attention is called to the author's definition of infiltration-capacity. It is the maximum rate at which the soil surface, when in a given condition, can *absorb rain as it falls.* Actually a rain intensity as high as 1 inch per hour probably never occurs with drops of 0.01 inch in diameter, and since in general the rain intensity increases with the size of drops, there is so far little evidence of increase of infiltration-capacity with either increase of rain intensity or increase of drop size, under natural conditions.

There is, however, another factor to be considered. Natural ground surfaces are never perfectly smooth. If very large drops fall on a steep sloping surface, such as the slope of a tillage mark, a part of the drop runs downward into the intermediate gully or depression and begins to build up surface detention and runoff, even at times when the soil surface is not all absorbing water at its maximum rate—in fact, it is quite doubtful, because of the increase of drop size with rain intensity, whether the entire soil surface, if it remained bare or free of surface detention, would all be absorbing water at its maximum rate, even in the most intense rain, and it is this fact which led specially to the inclusion in the definition of infiltration-capacity of the statement that it is the maximum rate at which the soil can absorb rain as it falls. This fact, however, has an important bearing on the relation between infiltration-capacity under natural conditions and the use of certain types of apparatus for the measurement of infiltration-capacity. In the use of the tube method, for example, the entire soil surface is smoothed down and kept completely covered with water all the time and, as would be expected, as elsewhere noted, the measured infiltration-capacity in such cases is usually materially greater than that which occurs from natural rainfall or from sprinkled plat experiments.

CORRECTION OF INFILTROMETER EXPERIMENTS TO THE BASIS OF NATURAL CONDITIONS

Infiltrometer experiments provide a means of determining f under fully controlled conditions. The author's equation and the hypothesis that a critical time t_c and the value of the constant K_f are controlled by the energy of falling rain provides a means for correcting the results of such experiments to take into account (a) the effect of initial rain and (b) the effect of the use of higher rain intensity than usually occurs for equal durations in natural storms.

These corrections are approximate because of various facts, particularly because the rain impact effects are slowed down or stopped by the accumulation of surface detention of water on the soil after runoff begins, and the depth and distribution of surface detention, other things equal, varies with slope, roughness of the soil surface and vegetal cover. On a smooth soil, ¼ inch of surface detention may stop impact effects, while on a rough soil the same depth of detention may be mostly accumulated in depressions, leaving the ridges exposed. Vegetal cover breaks the force of raindrops and slows down the impact effects until surface detention builds up to a point where these effects are no longer operative, thus increasing t_c and maintaining both a higher average value of f and a higher value of f_c.

Probably the best solution of the problem of simulation of natural rainfall in infiltrometer apparatus would be to determine from experiments similar to those of Lenard the total kinetic energy per inch of rain, by the summation of the kinetic energies of the drop sizes and frequencies. Then design the sprinkler or rain distributor for a rainfall simulator in such a manner that it will give the same kinetic energy per inch of rain that the experiments show for an average storm. Actual drop sizes are larger and the kinetic energy per inch of rain materially greater in summer than in winter, so that a simulator which will give the true amount of kinetic energy per inch of rain for summer conditions may give greatly excessive kinetic energy, with increased erosion and reduction of infiltration-capacity, if used under winter conditions.

One result to which the hypothesis of energy effects of falling rain evidently leads is that for a given soil in a given condition, a certain definite quantity of work must be performed to change f from a given initial value f_0 to its final value f_c in a given experiment. This work is performed by the energy of the falling rain and, since, other things equal, the energy of the falling rain is proportional to the rainfall amount, it follows that a certain definite and constant quantity of rain is required for a given soil, when in a given condition, to change f_0 to f_c.

Let P_c = the critical amount of rain required at a given intensity I to change f from f_0 to f_c. Then

$$P_c = It_c.$$

Since P_c is constant,

$$P_c = It_c = I' t'_c,$$

where t'_c is the time required to reduce f from f_0 to f_c, using a rain intensity I'. From this

$$t'_c = \frac{It_c}{I'} = \frac{P_c}{I'}. \qquad 8$$

Thus for a rain intensity $I' = \frac{1}{2} I$, the critical time t_c would be doubled.

