This paper has dealt principally with the application of the index-area method to the prediction of total runoff. Its possibilities in connection with flood-stage prediction have been barely touched upon. It seems fairly obvious that the method possesses a potential value for the prediction of storm- and flood-flows exceeding that of any other type of observation. It should also be borne in mind that not only will the establishing of index-area stations serve this purpose but they will provide a wealth of material for investigating the fundamental elements controlling runoff-phenomena.

It is perhaps unnecessary to add that matters involving hydrology are too often slighted or relegated to the domain of routine work. The attainment of successful results in storm-flow prediction is mostly to be accomplished if under the direction of some one having wide experience and excellent judgment in such matters and these qualifications, in general, are only attainable where the incentive for their acquisition is an interest in scientific hydrology.

It is not the purpose here to discuss the commercial aspects of stream-flow prediction. In general the expense of establishing and equipping index and supplemental stations will not be large. It may happen that the increased energy-production for a system of power-plants resulting from the saving of water based on storm-flow prediction in a single storm period will cover the cost of carrying on the work for a year or more.

Voorheesville, New York

THE RÔLE OF INFILTRATION IN THE HYDROLOGIC CYCLE

Robert E. Horton

Introduction--Definitions

For some years the author has used the term "infiltration" to describe the process involved where water soaks into or is absorbed by the soil. Absorption, imbibition, and percolation are often used in much the same sense. It seems better to confine the use of "percolation" to the free downward flow by gravity of water in the zone of aeration--a process for which a distinctive term is needed. "Absorption" includes the entrance of air as well as water, both liquid and vapor, into the soil (see Patten and Gallagher, Absorption of vapors and gases by soils, U.S. Dep. Agric., Bul. 51, Bur. Soils, Wash., 1908; also Charles H. Lee, On absorption and transpiration, Trans. Amer. Geophys. Union, 1932, pp. 288-298). "Infiltration" is limited to water in the liquid form and is more accurately descriptive of the physical processes by which rain enters the soil. "Water-penetration" is also sometimes used as if synonymous with infiltration. Its use should be restricted to the depth below soil-surface reached by the given surface infiltration.

"Infiltration-capacity" will be used to describe the maximum rate at which rain can be absorbed by a given soil when in a given condition. Infiltration is (a) the sole source of soil-moisture available to supply the transpiration stream and sustain the growth of vegetation, and (b) the sole source of ground-water supply of wells, springs, and streams.

The surface of a permeable soil acts like a diverting dam and head-gate in a stream, where the head-gate can be opened to a certain width only or closed so as to still leave a fixed opening. With varying rates of flow in the stream, all the flow is diverted up to the then capacity of the opening. Similarly, with varying rain-intensity, all of the rain is absorbed for intensities not exceeding the infiltration-capacity, while for excess rainfall there is a constant rate of absorption as long as the infiltration-capacity is unchanged. As in the case of the dam and head-gate, there is usually some pondage which remains to be disposed of after the supply to the stream is cut off, so in the case of infiltration, surface-detention remains after rain ends. Infiltration divides rainfall into two parts, which thereafter pursue different courses through the hydrologic cycle. One part goes via overland flow and stream-channels to the sea as surface-runoff; the other goes initially into the soil and thence through ground-water flow again to the stream or else is returned to the

air by evaporative processes. The soil therefore acts as a separating surface and the author believes that various hydrologic problems are simplified by starting at this surface and pursuing the subsequent course of each part of the rainfall as so divided, separately. This has not hitherto, in general, been undertaken.

The following terms require definition. (Quantities used in this paper are inches depth per hour unless otherwise stated.)

Infiltration-capacity may be defined as the maximum rate at which a given soil can absorb rainfall when the soil is in a specified condition. Infiltration-capacity, in general, is designated f. As subsequently shown, for a given soil there is a fairly definite maximum infiltration-capacity, designated f_g and a more definite minimum infiltration-capacity, designated f_ℓ.

Ground-rainfall may be defined as the part of the rainfall which actually reaches the ground, or it equals the total rainfall minus interception by vegetation. It is designated P_g.

Rainfall-excess (P_e) is the part of the rainfall which falls at intensities exceeding the infiltration-capacity. For example, if the rain-intensity is 1.5 inches per hour for a 30-minute interval and the infiltration-capacity is 0.8 inch per hour, then the rainfall-excess is $0.7 \times 0.5 = 0.35$ inch.

Surface-detention is that part of the rain which remains on the ground-surface during rain and either runs off or is absorbed by infiltration after rain ends. A part of this surface-detention is usually contained in small pockets or depressions in the ground-surface and none of this runs off. This portion is designated *detention-storage*.

Field moisture-capacity (designated fmc or m_c) is used in the sense of the quantity of water which can be permanently retained in the soil in opposition to the downward pull of gravity. It may be expressed in per cent of dry weight or in inches depth for a given depth of soil.

Field moisture-deficiency (designated fmd or m_d) for any soil and time is the quantity of water, similarly expressed, which would be required to restore the soil moisture-content to field moisture-capacity.

The term *ground-water accretion* is used to describe the total quantity of water added to the water-table in any given time-interval. It is synonymous with the term *re-charge* as used in western United States and *ultimate percolation* as used in England.

Soil-moisture accretion is that part of infiltration which is retained in the zone of soil-moisture and which does not pass on downward to the water-table.

The *storm-interval* is the natural hydrologic time-unit. It may be defined as the interval from the beginning of a rain through the rain-period and the subsequent dry or rainless period to the beginning of the next subsequent rain-period.

Rise is used, for want of a better name, to define the period during and following rainfall from the time when the hydrograph first departs from the normal depletion-curve until it again becomes coincident with the normal depletion-curve. All of the surface-runoff due to the storm takes place in this interval. A rise consists of a period of increasing flow, which may result either from increased ground-water flow, from surface-runoff, or both. This culminates in the crest or peak of the rise, which is followed by a recession period.

Concordant flow is a condition of a stream such that if the rate of ground-water inflow to the stream remained unchanged, there would be no change in the stage of or rate of outflow from any given reach of the stream.

Normal depletion-curve

In the determination of total infiltration from runoff-records it is necessary to subdivide total runoff into two principal components: Ground-water flow and surface-runoff. This may be accomplished by the use of a "normal depletion-curve." Consider a period of little or no rain. Stream-flow is then derived from storage. If there is no artificial regulation and no lakes or marshes on the drainage-basin, the stream-flow is derived either from ground-water or from waters in transit in stream-channels. At lower stages of the stream and when flood-waters are not passing downstream, the water in transit in stream-channels is itself derived from ground-water. For practical purposes and for the sake of brevity the flow of a stream at such times may be referred to as "ground-water flow."

