INFILTRATION AND RUNOFF DURING THE SNOW-MELTING SEASON, WITH FOREST-COVER

Robert E. Horton

Synopsis--This paper presents a new method of analysis of rainfall- and runoff-data which permits surface-runoff and ground-water flow to be segregated and infiltration-capacity determined during stream-rises. The method is equally applicable to areas with and without snow-cover. The determination of infiltration-capacity during the snow-melting periods is, however, the most difficult problem and the method is here applied to this case, using data for areas in the Allegheny Experimental Forest, with varying degrees of forest-cover density. For these areas the rate of snow-melting per degree-day of temperature excess above 32° decreased as the cover-density increased.

During snow-melt, infiltration took place at rates governed by the rate of supply of rain and melt-water, averaging for the entire snow-melting period one-third to one-quarter of the infiltration-capacity of the soil. The infiltration-capacity under snow-cover with unfrozen soil was found to be about 0.05 inch per hour or 1.20 inches per day. There was no significant difference between infiltration-capacity of these areas with different forest-cover densities. Since the infiltration-capacity of these areas greatly exceeded the average rate of supply of melt-water during the melting-period, and the rate of supply of melt-water decreased as the forest-cover density increased, it appears that, under the conditions of the experiments, increased forest-cover may operate to materially reduce runoff-intensity during the snow-melting period. The opposite effect can, however, be brought about by the occurrence of a rain on ripe snow in the forest at a time when the snow-cover would have disappeared from an open area. On the other hand, snow-cover in forest may absorb a rain which would produce heavy runoff from decreased snow-cover or bare ground in the open, especially if the soil-surface in the open has frozen after the snow disappeared.

Data used--Data collected during the snow-melting period on four small drainage-basins in the Allegheny National Forest near Kane, Pennsylvania, in the spring of 1940, are shown in Figures 1, 2, 3, and 4. Data of rainfall, snow-cover, and runoff are from data collected by the United States Forest Service [see 1 of "References" at end of paper]. Lines showing maximum and minimum temperatures, gain or loss of ground-water storage, and ground-water flow have been added by the author.

The vegetal cover-conditions on these areas are described as follows (op. cit.):

Gilfoyle Run--"This area is relatively free of forest-cover and is representative of the logged and severely burned lands of northwestern Pennsylvania. In the valley and on the slopes are scattered clumps of beech, aspen, and black and fire cherry. The headwaters-areas above the slopes are fairly well stocked with sapling stands of northern hardwoods. Many of the understocked and open portions of the watershed are planted to red pine and spruce. Crown-closure of these plantations cannot be expected for another 10 or 15 years."

McKee Run--"McKee Run has been logged once for saw timber and recut for chemical wood. Approximately 30 per cent of the area appears to have been severely burned. The watershed is now almost completely covered with young stands composed chiefly of northern hardwood species of sprout origin. Scattered groups of aspen occur on the burned areas, and on certain sites, especially northern slopes, there is a mixture of hemlock and hardwoods. On the whole, the density of stocking is below average for the region."

Ackerman Run--"This area has been logged at least once, and is now almost completely covered with a second-growth stand of northern hardwoods 40 to 50 years of age. On the northern exposures, there is a relatively high percentage of hemlock. Taken as a whole, the density of stocking is about average for the region."

Hemlock Run--"This watershed, like Ackerman Run, of which it is a tributary, supports a relatively good stand composed chiefly of second-growth northern hardwoods from 40 to 50 years of age. The most important difference in cover is that Hemlock Run has a higher percentage of hemlock. This species occurs in almost pure stands on certain sites, especially northern or western slopes. The density of stocking is average or above for the region."