It has elsewhere been shown that

$$t_c = \frac{1}{K_f} \ln \frac{100\,(f_0 - f_c)}{f_c}.$$

Since it is assumed that f_0 and f_c are unchanged by the change in rain intensity, the new value of K_f, which may be designated K'_f, corresponding to a given rain intensity I', can be determined from the equation

$$K'_f = \frac{1}{t'_c} \ln \frac{100\,(f_0 - f_c)}{f_c} \qquad 9$$

or, more simply, since the logarithmic term in equation 9 is assumed to remain constant,

$$\frac{K'_f}{K_f} = \frac{t_c}{t'_c}$$

or

$$K'_f = \frac{t_c}{t'_c} K_f = \frac{I'}{I} K_f. \qquad 9a$$

Since only K_f is changed, this simple equation makes it possible to easily derive the equation for f in terms of t for any given rain intensity when the equation has been determined for the rain intensity I used in the infiltrometer experiment.

In most sprinkled plat experiments only one rain intensity is used. Hence these experiments do not in general provide data for directly checking the assumption that P_c is constant and that, consequently, t_c varies inversely as I. Neal's experiments (8) afford some confirmation of this. In Neal's experiments an artifically filled soil tank was used; hence the soil contained no macro-structures. Furthermore, heavy erosion took place, so that the results are not necessarily representative of those for natural soils.

Neal used four rain intensities of approximately 1.5, 2.0, 3.0 and 4.0 inches per hour, respectively. Averaging groups of experiments with the same rain intensities and platting the results, the points shown by circles on Fig. 3 were obtained. The numbers indicate the number of experiments averaged for a given rain intensity. The solid line shows the relation of t_c to I computed by the equation

$$t_c = \frac{3.00}{I}. \qquad 10$$

indicating that in these experiments P_c is constant and equal to 3.00 inches of rain. For the purpose of illustrating the effect of rain intensity on the form of the infiltration-capacity curve, an actual experiment has been used. For this experiment I = 1.58 inches, t_c = 1.11 hour, K_f = 6.1, and the equation of the experimental infiltration-capacity curve, as shown by the line "A" on Fig. 4, is

$$f = 0.22 + 1.96\, e^{-6.1\,t} \qquad 11$$

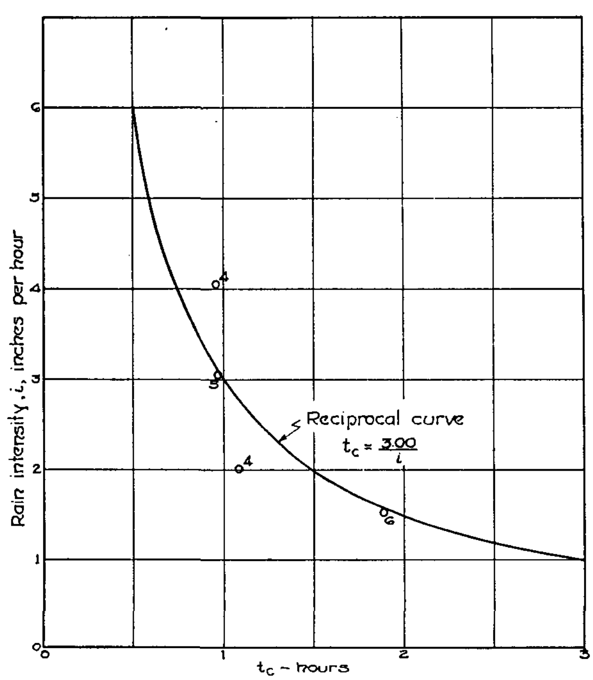

FIG. 3.—Relation of t_c to rain intensity, Neal's experiments.

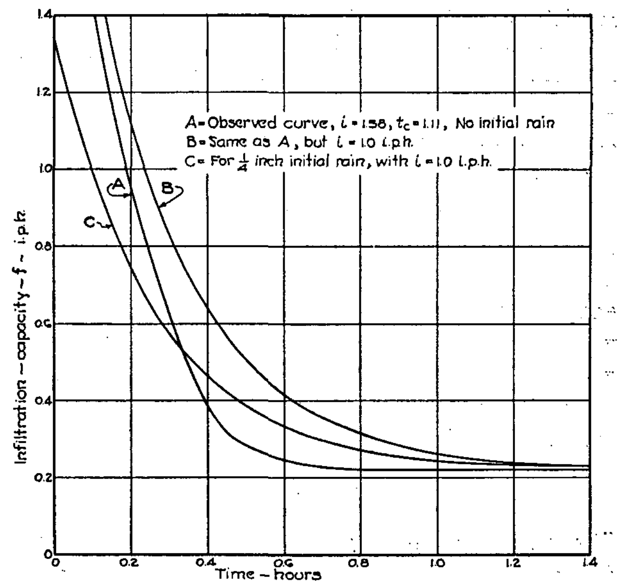

FIG. 4.—Effect of rain intensity and initial rain on infiltration-capacity curves.