After the passage of a flood or a rise due to surface-runoff, a stream settles down to what may be called a condition of concordant flow. The flow is variable in a hydraulic sense in that the same quantity does not pass each cross-section but the conditions are also such that if the inflow from ground-water remained unchanged there would be no change in depth or quantity of water stored in any reach of the stream.

A curve representing a segment of a hydrograph under conditions of concordant flow may be called a normal depletion-curve. It is also a time-discharge rate relation-curve. Since the area under the depletion-curve between two dates equals the total runoff and also equals the total draft from storage for the given period, it is easy to construct a second or storage-discharge rate relation-curve. If ground-water level-records are available this may be in the form of a ground-water level and discharge-rate curve, or virtually a rating curve for ground-water flow. For streams where the ground-water level underneath the drainage-basin is at a depth beyond the reach of direct abstraction by plants or vegetation, the normal depletion-curves in different years are often nearly identical throughout their common range within the limit of errors of observation and excluding the effects of barometric changes, etc., on ground-water flow.

The normal depletion-curves may differ to a considerable extent in different years or seasons in cases where there is a direct abstraction of ground-water from the water-table by vegetation or evaporation. Even in such cases the difference between summer season depletion-curves in different years is often so small that for practical purposes in separating ground-water and surface-runoff, an average normal depletion-curve can be used. [The author first noticed the characteristics of normal depletion-curves during a long drought which occurred in the eastern United States in the spring of 1903 and published depletion-curves for this drought-period in the Annual Report of the State Engineer and Surveyor of New York, 1903, v. 2, p. 16. Such curves were foreshadowed by the "storage curves" used by Vermeule (Geol. Sur. N.J., v. 3, Water supply, 1894).] Owing to interruption by rain and surface-runoff it is generally impossible to obtain a complete normal depletion-curve directly from a hydrograph. It can be shown that for a simple phreatic drainage-basin (with no direct abstraction from the water-table by transpiration or evaporation within the soil) the equation of the normal depletion-curve is

$$q = q_o e^{-ct}$$

where q is the ground-water flow-rate at the time t, and t is time elapsed subsequent to a date when the flow was q_o (Robert E. Horton, Discussion on yield of drainage-areas, J. New England Water Works Assn., v. 28, No. 4, Dec., 1914, pp. 538-539). [This particular formula was derived by the author from theoretical considerations in 1904 and applied to the depletion-curves of several streams. Its applicability to the springs of Cerilly was shown by Maillet (Eaux souterraines, 1905). In 1921 D. Halton Thomson (Trans. Inst. Water Eng.) showed that this type of expression accurately represents the law of decrease of ground-water levels in chalk regions of West Sussex, England, during rainless periods. Maillet states that this formula as applied to ground-water was first derived by him in 1903 and was independently derived by Boussinesq the same year.] Where a drainage-basin contains many phreatic sub-basins of different characteristics the normal depletion-curve for ground-water flow from the entire drainage-basin can in general be represented by an equation of the form

$$q = q_o e^{-ct^n}$$

in which n is a constant exponent. For a drainage-basin in which the gravitational capacity of the soil decreases proceeding downward, as is not uncommonly the case, the normal depletion-curve can in general be represented by an equation similar to one or other of those above given but consisting of the sum of two exponential terms. By deriving the equation of the normal depletion-curve for a drainage-basin the curve can be extended so as to show the rate at which ground-water would be supplied to the stream: (a) During a drought-period of any duration and (b) during periods when surface-runoff is taking place if there was no coincident accretion to the ground-water table.

By shifting the normal depletion-curve horizontally across a hydrograph, segments of the hydrograph which coincide with the normal depletion-curve may be noted and these represent periods during which the runoff is derived entirely from ground-water flow. Connecting the points where the hydrograph departs from and rises above the normal depletion-curve, the accretion to ground-water and the ground-water flow during periods of surface-runoff can also be determined. In this way the ground-water runoff of the stream can be separated from the total runoff, thus making it possible by simple subtraction to determine the surface-runoff Y_s, since $Y_s = Y - Y_g$, where Y and Y_g are the total and ground-water runoff, respectively.

The many interesting and important properties of normal depletion-curves and their applications cannot be given in detail here. [Reference is made to the following papers: Samuel Hall, Stream-flow and percolation-water, Trans., Inst. Water Eng., v. 23, pp. 92-127, 1918; D. Halton Thomson, Hydrological conditions in the chalk at Compton, West Sussex, Trans., Inst. Water Eng., London, 1921. According to Gravelius (Flusskunde) the separation of ground-water from surface-runoff by drawing a line across the base of the hydrograph of a stream-rise has been practiced in France for more than 50 years. It seems necessary to point out that the method of separating ground-water flow from surface-runoff, used by Houk (Rainfall and runoff in the Miami Valley, Tech. Reports, Miami Conservancy Dist., Part 8, 1921) and by Meinzer and Stearns (W.S.P. 597-B) is incorrect and leads to underestimates of ground-water runoff, especially during wet months.] The author expects, however, to publish a full account of ground-water depletion-curves and their application in the near future.

Rain-intensity duration-curve

The rain-intensity duration-curve provides a good starting point for consideration of the rôle of infiltration in hydrology. Such a curve may be prepared either for an individual storm or for a season, a year, or other period in the same manner as the familiar runoff duration-curve. For a single storm, rain intensities for hourly or shorter intervals should be used and must be derived from the record of a recording rain-gage.

The lower diagram on Figure 1 shows the actual rain-intensity distribution in a typical summer storm on the drainage-basin of Relston Creek at Iowa City, Iowa. The total rainfall of 1.96 inches produced a runoff of 0.67 inch. There was no initial ground-water flow and the area under the runoff-curve extended to zero represents the total surface-runoff and is also equal, when suitable scale-factor is applied, to the portion of the rainfall shown by the shaded area. The shaded area on the rainfall-diagram represents that part of the rain which fell at intensities exceeding 0.55 inch per hour, which in turn was the infiltration-capacity of the drainage-basin during this storm. Inset A of Figure 1 shows the same rainfall plotted as a rainfall-intensity duration-diagram. If a horizontal line corresponding to some particular intensity is drawn across this diagram, the area between the intensity-curve and this line is the rainfall-excess for the given intensity. The line marked "rainfall-excess" on inset B of Figure 1 was derived in this way. From this diagram it is possible to read off directly the rainfall-excess corresponding to any given infiltration-rate. The total infiltration equals the total rainfall minus the rainfall excess, and a line of total infiltration has been added to Diagram B.

If the infiltration-capacity of a drainage-basin is known it is possible by an analysis of the rainfall-excess in individual storms, in the manner described, to determine, approximately at least, the surface-runoff which will take place directly from rainfall-data.

Also having given the runoff and the rain-intensity distribution it is possible to determine from these data the infiltration-capacity of a drainage-basin. For large areas it is, of course, necessary to determine the rainfall-excess for several stations.