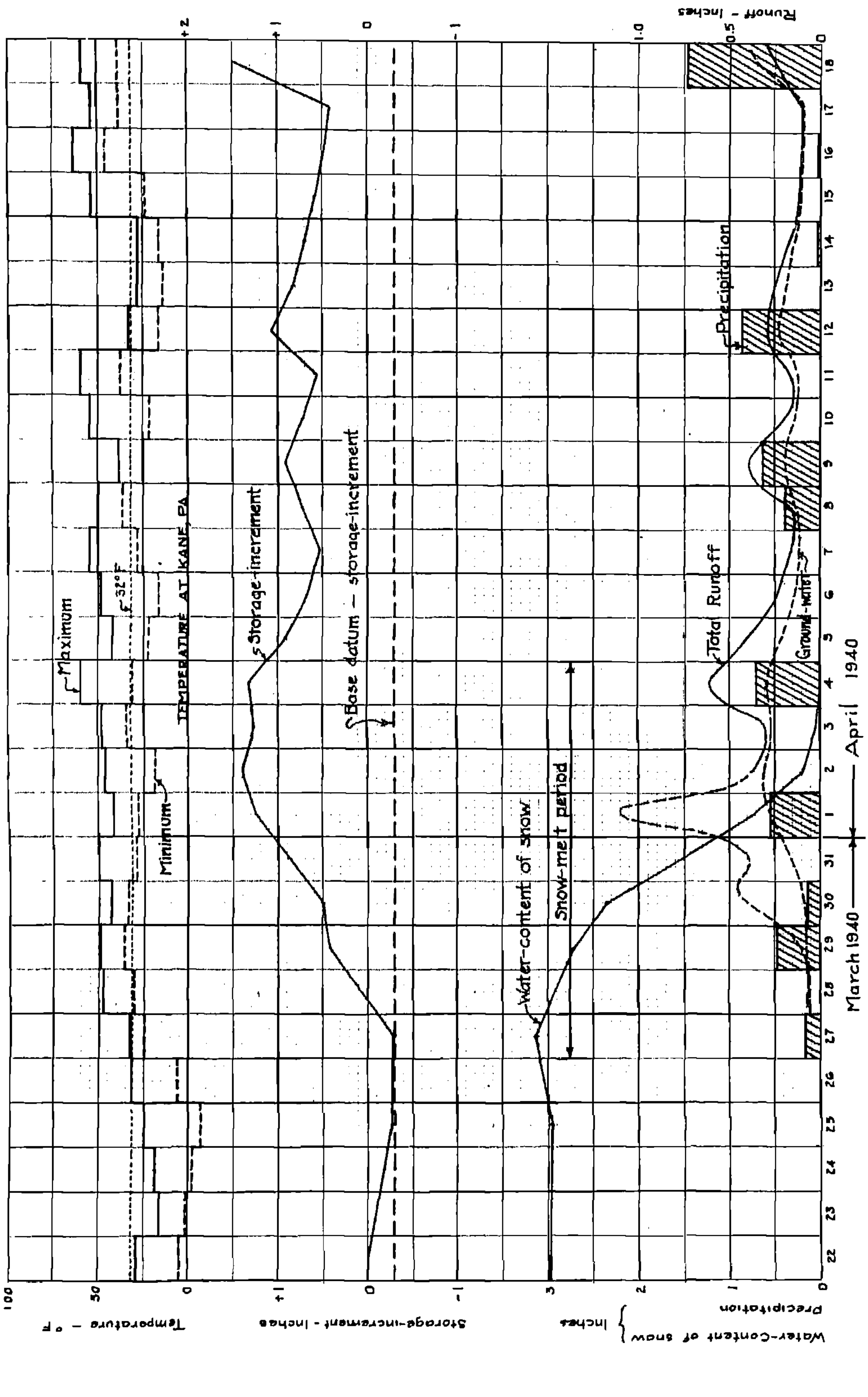

Fig. 1--Hydrologic phenomena, melting-snow period, Gilfoyle Run, Elk County, Pennsylvania