Suppose the equation and curve are required for a rain intensity of 1.0 inch per hour. Then from equation 8.

$$t'_c = \frac{1.75}{1.0} = 1.75.$$

From equation 9a

$$K'_f = \frac{1.11}{1.75} \times 6.1 = 3.87$$

and the equation of the infiltration-capacity curve for a rain intensity of 1.0 inch per hour is

$$f = 0.22 + 1.96\, e^{-3.87t} \qquad 12$$

The infiltration-capacity curve given by this equation is shown by line "B" on Fig. 4. It will be noted that changing the rain intensity from 1.58 to 1.0 inch per hour materially increases the infiltration-capacity during storms of 1.0 hour or less duration. This is one reason why low intensity rains rarely produce floods and frequently produce no run-off. The infiltration-capacity is better sustained and has a higher average value as the rain intensity decreases, even though f_0 and f_c remain unchanged.

EFFECT OF INITIAL RAIN ON INFILTRATION-CAPACITY CURVE DURING SUBSEQUENT RAINFALL EXCESS

In sprinkled plat experiments there is but slight if any initial rain. In natural storms there is nearly always more or less initial rain before rainfall excess begins. In order to determine how much the infiltration-capacity is reduced by this initial rain before rainfall excess begins, the principle used in discussing the preceding topic may be applied to the results of infiltrometer experiments to derive therefrom curves which can in turn be applied to natural rainfall conditions with initial rain.

Since the amount of rain P_c required to change the infiltration-capacity from f_0 to f_c is known for the experimental rain intensity I, it is evident that if there is an initial rain of the total amount P_1, then at the end of this initial rain the infiltration-capacity value will have been reduced from f_0 to some value f to which it would have been reduced by the same total amount of rain falling at the intensity I used in the experiment. Hence

$$T_H = \frac{P_1}{P_c} \cdot t_c. \qquad 13$$

The quantity T_H may be designated "equivalent duration of initial rain." It is the duration of initial rain which would give the same total initial rain if the intensity of the initial rain had been the same as the intensity I used in the experiment.

Referring to Fig. 4, if, for example, there had been ¼ inch of initial rain, then, since in this case

$$P_c = 1.75 \text{ inches}, T_H = \frac{0.25}{1.75} = 0.145 \text{ hour},$$

the actual curve of infiltration-capacity during rainfall excess, for a rain intensity of 1.58 inches per hour, would be the same as curve "A" moved to the left 0.145 hour, and the infiltration-capacity curve for a rain intensity of 1.0 inch per hour during rainfall excess would be the same as the curve "B" moved to the left 0.145 hour. Line "C" shows the curve "B" moved to the left this amount, and line "C" therefore represents the infiltration-capacity curve during rainfall excess, as derived from this particular experiment, for the condition of 1.0 inch per hour rain intensity and 0.25 inch initial rain.

It has been shown that the equation for f holds true for any given value of f_0 with the same value of K_f if time is measured from the point on the original curve for which f becomes equal to the chosen value of f_0. Consequently, changing f_0 from 2.18 to 0.86, its value at a time t = 0.145 hour on curve "B", gives as the equation of line "C"

$$f = 0.22 + 0.78\, e^{-3.87t} \qquad 14$$

Comparing lines "A" and "C", Fig. 4, it will be noted that initial rain decreases infiltration-capacity, and lower intensity increases the critical time t_c. These two effects are opposite and consequently tend to counterbalance. The corrected curve "C" gives lower infiltration-capacity for the first 20 minutes and higher infiltration-capacity thereafter, with the result that for the duration of a significant storm the average infiltration-capacity as given directly by the experimental curve and that obtained from the corrected curve may not be greatly different. In practice, experimental curves can if required be corrected to the basis of curves for an average storm of given intensity by determining from the rainfall record the amount of initial rain and the average rain intensity during rainfall excess and applying these values in the manner above given.