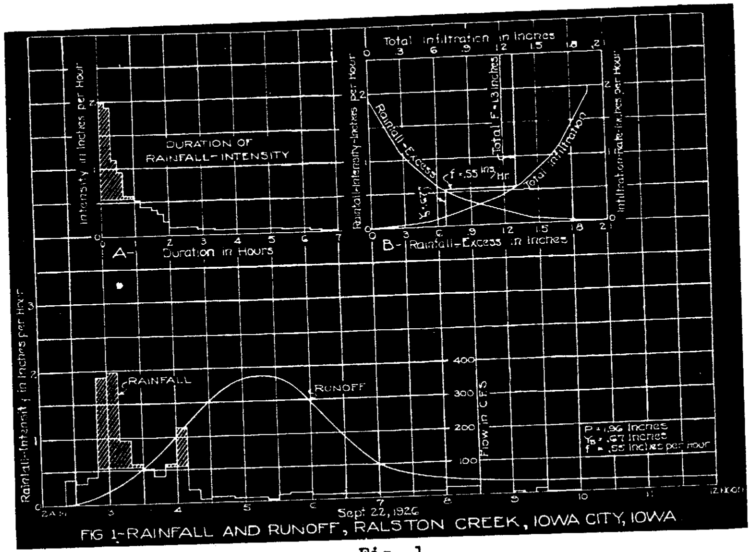

FIG 1-RAINFALL AND RUNOFF, RALSTON CREEK, IOWA CITY, IOWA

Fig. 1

Infiltration-capacity

Infiltration-capacity of a soil is closely related to but not necessarily and, in general, not actually identical with the transmission-capacity as used, for example, in Slichter's formula. The infiltration-capacity of a specific soil can be determined: (a) From laboratory experiments, using artificial rainfall; (b) from runoff-plat experiments, with natural rainfall; (c) from rainfall- and runoff-records for small drainage-basins with homogeneous soils; and (d) the average equivalent infiltration-capacity for a drainage-basin where the soil-type varies areally can be determined from runoff and rainfall-intensity records.

Few data have been published giving directly the infiltration-capacity of soils. Experimental and correlative researches for the determination of infiltration-capacity of soils have been carried out from time to time at the author's laboratory for a number of years. Only the briefest outline of the results can be given here. In the author's experiments, water was applied in a manner simulating rainfall to pans of soil of different types, under fully controlled conditions.

Various series of experiments by other investigators, made primarily for the determination of runoff-characteristics, have been analyzed for the determination of infiltration-capacity. These include laboratory experiments with artificial rainfall, made by Houk, by W. W. Horner, and by Duley and Hayes. Infiltration-capacities have also been determined from various series of runoff-plat experiments and from runoff-data for small drainage-basins, in particular, Ralston Creek, at the University of Iowa.

In discussing infiltration-capacity, two cases must be considered: (a) Natural soils, such as those of forest-covered areas, natural meadows, brushlands, and desert areas and, in general, all areas where the soil has remained fallow for a year or more; and (b) soils which have recently been cultivated.

Considering first the case of a natural soil, here the infiltration-capacity passes through a fairly definite cycle for each storm-interval. Starting with a maximum value when rain begins, the infiltration-capacity decreases rapidly at first as the result of the operation of some or all of the following processes: (1) Packing of the soil-surface by rain; (2) swelling of the soil, thus closing sun-checks and other openings; and (3) inwashing of fine materials to the soil-surface openings.

These effects are confined to a thin layer at the soil-surface. Infiltration-capacity during prolonged rain is, therefore, generally less than the gravitational transmission-capacity within the soil-mass. This is the principal reason why soils free to drain are seldom if ever fully saturated during rain, however intense or prolonged. Another reason is the necessity for escape of air as fast as the water enters the soil. This reduces the pore-space available for water within the soil.

The change from maximum to minimum infiltration-capacity during rain at once accounts for increased surface-runoff from initially wet soils or in a succession of storms, an effect commonly but erroneously attributed to saturation of the soil.

In the case of natural soils the infiltration-capacity may drop from one inch per hour or more at the beginning of rain to one-half inch per hour or less within an interval ranging commonly from one hour to two or three hours.

Thereafter, if the rain continues or the soil remains thoroughly wetted, a further slow decrease in infiltration-capacity takes place for a time, especially in the case of soils containing large percentages of colloidal material. When this colloidal readjustment becomes complete, the infiltration-capacity reaches a stable minimum value. This may not be materially less than the value attained shortly after rain begins.

After rain ends, restoration of the infiltration-capacity begins. Wind-action and differential temperatures close to the soil-surface aid in reopening the soil-pores, shrinkage of colloids takes place, perforations of earthworms and insects are restored, and the infiltration-capacity returns to its maximum value usually within a period of a day or less for sandy soils, although several days may be required for clays and fine-textured soils. Apparently the maximum and minimum infiltration-capacities for a given soil have fairly definite values at a given season of the year.

The range of variation of infiltration-capacity depends on the type of soil as well as its condition. Because of its large absorption-area per unit of surface-area and because of the temporary storage of rainfall in sun-checks, a sun-checked clay soil can initially absorb rain as fast as it falls. Similar conditions pertain in case of a newly plowed or cultivated field. In both instances the high initial infiltration-capacity is partly due to storage of water which is held in sun-checks, furrows, or small depressions until absorbed. Neglecting these exceptional cases, the range of infiltration-capacity between the maximum and minimum values is usually of the order of one inch in the case of loam soils, the range decreasing as the soil-texture becomes coarser. In the case of sandy soils which do not pack or sun-check and in which there are few earthworm or other artificial perforations, infiltration-capacity is apparently nearly constant or the range of variation is slight.

There is also a marked seasonal variation in infiltration-capacity. Apparently this is in part related to temperature but also in part results from the fact that earthworm and other perforations which freely admit water or permit the escape of air from the soil are present only during the summer season.

Table 1 shows the infiltration-capacity of the loess soil comprised in the drainage-basin of Ralston Creek at the University of Iowa, Iowa City, Iowa, derived from the analysis of 56 storms. In the case of storms designated "Class A" the soil-surface was initially dry, as there had been at least two preceding days without rain. In case of storms designated "Class B," rain of at least moderate intensity had occurred within an interval of not more than one day. It will be noted that the average infiltration-capacity during summer storms for initially dry soil was 1.25 inches per hour, while for Class B storms the average is 0.62 inch per hour or practically one-half as much. It will also be noted that the average infiltration-capacity in Class A storms varied in different years. The variation in different years is due in part to the effect of cultivation. About 20 per cent of the area was devoted to the growth of cereal crops; most of the remainder was grassland, including meadow and pasture.

An analysis was also made of ten winter storms which occurred during the months November to April. These gave an average infiltration-capacity of 0.12 inch per hour. This illustrates the marked difference in the ability of a soil to absorb rain under winter and summer conditions.