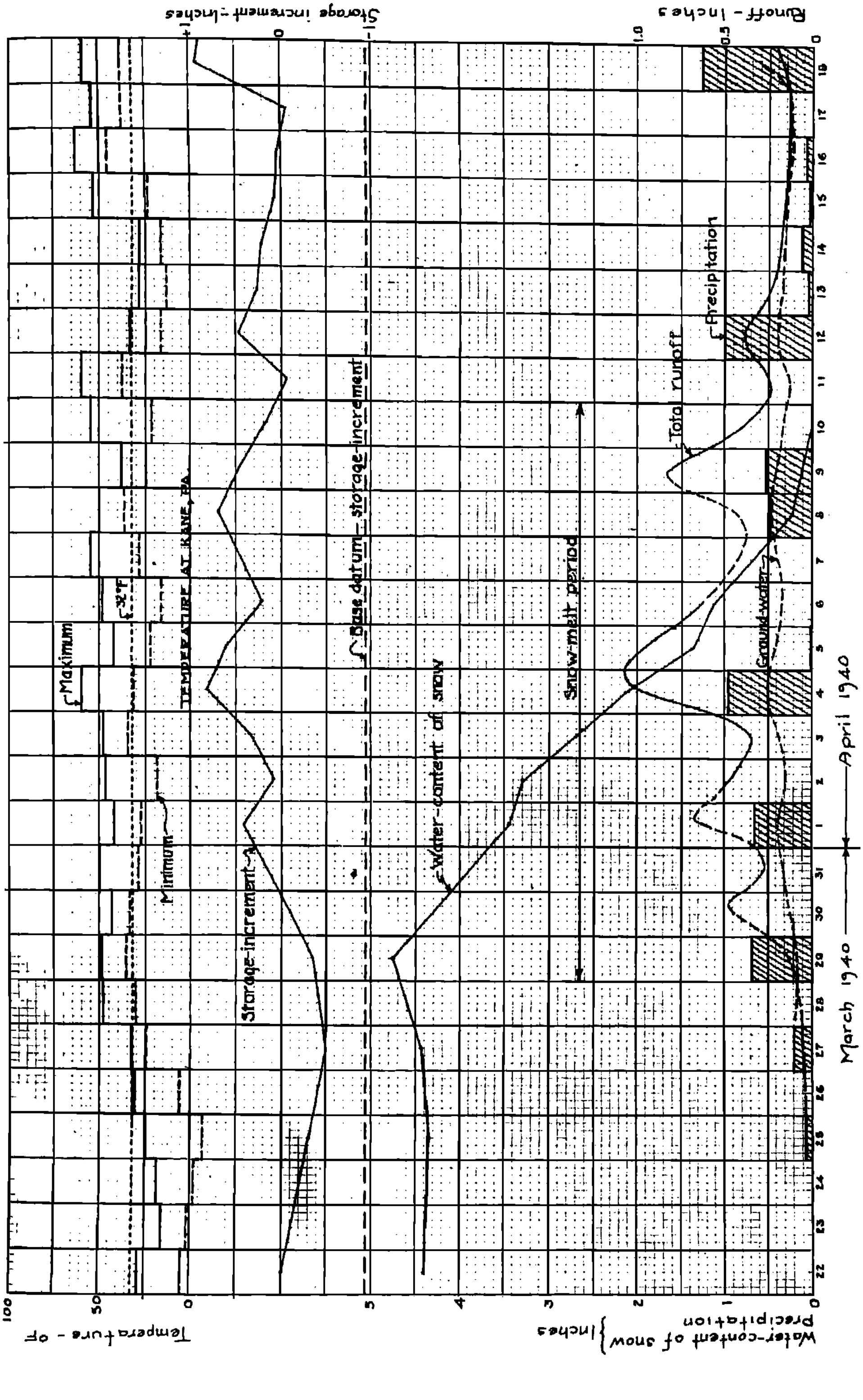

Fig. 2--Hydrologic phenomena, melting-snow period, McKee Run, Elk County, Pennsylvania