In this discussion it is assumed that f_c remains the same for rain intensities I and I′. That f_c tends to remain constant, while I varies, is indicated by the fact that while an increase of I increases the rate of reduction of f below its initial value f_0, surface detention is also built up faster with increased rain intensity. These two effects operate oppositely, resulting in a tendency for the final value of f_c to be relatively constant.

ESCAPE AND DISPLACEMENT OF AIR AS RELATED TO INFILTRATION-CAPACITY

With natural rain, infiltration of water to the soil can occur only as fast as the escape or displacement of an equal volume of air; hence the relation of air to infiltration becomes highly important. It has been alleged, particularly by Russian scientists, that infiltration may be checked or inhibited over large areas, particularly flat steppe terrain, by compression of air within the soil. The author has yet to find a well authenticated example of this phenomenon in the United States.

In case of rain over a wide area, air, if it does not escape at the surface, must be compressed within the soil. Ordinarily it escapes vertically but there are various factors which limit the location and manner of its escape, as follows:

1. The volumes of spheres vary as the cubes of their diameters. Thus the buoyancy of air bubbles increases rapidly with the diameters of the soil pores in which they are contained.

2. The volume of flow of air through a capillary tube of given length and with a given pressure difference varies as the 4th power of the diameter or bore.

3. Owing to differences of density, the volume of air flowing through capillaries of given size, length and pressure difference is much greater than the flow of water. This follows from simple hydrodynamic laws but it has been experimentally proven by King (11).

4. In addition, molecular forces, i.e., surface tension or capillary forces, tend to restrict the movement of air in minute soil pores. As a result of these factors, two things follow:

(a) The minute air bubbles do not move readily through fine soil pores, and (b) if minute air bubbles reach the soil surface, they do not readily escape through an appreciable depth of water, or surface detention.

As a result of all these factors it appears that:

1. The escape of air from the soil during infiltration takes place chiefly through the large soil pores and through macro-openings, such as insect, root and earthworm perforations and sun-checks.

2. The escape of air takes place chiefly through the summits of the soil surface irregularities where the detention depth is slight, often only a thin film, and little or no escape of air occurs in the bottoms of depressions where there is a depth of one-quarter inch or more of water. The last condition can sometimes be actually observed in a cultivated field during a hard rain, where the furrows between tillage marks are partly filled with water but only a thin film exists on the summits of the ridges. The air bubbles will be seen to escape from the ridges, while no bubbles will escape through the water in the valleys.

In order to show quantitatively the possible effects of air on infiltration-capacity under different conditions in experimental work, the following analysis has been made.

King (11) carried out numerous experiments on the flow of air through soil and showed that the movement of air, like that of water, follows closely the law of Poiseuille for capillary flow. He also carried out experiments to determine the relative quantities of air and water flowing through a soil column under identical conditions. The experiments were carried out with King's aspirator. He does not state the size or length of the soil and air columns.

King's experiments show that for identical conditions, at temperature averaging about 16° C and with different grades of sand, the volume of flow of air through the soil column averaged about 26.5 times the volume of flow of water through the same soil column, and that in both cases the observed flows were in good agreement with the computed rates of flow.

Further light on the relation of the escape of air to infiltration-capacity is afforded by the experiments described below, which were carried out at the author's laboratory.

Referring to Fig. 5, A, 10 pounds of air-dry soil, comprising 25% fine uniform silt and 75% fine sand, were placed in a glass jar 5 inches in diameter and 8 inches deep and shaken down to a definite volume. In the experiments water was maintained to a depth of ¼ inch on the soil surface and the quantity of water applied was measured at frequent intervals. A U-tube manometer was used to measure the air pressure within the soil mass, one connection of the manometer being through the open end of a 0.3 inch internal diameter glass tube inserted in the center of the soil mass.