Table 1--Average values of infiltration-capacity f from analysis of individual storms, annual and eight-year means, Ralston Creek drainage-basin, Iowa

Year	Class A		Class B		All storms	
	Average f	No. of storms	Average f	No. of storms	Average f	No. of storms
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Summer storms, May-October, inclusive						
1925	1.55	3	0.53	2	1.14	5
1926	0.98	4	0.86	3	0.93	7
1927	1.43	3	0.28	5	0.71	8
1928	0.98	6	0.36	4	0.74	10
1929	1.65	3	0.97	3	1.31	6
1930	1.57	3	0.44	1	1.29	4
1931	1.07	2	1.92	1	1.35	3
1932	1.09	3			1.09	3
Average,[a] 1925-1932, inclusive	1.25	27	0.62	19	0.99	46
Winter storms, November-April, inclusive						
Average,[a] 1925-1932, inclusive	....	..	....	..	0.12	10
All storms						
Average,[a] 1925-1932, inclusive	....	..	....	..	0.84	56

[a] Average of all storms--not average of yearly means.

Table 2--Summary of mean monthly values of infiltration-capacity, Ralston Creek at Iowa City, Iowa

Month	Average values of f, inches per hour					
	Class A		Class B		All storms	
	f	No. of values	f	No. of values	f	No. of values
(1)	(2)	(3)	(4)	(5)	(6)	(7)
February	0.17	2	....	..	0.17	2
March	0.12	3	0.03	1	0.10	4
April	0.12	1	0.10	1	0.11	2
May	1.30	3	0.24	2	0.87	5
June	1.57	9	0.81	8	1.21	17
July	1.36	4	0.32	3	0.91	7
August	0.75	5	0.47	3	0.65	8
September	1.11	6	1.92	1	1.23	7
October	....	..	0.25	2	0.25	2
November	0.11	2	....	..	0.11	2
All values	....	..	....	..	0.84	56

Note--Class A: f for storms following two or more rainless days.
Class B: f for storms following one or less than one rainless day.

Seasonal effects, also the effect of cultivation, are further revealed by the data given in Table 2, which shows the average infiltration-capacity for storms occurring in different months of the year. For Class A storms, which represent approximately maximum infiltration-capacity, the value of f is of the same order for the months May, June, July, and September, but drops to a lower value in August, in which month tillage-operations on farms are generally at a minimum, as the season of corn-cultivation is over and the sowing of fall grain has not begun.

The other experimental data above referred to give results of the same general character. It is expected that these data will be published in full in the near future.

In view of the large variations of infiltration-capacity, even for the same soil when in different conditions, the question naturally arises as to the practicability of using infiltration-capacity as an independent variable in hydrologic studies. As already noted, infiltration-capacity changes rather quickly from its maximum to its minimum value during heavy rain, and after a rain its maximum value is restored, usually before the next succeeding heavy rain.

Actual variations in infiltration-capacity are not as great as they appear to be. Owing to the method of calculation of f, especially for large areas involving a deduction for ground-water, errors in the determination of either the rainfall or runoff may combine so as to produce a considerably greater error in the calculated infiltration-capacity.

The data thus far analyzed indicate that if there has been no recent rain, f is close to its maximum value during short intense storms of the summer thunder-storm type. This would be true, for example, for storms of less than one hour total duration of rainfall. For longer storms of the same type the value of f is about the average of the maximum and minimum values. For long storms of the cyclonic type and for all storms where there has been at least a moderate fall of rain within one day preceding, the value of f is close to the minimum value. In other words, if two heavy rains occur not more than a day apart, the ground being dry antecedent to the first rain, and if both rains are of short duration, the value of f will be close to the maximum value for the first rain and close to the minimum value for the second rain. If the maximum and minimum infiltration-capacities of the soil are known, a study of the rainfall-record will usually show the value of f applicable to a given storm.

A simple method of determining the range and approximate values of f for a small drainage-area consists in noting the intensities of the heaviest rains which do not produce surface-runoff--this will indicate f_g; and also the lightest rains which produce surface-runoff--this will indicate f_ℓ.

Relation of infiltration to runoff

There are three ways of viewing runoff:

(1) As a fraction or percentage of rainfall. This is the usual concept when applied to average conditions. The average runoff can be determined by multiplying the rainfall by the ratio of runoff to rainfall or runoff-coefficient. There is, however, only an indirect relation between the average runoff-coefficient for permeable areas and the runoff-coefficient for particular storms. The average runoff may include a large percentage of ground-water flow, while runoff for an individual storm is mainly or wholly surface-runoff. Since surface-runoff is approximately equal to the rainfall-excess, and this is zero for rain-intensities less than the infiltration-capacity, it follows that the runoff-coefficient is not a constant, neither is it directly a function of the amount of rainfall. It is a direct function of the rainfall-excess intensity for rains of sufficient intensity to produce a rainfall-excess.

(2) Runoff may be considered as the difference between rainfall and water-losses. The water-losses include interception, transpiration, and evaporation from the soil. Runoff is the residuum left after these evaporative processes have taken their toll. This is the basis of the water-loss method of estimating runoff, largely used in England. It directly reflects the effect of the physical processes involved but makes no distinction between ground-water and surface-runoff and does not directly take storage-effects into account. It is therefore, applicable primarily to average conditions and not to individual storms.

(3) The infiltration-theory—Runoff from a permeable area generally consists of two parts: (a) Surface-runoff; (b) ground-water runoff. Neglecting interception by vegetation, surface-runoff is that part of the rainfall which is not absorbed by the soil by infiltration. If the soil has an infiltration-capacity f, expressed in inches depth absorbed per hour, then when the rain-intensity i is less than f the rain is all absorbed and there is no surface-runoff. It may be said as a first approximation that if i is greater than f, surface-runoff will occur at the rate $(i-f)$.

Many attempts have been made to correlate annual seasonal or monthly runoff with rainfall-amount, or with rainfall-amount and evaporation or temperature, it being assumed that at a given locality temperature is the principal independent variable controlling evaporation-rate. The results have sometimes been expressed in terms of a method for computing runoff or extending runoff-records, such as the methods of Vermeule and Meyer. More often they have been expressed as runoff-formulas, of which there are many. Neither of these methods of procedure has met with any marked success.

An analysis of the relation of runoff for the summer season, May to October, inclusive, to rainfall, evaporation, and to rainfall and evaporation together, has been made for West Branch Delaware River for the 25-year period, 1904-29, for the purpose of determining the degree of correlation existing between these quantities. Briefly stated, the results indicate that the best which can possibly be done, even where the coefficients and relationships are derived directly from a long runoff-record, is to duplicate the record for individual seasons with an average error of about ten per cent but with much larger actual errors in the estimated runoff in individual seasons.