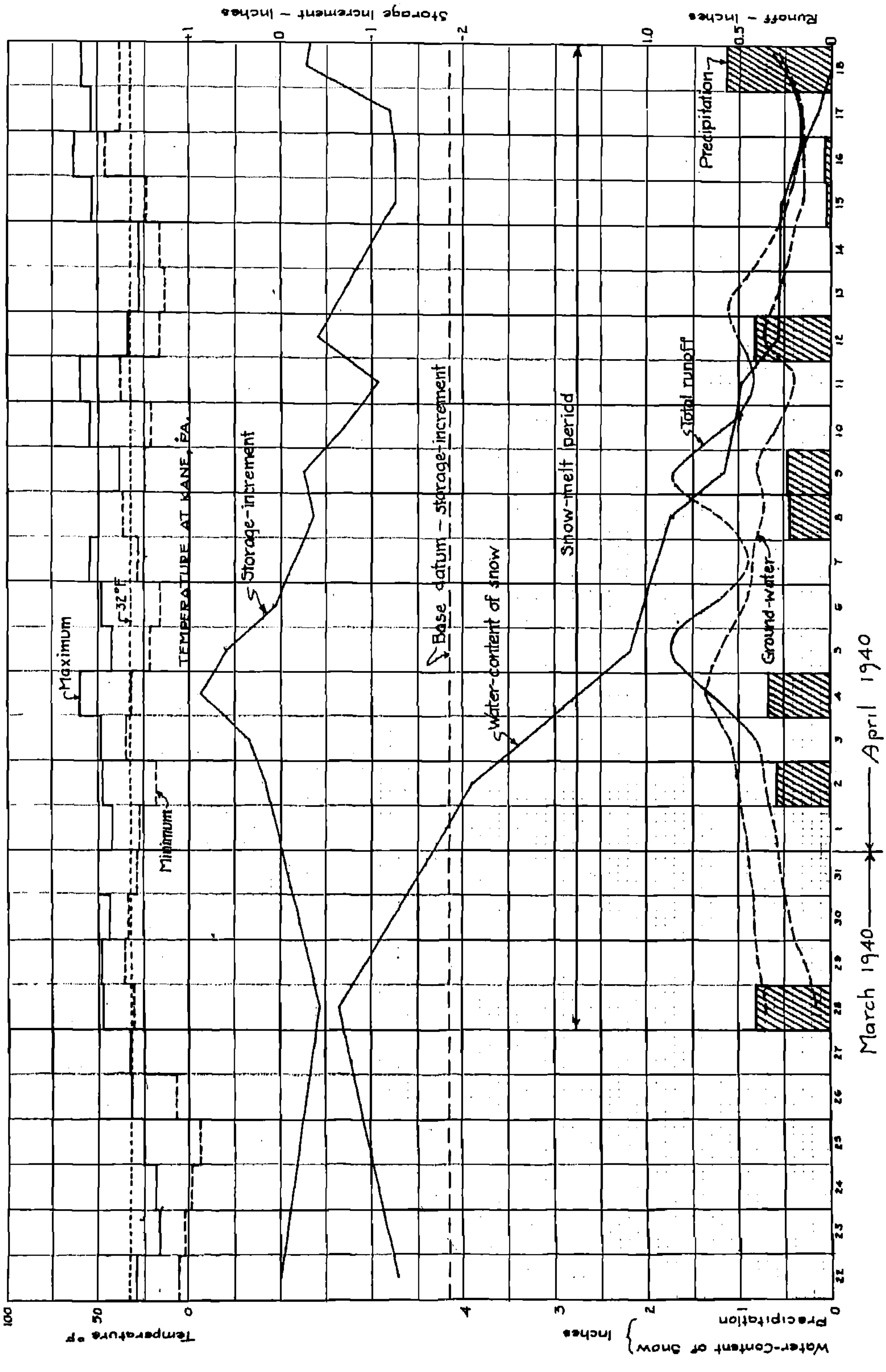

Fig. 3--Hydrologic phenomena, melting-snow period, Ackerman Run, Elk County, Pennsylvania