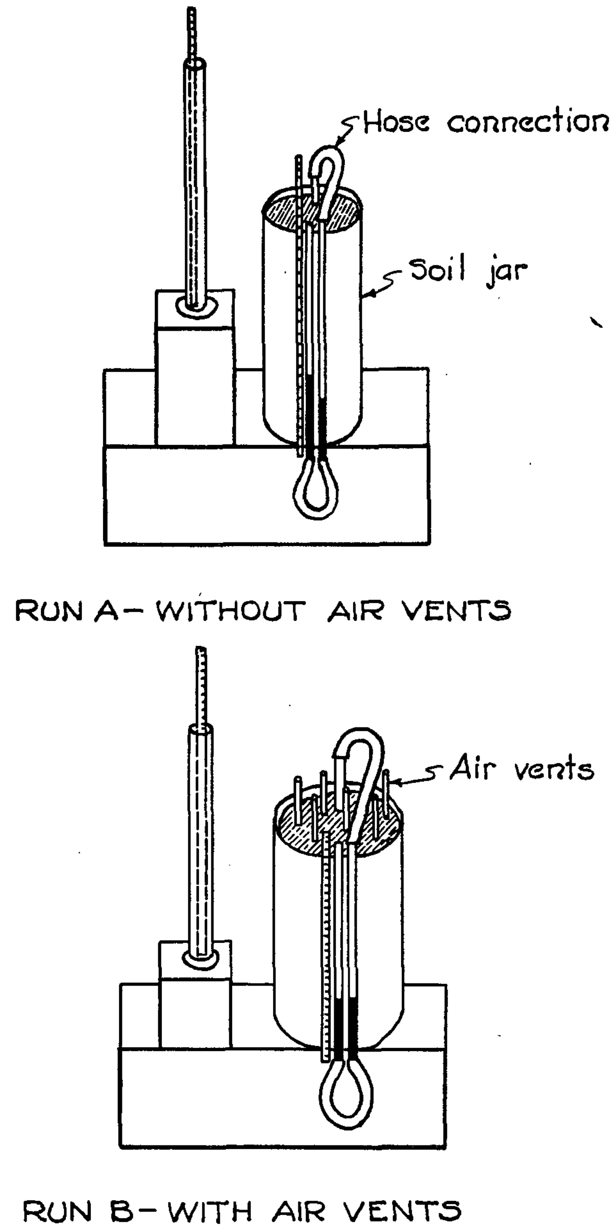

FIG. 5.—Effect of air vents on infiltration-capacity.

In the second experiment (Fig. 5, B), the jar was filled with the same weight of the same soil, air-dry, shaken down to the same volume and, in addition to the manometer, six 1-mm diameter glass capillary tubes were inserted to various depths in the soil mass, thus providing ready escape for air.

Fig. 6 shows the infiltration-capacity curves obtained in the two experiments. In the first experiment, without air vents, it was noted that air did not escape through the water but did escape intermittently around the perimeter of the soil mass. Also the manometer showed a gradual building up of air pressure within the soil mass, as shown by the dotted line on Fig. 6. In the second experiment, with capillary tubes within the soil, there was no escape of air through the water surface or around the perimeter, the air pressure within the soil mass remained at zero throughout the experiment and the infiltration-capacity was materially increased, being, at the end of the experiment, about twice as great as in the experiment without provision for escape of air. Since the conditions of the experiments were closely similar to those of tube infiltrometer experiments, it appears certain that free lateral escape of air around the bottom of an infiltrometer tube may materially increase the measured infiltration-capacity.

RELATION OF INFILTRATION-CAPACITY TO SOIL TRANSMISSION-CAPACITY

Transmission-capacity in ground-water hydrology is defined as the rate of flow of water through a fully saturated column of soil, free from air, under conditions such that the gradient is unity or the hydraulic head equals the length of the soil column. It has sometimes been assumed that infiltration-capacity and transmission-capacity are either identical or so closely related that infiltration-capacity is determined wholly by conditions within the soil. What has already been given in relation to soil surface conditions shows that this is not the case. In general, infiltration-capacity is less than transmission-capacity, for two reasons:

1. Because of packing and related effects, the soil mass can transmit water downward faster than it can enter the surface.

2. In case of infiltration of rainfall, air must escape from the soil surface as fast as water enters, whereas in case of percolation through a saturated soil, the question of air escape is not involved and the entire pore space is available for water transmission. King's experiments indicate that if the soil pores were uniform tubes of the same diameter, some containing water only, the others containing air only, only about 4% of the pore space would be required to permit air to escape at the same rate at which water enters. These conditions are, however, not at all like those of the flow of air and water in opposite directions in the soil because the air escapes (a) chiefly from the larger pores, (b) chiefly at the summits of irregularities of the soil surface, and (c) not as a continuous stream but in bubbles. In small pores a few bubbles may inhibit the inflow of water.