The imperfect correlation between total rainfall and evaporation, on the one hand, and runoff, on the other hand, is illustrated by Table 3, showing various data for West Branch Delaware River for the summer season, May to October, inclusive. The ground-water flow was determined by the use of a normal depletion-curve and the total runoff separated into its two elements: Ground-water runoff (Y_g), Column 4, and surface-runoff (Y_s), Column 5. Column 6 shows the ratio of seasonal evaporative capacity computed by the author's formula (Robert E. Horton, A new evaporation formula developed, Eng. News-Rec., Apr. 26, 1917, pp. 196-199). The apparent water losses, L', Column 7, represent the difference between rainfall and total runoff, without correction for gain or loss of storage. It will be noted that there are large differences in total runoff and surface-runoff, particularly the latter, in different years having approximately the same rainfall. For example, in 1909 we have $P = 15.59$, $Y = 6.78$, and $Y_s = 3.42$, while for 1913 we have $P = 16.20$, $Y = 2.40$, and $Y_s = 0.94$. These differences are not wholly accountable to variations in evaporation. While in most years excessive evaporation is accompanied by water-losses larger than the normal, this is not always true and, in any event, departures of evaporation from the normal are usually small compared with variations in either total or surface-runoff with the same amount of rainfall.

The author has long felt that there was some independent variable or variables other than total rainfall and evaporation-rate which should be taken into account. It will be noted that the infiltration-theory of runoff includes two new variables, namely, rainfall-excess and infiltration-capacity. Just how far the introduction of these new variables will serve to bridge the gap between observed and computed runoff remains to be determined. In accordance with this theory, total runoff consists of two parts:

(1) Surface-runoff, which is dependent on rainfall-amount, rain-intensity, and infiltration-capacity and is practically independent of evaporation-rate.

(2) Ground-water runoff. This is dependent on (a) total infiltration and hence indirectly on the same factors which control surface-runoff and is also dependent on (b) vegetational activity and evaporation, which in part determine the water losses, and on (c) the complex interrelations between infiltration-capacity, field moisture-capacity, vegetational activity, and accretion to the water-table. These relationships will be subsequently discussed.

Referring again to Table 3, Column 9 gives the ratio of the apparent water-losses to total infiltration. Attention is particularly directed to the relative constancy of this ratio. West Branch Delaware River drainage-basin is in a large degree covered with natural forest vegetation. The meaning of the constancy of this ratio seems to be that the natural vegetation of a region tends to develop to such an extent that it can utilize the largest possible proportion of the available soil-moisture supplied by infiltration. The constancy of this ratio also suggests its utility as a factor for use in estimating water-losses from drainage-areas and, furthermore, it is apparent that the total infiltration represents the maximum amount of available or "effective rainfall" in relation to the growth of vegetation.

TABLE 3 - SEASONAL RAINFALL, RUNOFF, AND WATER-LOSSES
WEST BRANCH OF DELAWARE RIVER AT HANCOCK AND HALE EDDY, N.Y.
SUMMER SEASON - MAY TO OCTOBER INCL.
(All quantities except ratios are in Inches Depth)

Year (1)	P (2)	Y (3)	Y_g (4)	Y_s (5)	E_r (6)	L' (7)	$F = P - Y_s$ (8)	$\frac{L'}{F}$ (9)	f[(a)] (10)
1905	23.29	6.06	2.97	3.09	0.932	17.23	20.20	0.853	0.88
06	23.08	7.11	4.21	2.90	1.01	15.97	20.18	.791	.79
07	20.30	6.83	3.98	2.85	0.928	13.47	17.45	.772	.98
08	16.71	5.32	2.95	2.37	1.12	11.39	14.34	.794	.80
09	15.59	6.78	3.36	3.42	1.05	8.81	12.17	.724	.34
1910	15.66	4.56	2.90	1.66	1.13	11.10	14.00	.793	.68
11	20.65	5.42	3.09	2.33	1.06	15.23	18.32	.831	1.05
12	18.71	4.43	3.10	1.33	1.04	14.28	17.38	.822	1.09
13	16.20	2.40	1.46	0.94	1.08	13.80	15.26	.904	1.03
14	20.90	5.67	3.55	2.12	1.04	15.23	18.78	.811	.68
1915	24.90	8.89	5.12	3.45	0.967	16.01	21.45	.746	1.14
16	23.19	7.87	5.68	2.19	1.08	15.32	21.00	.730	1.14
17	32.14	13.41	7.46	5.95	0.953	18.73	26.19	.715	.72
18	28.60	8.62	6.40	2.22	1.08	19.98	26.38	.758	.82
19	21.18	5.25	4.00	1.25	1.00	15.93	19.93	.799	1.18
1920	27.40	8.89	5.94	2.95	1.00	18.51	24.45	.757	1.10
21	23.18	4.69	3.68	1.01	1.11	18.49	22.17	.834	.73
22	26.03	8.28	5.35	2.93	1.01	17.75	23.10	.768	1.18
23	21.85	5.08	3.17	1.91	1.00	16.77	19.94	.841	1.00
24	24.53	10.40	5.46	4.94	0.835	14.13	19.59	.721	.62
1925	23.02	8.14	4.82	3.32	0.852	14.88	19.70	.755	.82
26	20.37	5.88	3.78	2.10	0.960	14.49	18.27	.793	1.00
27	26.69	11.56	5.39	6.17	0.812	15.13	20.52	.737	.82
28	25.35	13.06	7.54	5.51	0.880	12.29	19.84	.619	.63
1929	22.39	7.18	4.96	2.22	1.01	15.21	20.17	.754	1.20
Mean	22.48	7.27	4.42	2.85		15.20	19.63	0.777	0.90

(a) This is apparent infiltration-capacity in inches per day as deduced from daily rainfall-records. The actual infiltration-capacity is greater in the ratio of 24 to the number of hours per day of rainfall-excess duration.

Phenomena of a stream-rise

The segment of a hydrograph from the end of a period of concordant flow when a rise begins and continuing through to the beginning of the next period of concordant flow may be designated a "rise." In reality, of course, it involves both a rise and a recession. A rise of a perennial stream begins as a result of rain of an intensity exceeding the infiltration-capacity f.

It can be shown that on a permeable drainage-area direct surface-runoff to the stream after rain ends takes place only from a restricted belt bordering the stream. From portions of the drainage-basin more remote from streams all of the overland flow or water in transit as surface-detention when rain ends enters the soil as infiltration and none of it reaches the stream.

As a result of this condition, direct surface-runoff into stream-channels ends very shortly after the end of the last period of rain-intensity exceeding infiltration-capacity. There is thereafter an interval of variable flow, its duration ranging from a few hours for very small areas to many days for large areas, after which the stream settles down again to a condition of concordant or nearly concordant flow. The flow is then represented by the normal depletion-curve. This continues until the beginning of the next rise. A hydrograph consists of a succession of alternating rises and intervals of concordant flow or flow derived from normal depletion of storage.

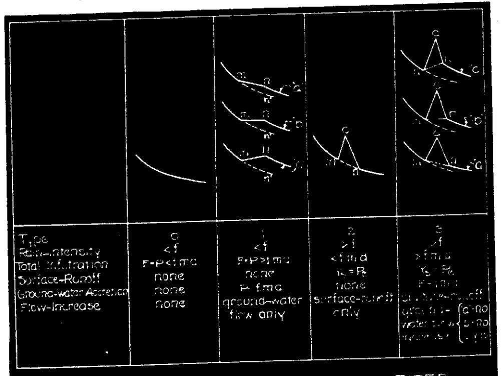

FIG 2-CLASSIFICATION OF STREAM-RISES

Fig. 2

Ground-water flow, of course, continues during the interval of the rise and follows the normal depletion-curve unless or until accretion to the water-table takes place. After accretion ends, ground-water flow in accordance with the normal depletion-curve is resumed, though perhaps at a higher level. Accretion to the water-table does not, however, occur during a rise unless the infiltration is in excess of field moisture-deficiency between the water-table and the soil-surface. These principles make it possible to classify rises appearing on a hydrograph in terms of rain-intensity, infiltration-capacity, and field moisture-deficiency.

The author's classification of rises is shown on Figure 2.

Type 0 is so designated because nothing happens as far as the stream is concerned. For this type the rain-intensity is less than the infiltration-capacity. There is, therefore, no surface-runoff. The total infiltration is less than the field moisture-deficiency and there is, therefore, no accretion to ground-water. The normal depletion-curve continues its downward course uninterrupted. There is, therefore, no rise in the stream. These phenomena are characteristic of light rains occurring during generally dry weather, particularly after long droughts when the soil has the maximum infiltration-capacity f_g. Type 0 is, however, something more than a gesture since soil moisture-accretion takes place. Soil moisture-accretion effects are cumulative and the occurrence of conditions of Type 0 may hasten the time when a real rise in the stream will occur.

Type 1--Again the rain-intensity is less than infiltration-capacity and no surface-runoff occurs. The total infiltration is greater than the field moisture-deficiency and some accretion to the water-table takes place, accompanied either by an increase in ground-water flow or a slowing down of the ground-water depletion-rate. These small irregularities in a hydrograph look like the effects of observational errors or barometric changes but they frequently result from rain. They are typical effects of light rain in the spring and of somewhat heavier rain of low intensity in the summer and fall.

Three different cases occur under Type 1, as shown on the diagram. In each case accretion to the water-table takes place during the interval denoted by mn. Normal ground-water depletion interrupted at m is resumed at n, while n' shows the corresponding stage had there been no ground-water accretion. In case (a) the rate of accretion is less than the rate of normal ground-water depletion. The depletion, therefore, continues but at a reduced rate. In case (b) the accretion and depletion rates are equal and the ground-water flow-rate remains constant for a time. In case (c) the rate of ground-water accretion exceeds the rate of normal depletion and there is a rise of the water-table and an increase in the ground-water outflow-rate.

Type 2--Here the rain-intensity exceeds the infiltration-capacity and surface-runoff occurs, but the total infiltration is less than the initial field moisture-deficiency and there is no accretion to the ground-water and hence no change in ground-water flow. The normal depletion continues during the rise and the ground-water regimen is resumed at n. The stream falls after the rise to a lower stage than pertained when the rise began. This is a growing season or midsummer type and commonly occurs when the field moisture-deficiency is large enough so that the field moisture-capacity is not fully restored by infiltration. Such rises are typical of the effect of short, sharp showers of the thunder-storm type.

Type 3--Again the rain-intensity exceeds the infiltration-capacity and surface-runoff occurs. In this type of rise, the total infiltration exceeds the field moisture-deficiency and accretion to the water-table takes place. The point n at which the rise ends is the point at which the recession-side cn of the discharge-graph coincides with the normal depletion-curve.

There are three cases under Type 3 identical with those for Type 1-rises and dependent on the rate of ground-water accretion. Normal depletion-flow is resumed at the end of a rise of Type 3 at a higher stage than for a rise of Type 2, other things equal, but the stage at the end of the rise may or may not be higher than the initial stage. In cases (a) or (b), Type 3, the stage at which the normal depletion-flow is resumed will not be higher than the initial stage; in case (c) it will be higher. Whether a given rise is of Type 2 or Type 3 can be determined by extending the normal depletion-curve underneath the rise. If the recession-side of the graph returns to this curve as extended, the rise is of Type 2. If the normal depletion-curve at the end of the rise is at a higher level than the extended curve under the graph, the rise is of Type 3.

Compound rises occur where, as the result of a second intense rainfall, a second rise begins before the completion of the recession-phase of the first rise. There are, however, only three fundamental cases: Types 1, 2, and 3, as may readily be seen. A compound rise may, of course, be decidedly complex since any of the three types may be partly superposed on any other. This gives six cases for a compound rise, Type 1 on 2, 1 on 3, 2 on 3, 3 on 2, 3 on 1, and 2 on 1. Also each of the three types may succeed itself.

As regards its relation to ground-water accretion, a compound rise may always be resolved into one of the three fundamental types, since a rise of any one of these types always involves a reduction in field moisture-deficiency. A storm which produces a rise of a given type will, if compounded with a second rise, generally produce a compound rise of an order equal to or higher than that of either of its two components. Thus a rise of Types 1 and 2 combined will generally be of Type 3.

It may be noted that in order to bring out the various relationships described on a hydrograph a fairly open time-scale is required, say one inch equals five or ten days, together with not too small a discharge-scale.

Classification of stream-rises in the manner above described not only affords a definite basis for separation of ground-water flow from surface-runoff on a hydrograph but it affords a convenient starting point for determining what is going on within the non-saturated zone of the soil during and following rain.

Interrelations of infiltration, vegetation, soil-moisture, and ground-water

There are four hydrologic factors which limit and determine the adaptability of the soil of a given region to the growth of vegetation: (1) Rainfall-amount, duration, intensity, and seasonal distribution; (2) infiltration-capacity of the soil; (3) field moisture-capacity of the soil; and (4) depth to water-table, if one exists.

Infiltration-capacity limits the amount of water which can enter the soil. The excess is rejected as surface-runoff. The field moisture-capacity limits the part of the infiltration that can be retained in the non-saturated zone of the soil and is available to supply vegetation therefrom. If at a given time when infiltration occurs, there is a certain aggregate field moisture-deficiency, measured in inches depth of water, the excess of infiltration over field moisture-deficiency, if any, is rejected and percolates downward to the water-table. In general, the part of the ground-rainfall which remains in the soil available to supply soil-moisture requirements is that which remains after the rejection (1) of rainfall-excess at the soil-surface and (2) of excess of infiltration over field moisture-deficiency within the soil.