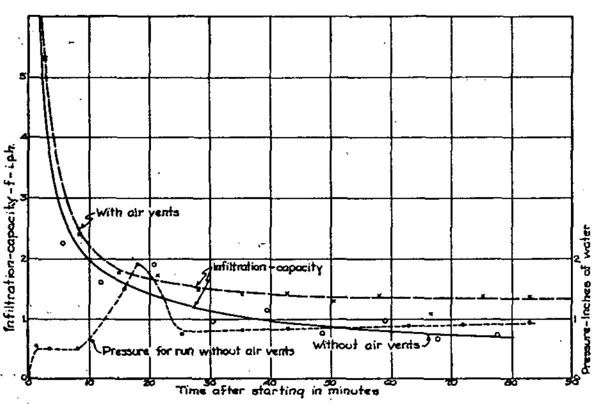

FIG. 6.—Infiltration-capacity curves with and without air vents.

Experiments can easily be devised, and unfortunately many such experiments have been performed that purport to be determinations of infiltration-capacity which were more nearly determinations of transmission-capacity (4). That more or less high correlation between the factors which govern transmission-capacity and the resulting measured quantity of water flowing into the soil should have been found in such experiments is not surprising, but it does not prove that a similar high correlation exists between infiltration-capacity and soil characteristics within the soil mass.

The following analysis, somewhat along the lines of that of Green and Ampt (5) serves to illustrate the effect of capillary pull on downward advance of a moisture front in a column of soil which is saturated above the moisture front. It is assumed that:

1. The soil is saturated.

2. Water is applied at just the rate at which the surface can absorb it, or that there is a negligible but constant depth of water on the soil surface.

3. There is no upward flow of air.

These are the conditions for transmission-capacity—not for infiltration-capacity. If k_1 is the rate of downward flow due to gravity alone under unit head or, in other words, the gravitational transmission-capacity, and c is the rate of downward flow due to capillary pull alone, for the given moisture conditions, and both are expressed as surface depths per unit of time, then if ϕ is the available void space, the downward flow will be that due to the combined gravitational force of the water in the soil and the capillary pull at the moist front, and this flow will take place in accordance with Poiseuille's law. The flow due to each of the two forces will be proportional to the pressure gradient it produces, and the total flow will be that due to the sum of the forces or, if this is expressed by K,

$$K = \frac{k_1(\zeta + \delta)}{\zeta} + \frac{c}{\zeta} = \frac{k_1(\zeta + \delta) + c}{\zeta}, \qquad 15$$

where δ is the depth of water on the soil surface and ζ is the depth of penetration of the moisture column below the soil surface.

If δ is zero or negligible, this reduces to

$$K = k_1 + \frac{c}{\zeta}. \qquad 16$$

If ζ is initially zero, then the intake of water by the soil will start at an infinite rate and will approach the constant gravitational value k_1 as $\zeta \longrightarrow \infty$. The part of the flow due to capillary pull will vary inversely as the depth of penetration of the moist front.

The relation of the depth of penetration ζ and the rate of water intake K to time t, or duration of application of water, can be obtained as follows. To satisfy the equation of continuity the depth ζ of penetration must be such that in the time dt the increase of volume of water within the soil is equal to the volume of water added at the soil surface. The former is $\phi\, d\zeta$ and the latter is $\left(k_1 + \frac{c}{\zeta}\right) dt$. Hence

$$\phi d\zeta = \left(k_1 + \frac{c}{\zeta}\right) dt$$

and

$$\frac{t}{\phi} = \int_0^t \frac{\zeta\, d\zeta}{c + k_1 \zeta}$$

$$= \frac{1}{k_1^2}\left[c + k_1\zeta - c \ln (c + k_1\zeta)\right] + \text{const.}$$

When $t = 0$, $\zeta = 0$ and $\text{const.} = -\left[c - c \ln c\right]$,

giving

$$\frac{k_1^2 t}{\phi} = k_1\zeta - c \ln \frac{c + k_1\zeta}{c}. \qquad 17$$

This equation shows the relation of penetration to time. The depth ζ or the rate of downward movement is inversely proportional to the available void space ϕ; in other words, if the soil is initially close to saturation, then the rate of advance of the moist front is rapid, and *vice versa*.

To express the rate of absorption K in terms of t, substituting $K = \frac{c + k_1\zeta}{\zeta}$ in equation 17 gives, since $\zeta = \frac{c}{K - k_1}$,

$$\frac{k_1^2 t}{c\phi} = \frac{k_1}{K - k_1} - \ln \frac{K}{K - k_1} \qquad 18$$

or

$$\ln \frac{K}{K - k_1} = \frac{k_1}{K - k_1} - \frac{k_1^2 t}{c\phi}.$$

This implicit equation shows how, under the assumed conditions, K is related to t and to the constants k_1, c, and ϕ.

It is to be noted that the above equations are those of permeability or transmission-capacity of a saturated soil—not infiltration-capacity. They are, however, closely related to the latter but subject to the difference that in case of infiltration the soil is not usually saturated, a part of the pore space is occupied by an ascending air current; hence k_1 is smaller for infiltration- than for transmission-capacity and, furthermore, as the depth of penetration increases, the length of soil column through which upward air flow takes place also increases, and with it the resistance to air flow is increased, providing a further and more rapid decrease of intake of water for infiltration than for transmission under saturation conditions. Actually the conditions assumed in deriving these equations seldom if ever occur in nature. They are, however, nearly identical with the conditions provided by the so-called tube method of determining infiltration-capacity, and it is obvious, therefore, that results obtained by the tube method are more nearly values of permeability in the ordinary sense, for a saturated soil, than of infiltration-capacity.

Much confusion and serious errors have resulted from failure to recognize the distinction between permeability and infiltration-capacity. For example, in a recent paper (12), the experiments of Slater and Byers (14) have been cited as representing infiltration-capacity. The experiments of Slater and Byers were carried out on cores of soil encased in paraffin, with free drainage and with a depth of 2 cm of water on the soil surface, the conditions being those for determination of permeability—not infiltration-capacity—and Slater and Byers nowhere refer to their experiments as representing values of infiltration-capacity but describe them as permeability determinations or field percolation rates.

Slater and Byers found some evidence of decreased permeability in successive application of water to some soils but not to others. When subsequent applications of water were made, those soils which showed decrease of permeability in the second application generally showed no further decrease. The decrease of permeability in successive applications of water in Slater and Byers' experiments, where it occurred, was certainly not due to increased depth of percolation or to decreased capillary pull, since the length of the soil column remained constant. It may have been due to swelling of colloids throughout the soil mass.

Slater and Byers apparently concluded that the decrease of percolation in successive applications of water was due to filling up or closing of the micro-openings within the soil, not to the soil mass itself.

In case of flow through a saturated soil column, if there is water standing on the top of the soil column the rate of flow is proportional to the total head, i.e., length of soil column plus surcharge depth. In case of infiltration no definite relation has thus far been found between depth of surface detention and infiltration-capacity. Such a relation may, however, exist but experimental data now available are not of a suitable nature to reveal it.

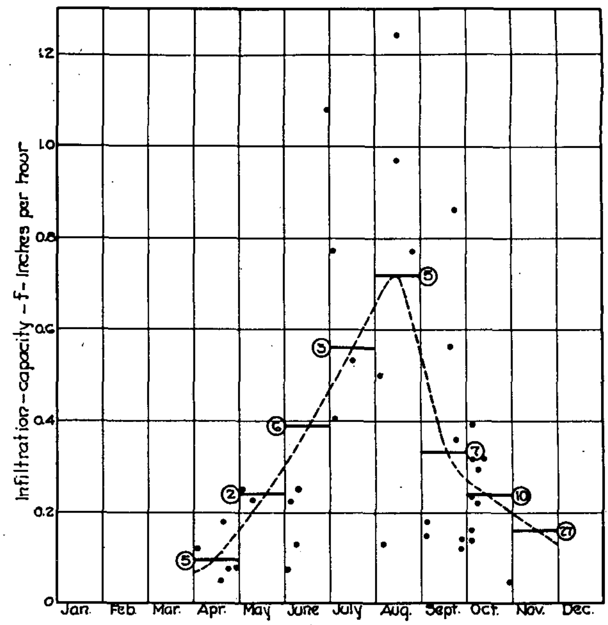

FIG. 7.—Seasonal variation of infiltration-capacity. Numbers in circles are number of values of f included in monthly average.

SEASONAL VARIATION OF INFILTRATION-CAPACITY AND TEMPERATURE EFFECT

The author pointed out in 1933 the existence of a marked seasonal cycle of variation of infiltration-capacity values derived from areal determinations (6). (See Fig. 7.) Another example, derived from determinations of apparent infiltration-capacity during rains which produced only incipient runoff on the North Concho River drainage basin, Texas, is shown in Fig. 8. Other similar seasonal curves have been obtained for various regions and terrains, both from natural areas and from runoff plat experiments.