Depth to ground-water operates in three ways: (a) The water-table if too near the surface inhibits the growth of mesophytic vegetation, although hydrophytic plants may thrive, as on swampy areas; (b) if within the reach of plant-roots, the water-table may provide an important and even the larger part of the moisture-supply used by vegetation; and (c) if at a depth below the reach of plant-roots and evaporative uplift, the presence of a water-table has no effect on vegetation.

There is a close interrelation between infiltration-capacity, field moisture-capacity, and depth to water-table which does not seem to have been pointed out.

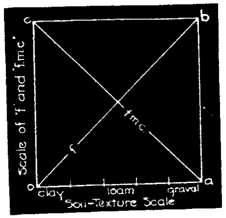

Fig. 3

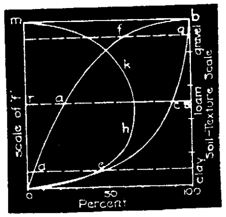

Fig. 4

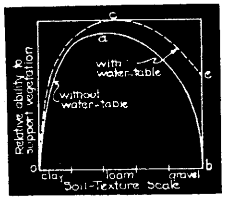

Fig. 5

Fig. 3--Relation infiltration-capacity and field moisture-capacity to soil-texture (schematic)

Fig. 4--Infiltration oab and accretion to water-table ocb, per cent of total (schematic)

Fig. 5--Relative ability of soils to support vegetation with and without a water-table (schematic)

Infiltration-capacity and field moisture-capacity are in a large measure complementary functions of soil-texture, the former increasing, the latter decreasing as one proceeds along the scale of soil-texture from clay and silt to sand and gravel. This fact and some of its consequences are illustrated by Figure 3. The base-scale oa represents soil-texture. The diagonal lines ob and ac may be taken to represent infiltration-capacity and field moisture-capacity, respectively.

For fine soil-textures near the left-hand end of the texture-scale, the infiltration-capacity f is small and the field moisture-capacity fmc is large. Plants may suffer because not enough water enters the soil to support luxuriant growth. For these conditions also there is a large rejection of rainfall at the surface and but little rejection within the soil, so that the final residuum available to supply the water-table is small; hence ground-water accretion is limited and a perennial water-table may not exist.

For coarse-textured soils, corresponding to the right-hand portion of the texture-scale, f is large and fmc is small. There is little surface-rejection of water but a large rejection of infiltration within the soil, so that, again, plants may suffer for want of soil-moisture, but there is abundant accretion of moisture to the water-table and ground-water supplies from such soils are generally plentiful.

In the central portion of the diagram there is both a moderately large infiltration-capacity and field moisture-capacity, a condition most favorable to plant-growth, bearing in mind that rain occurs in quanta, not continuously, while the demands of the plant for moisture are incessant and if the moisture-supply is interrupted, wilting, retarded growth, and perhaps death of the plant results.

It is not to be assumed that the relations of infiltration-capacity and field moisture-capacity to soil-texture are actually linear, as indicated by the lines oa and bc. Quite certainly these quantities are not linear functions of the average size of the soil-grains. This, however, does not affect the validity of the diagram for the purpose for which it is here used.

For a given rainfall-régime, as infiltration-capacity increases, the total infiltration increases, at first rapidly, then more slowly as the maximum rain-intensity is approached. This is illustrated by the line oab, Figure 4. The base-scale in this case shows infiltration expressed as a percentage of total rainfall.

As the field moisture-capacity of the soil decreases, that is, as the infiltration-capacity increases, the proportion of infiltration which is rejected within the soil increases. The total rejection within the soil equals the total accretion to the water-table and can be determined from ground-water flow and runoff-records. The relations of the accretion to the water-table or total rejection of moisture within the soil to total infiltration and infiltration-capacity are somewhat as shown by the line ocb, Figure 4. Consider, for example, a loam soil having an infiltration-capacity as indicated by the horizontal line ac. The segment ra of this line is rainfall-excess rejected at the surface and which produces surface-runoff. The segment cs is rejected excess of infiltration over field moisture-deficiency and goes to the water-table. The remainder, represented by the intercept ac, represents the percentage of total rainfall which will be retained within the soil moisture-zone, presuming that vegetation is growing on the soil to the maximum extent which the soil can support. Similarly, the intercepts de and fg represent moisture available for vegetation in clay and sand. A series of intercepts similar to those described and corresponding to different infiltration-capacities has been taken off and plotted as shown by the line ohkm, Figure 4. This shows, as far as soil-moisture alone is concerned, the relative ability of soils of different infiltration-capacities to support vegetation from soil-moisture alone. The maximum point on this curve corresponds to a soil of medium texture. It is not possible at this time to convert this directly into a diagram expressing ability of a soil to support vegetation in terms of soil-texture. However, for illustrative purposes it may be assumed that infiltration-capacity and field moisture-capacity of the soil are linear functions of the texture or fineness. The result shown by the line oab, Figure 5, is then obtained (this corresponds to line ohkm, Fig. 4). This curve, derived solely from hydrological considerations, is in good agreement with practical experience. The curve shown is not symmetrical, and probably is not in fact. Heavy impervious soils because of their large field moisture-capacity can, with equal rainfall, tide vegetation over periods of drought better than coarse-textured soils. It is to be noted that this discussion does not take into consideration other requirements of vegetation than those for soil-moisture.

For a given rainfall-regime, that soil will best support vegetation which permits the largest percentage of the rainfall to be absorbed as infiltration and at the same time permits the smallest percentage of infiltration to pass downward to the water-table. For such a soil the surface-runoff will be relatively small, the water losses a maximum; the total runoff will not be large but will be somewhat regulated by ground-water flow; ground-water supplies will be of moderate amount but generally perennial.

Turning next to a consideration of the height of water-table, in a given phreatic basin with given rainfall characteristics this is controlled jointly by two factors, namely, (a) the amount of accretion to the water-table, and (b) the transmission-capacity of the soil. With the outlet level or sole of the aquifer fixed by topographic conditions, the average height of water-table at a given point within the phreatic basin will be such that, at the existing height, the average rate of outflow equals the average rate of accretion. If there is abstraction of water directly from the water-table by vegetation or evaporation, this is to be added to the outflow.

Considering first a case where there is no such abstraction, the rate of outflow is proportional to the product of depth of ground-water in the aquifer, the slope of the water-table and the transmission-capacity of the soil.