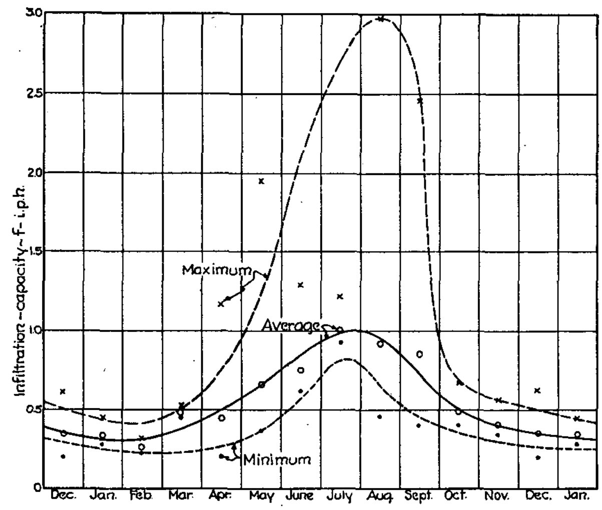

FIG. 8.—Seasonal variation of maximum, minimum, and average apparent infiltration-capacities, North Concho Drainage Basin.

While the seasonal infiltration-capacity curve for most natural terrains somewhat resembles the temperature curve, it usually has a much more marked rise in the spring months and a more rapid recession in the fall months.

While temperature is quite certainly a factor, the author believes that biologic factors are the principal cause of the seasonal cycle of infiltration-capacity. In case of cultivated soils there is a marked increase of infiltration-capacity immediately following cultivation. A marked rise of infiltration-capacity also occurs at about the time in the spring when earthworms, ants, beetles and other soil fauna become active, and a marked decrease of infiltration-capacity occurs in the fall at about the time they become dormant. That the two causes enumerated are principal factors in the seasonal variation is indicated by the wide range of infiltration-capacity at these times of the year. This wide variation seems to be explained in part by the fact that insects and earthworms, particularly the latter, prefer moist soil. The author and others have observed several hundred earthworm perforations to the square yard when the soil was thoroughly moist, and subsequent rains showed an exceptionally high infiltration-capacity in spite of the moist soil. In prolonged dry periods earthworms go down to moist soil, their perforations become filled with dust blown in or washed in by initial rains, and the infiltration-capacity at the same date of the year as before, and for the same soil, may be abnormally low, even though the soil is dry.

These facts help to account for the generally increased range and variability of infiltration-capacity under midsummer conditions as compared with other seasons of the year on such areas.

Data thus far available show that on sandy soils, comparatively free from biologic structures, the seasonal curve of infiltration-capacity quite closely resembles a temperature curve, and the range of variation under summer conditions is greatly reduced. Both the flow of water through a saturated soil and infiltration are, in general, laminar flow. It is known that there is a definite relation between temperature and transmission-capacity of saturated soils and, in general, between temperature and laminar flow of all types.

Under natural rainfall conditions water cannot in general enter the soil unless an equal volume of air escapes from the soil surface. During infiltration there is simultaneously a downward current of water and an upward current of air passing through the soil, though not necessarily through the same soil pores. Temperature operates to change laminar flow through a change of the viscosity of the fluid, the flow rate increasing as the viscosity decreases. While the viscosity of water decreases as temperature increases, the viscosity of air follows the inverse law or increases with increasing temperature. Thus in the dual process of intake of water and escape of air, increase of temperature tends to increase the inflow of water and to decrease the escape of air.

As shown by the following figures from the Smithsonian Physical Tables (Table 4), the increase of viscosity of air within the ordinary range of seasonal variation of soil surface temperature is relatively small compared with the decrease of viscosity of water throughout the same range of increasing temperature.

Owing to the opposite effects of change of temperature on the flow of air and water, the effect of temperature on infiltration is reduced as compared with its effect on the permeability of a saturated soil or flow of water through a saturated soil column.

TABLE 4.—*Viscosity of water and air at different temperatures in c.g.s. units (poises) or dyne-seconds per square cm.**

	Viscosity of water				
Temperature, C°	0	5	10	15	20
η:	0.0179	0.0152	0.0131	0.0114	0.0100

	Viscosity of air		
Temperature, C°	0	15	99.1
η:	0.000173	0.000181	0.000220

*From the Smithsonian Physical Tables.

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