The amount of accretion to the water-table for a given soil and rainfall-regime is doubly a function of the infiltration-capacity, since, as f increases, fmc decreases and an increasing portion of the total infiltration passes downward to the water-table; hence the average rate and the total amount of accretion increase rapidly, other things equal, as the soil-texture becomes increasingly coarser. Transmission-capacity is also a rapidly increasing function of increasing size of soil-grains. Thus proceeding from finer to coarser-textured soils the total accretion to the water-table increases, thus tending to maintain a higher ground-water level. At the same time the transmission-capacity of the soil increases and this tends toward a lowering of the water-table. The combined action of these two opposing factors tends toward the maintenance of a more or less invariant mean ground-water level under widely differing soil-conditions. The effect of their joint operation is revealed by the fact that the surface water-table in well-drained humid regions is generally at a depth varying from 10 to 30 feet, in soils ranging from those of the finest to those of the coarsest textures. Ability of a given region to supply ground-water is, however, more or less proportional to the infiltration-capacity alone.

Starting with the finest-textured soils, as the coarseness of the soil increases, ability to support vegetation and to supply ground-water both increase, the ability t support vegetation reaches a maximum for a soil of medium texture and thereafter decreases, while ability to supply ground-water continues to increase.

Thus far it has been assumed that vegetation is supplied wholly from the zone of aeration or that there is no direct abstraction from the water-table by plants. If the water-table is at a suitable but moderate depth, plants, including both native vegetation and cultivated crops, may and often do derive a part of their moisture-supply by direct abstraction from the water-table. For this condition the relation between soil-moisture and ability to support vegetation is considerably modified as compared with the case already considered, where the moisture-supply of vegetation is derived wholly from the zone of aeration. Assuming—as is apparently the case—that the plant derives moisture from the soil above the water-table and by abstraction directly from the water-table, respectively, in proportion to the facility with which it can get water from each, then the relation between soil-textures and ability of the soil to support vegetation will be somewhat as indicated by the dashed line oce, on Figure 5. The two curves on Figure 5 indicate, qualitatively, at least, the relative ability of a given soil to support vegetation according as there is or is not a water-table at a height within the reach of plant-roots. The purpose of this diagram is to show that the range of soil-textures through which mesophytic vegetation can thrive is, in general, considerably increased by the presence of a water-table of suitable depth.

Conclusions

Infiltration-capacity is an important physical characteristic of the soil. For a given soil the infiltration-capacity varies between a maximum value when the soil is dry and a minimum value after wetting and packing. The infiltration-capacity is generally close to the maximum during short storms following dry periods and close to the minimum during prolonged wet periods.

The infiltration-capacity of a drainage-basin can be determined from runoff and rain-intensity data and, conversely, if infiltration-capacity is known, in conjunction with rain-intensity data, the surface-runoff and total infiltration to the soil can be determined.

For small areas in and adjacent to cities, where rain-intensity records are available and estimates of storm-runoff are required in connection with sewer-design, the use of this method for estimating surface-runoff appears more rational than the so-called "rational method."

It is shown that rainfall-excess and infiltration-capacity are apparently two additional variables which need to be included in order to obtain a close correlation between runoff and the factors by which it is controlled.

Stream-rises are classified on the basis of infiltration-capacity and field moisture-capacity, and a definite procedure is established for separating ground-water flow from surface-runoff in streams.

There are close interrelations between infiltration-capacity, field moisture-capacity, growth of vegetation, and ground-water levels. It appears that natural vegetation generally develops to the maximum extent to which it can be continually supplied with moisture with a given rainfall-régime.

Owing to the fact that the demands of vegetation for moisture are incessant, whereas infiltration occurs intermittently and by quanta, that soil is best able to support vegetation which has a large infiltration-capacity and also a large field moisture-capacity.

Infiltration-capacity and field moisture-capacity are complementary, the first increasing and the second decreasing as the soil-texture ranges from fine to coarse. The best combination for plant-growth, from the viewpoint of hydrological considerations alone, is therefore a medium-textured soil within the class designated "loam."

There is a close correlation between total infiltration and the water-losses or water utilized directly or indirectly by vegetation, and total infiltration appears to be the best available basis of estimating the "effective rainfall" in relation to vegetation.

Voorheesville, New York

REVISED TEMPERATURE-FORMULAE FOR PREDICTING SEASONAL PRECIPITATION AND RUNOFF IN CALIFORNIA

A. F. Gorton

(Abstract)

Forecasts of seasonal precipitation in California based on observed ocean surface-temperatures at La Jolla during the midsummer upwelling-period correctly indicated an excess or deficit in practically three-fourths of the years from 1923 to 1931, but the divergence of computed and observed values in 1931-32 pointed to the need of a broader and more flexible index. Studies of the correlation between the precipitation or runoff and the ocean-temperatures of various months showed that a better fit might be secured by using values for certain months preceding as well as following the summer period.

The computations were performed by the ordinary least-squares method (Doolittle solution), also by a related method in which the element predicted is expressed as a joint function of two temperature factors

$$R = (a + bx)\ (c + dy) = A + Bx + Cy + Dz$$

where x, y are the temperature-factors, z is their product, and the coefficients $A\ldots$ are fitted by least squares. (In this case, actually y = current winter temperature, x = difference between preceding summer- and preceding winter-temperatures.)

These new formulae resulted in a much better verification than previous ones, when applied to the chief rainfall- and runoff-areas in northern California. For Huntington Lake District rainfall and Owens River runoff, agreement of sign of the departures was noted in 13 years out of 16, and the probable error was as low as 10 and 13 per cent, respectively, for the interval 1916-30. When air-temperatures at San Diego were substituted for ocean-temperatures at La Jolla, as an index, the error increased by several per cent, probably on account of the inherently variable nature of the former. [The complete paper will appear in Proceedings of the Fifth Pacific Science Congress.]

Scripps Institution of Oceanography,
La Jolla, California

A STUDY IN EVAPORATION AS AFFECTING THE RUNOFF OF OWENS RIVER, CALIFORNIA

Clem A. Copeland

The Bureau of Power and Light of the City of Los Angeles has been carrying on extended research for several years with the object of predicting the runoff of the Owens River and its tributaries which furnish the City with water and electric energy. Short-time predictions involving the expected runoff for the next year as indicated by phenomena of the previous year, have been made by means of least-square correlations of the ocean-temperatures at La Jolla, the air-temperatures of Tokyo, the precipitation at Nevada City, and other similar factors.

Based on the temperatures of the ocean six feet below the surface at the end of Scripps Pier at La Jolla, the prediction for the runoff of Owens River for 1932 was extravagantly high, there having been in 1931 the most unusually high temperatures since 1916 when records were initiated at this point. Other indications together with the La Jolla temperatures resulted in a final prediction of 125 per cent of the normal of 225 second-feet runoff of the River for 1932. The winter of 1931-32 seemed auspicious for fulfilling this prediction as the snowfall was the heaviest of any winter for the last 16 years. The actual runoff fell far short of the prediction, being 188 average second-feet, or 83.6 per cent of normal. The present concern is in determining the reason for the discrepancy.

By July, 1932, the deficiency was becoming apparent. It so happened that the author, in charge of the Research and Records Section of the Bureau of Power and Light