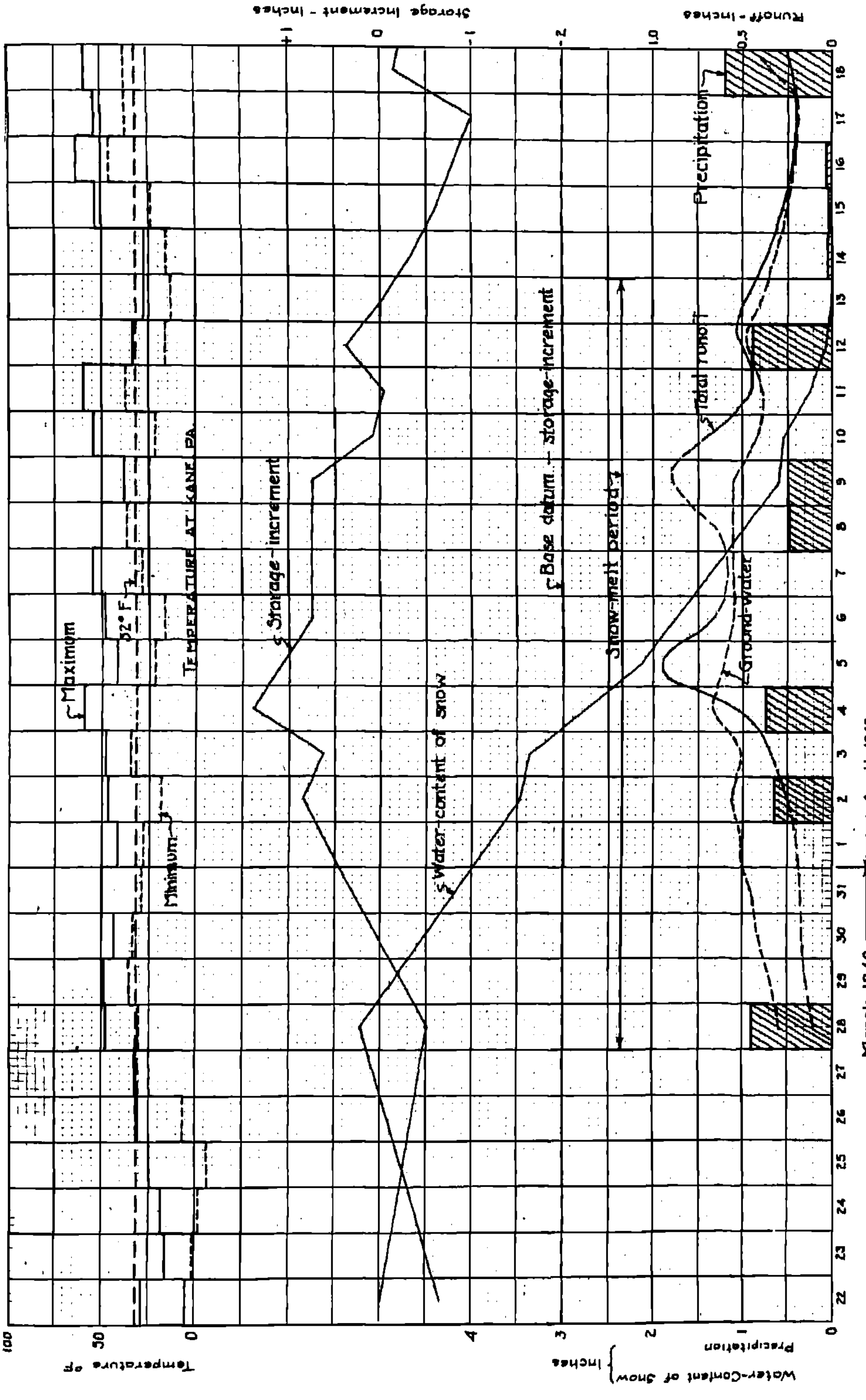

Fig. 4.--Hydrologic phenomena, melting-snow period, Hemlock Run, Elk County, Pennsylvania

The accumulated snow was determined for each area from observations at five to ten stations in each drainage-basin, observations being taken daily during the melting-period. From statistical analysis of the data the determinations of snow-storage appear to be correct within a probable range of ±10 per cent. Ackerman Run and Hemlock Run have regular gaging-stations of the United States Forest Service, equipped with water-stage recorders. Thin-edged weirs were established across the entrances to culverts on Gilfoyle and McKee runs and staff-gage readings taken several times a day. Rainfall was determined from records of several recording and non-recording rain-gages and appears to be substantially correct.

Field-observations show no ground frost under the snow-cover during the melting-period. The data afford an unusual opportunity to determine infiltration with unfrozen but snow-covered ground during the snow-melting period, with different degrees of density of vegetal cover. This is a subject on which data are greatly needed for various purposes but few are available. In order to determine the relation between infiltration and snow-melt it is, however, necessary to separate the total or measured runoff into its two components, surface-runoff and ground-water runoff. This was accomplished by a method of determining ground-water storage and flow, developed by the author. The valley-slopes of these drainage-basins are steep and the soil is shallow. Ground-water is confined to shallow hill-slope aquifers. For such an aquifer the POISEUILLE-DARCY law gives

$$y_g = y_0 e^{-k_g t} \quad \ldots\ldots (1)$$

where y_0 = ground-water flow-rate at a given time and y_g = ground-water flow-rate at the subsequent time t; e is the base of the Napierian logarithms, and k_g is called the ground-water constant. Starting with a ground-water flow-rate y_0, then t days later, if no accretion occurs meanwhile, the ground-water flow-rate will have the value y_g. The validity of this equation has been extensively tested for hill-slope aquifers of the type here occurring in the Susquehanna and other drainage-basins [2].

C. L. WICHT [3] found that equation (1) applied to hill-slope aquifers in drainage-areas within the Jonkershoek Forest Influences Research Station at Jonkershoek, Stellenbosch, Union of South Africa.

If, as is often the case during the growing season, there is direct abstraction of water from a shallow water-table by vegetation, a correction to equation (1) is required. Such abstraction apparently did not occur during the snow-melting period here considered.

Following the end of the snow-melting there were, with exception of Ackerman Run, a few days for each stream with no rainfall or appreciable residual channel-storage from preceding runoff. Consequently the runoff was wholly derived from ground-water during these days and the runoff for these days permits the constant k_g in equation (1) to be determined. If q_2 and q_1 are the measured ground-water flow-rates on two days separated by a time-interval t, within which no accretion occurs, then

$$k_g = (1/t) \log_e (q_1/q_2) \quad \ldots\ldots (2)$$

Values of k_g determined in this way for the different drainage-basins are shown in Table 1.

Table 1--Determination of k_g

Area (1)	Date (2)	y_1 (3)	Date (4)	y_2 (5)	(y_1/y_2) (6)	t, days (7)	k_g (8)	Half-time (9)
Gilfoyle	Apr. 14	.16	Apr. 17	.08	2.000	3	.23	3.01
McKee	Apr. 15	.17	Apr. 17	.11	1.547	3	.14	4.94
Ackerman	Apr. 5	.86	Apr. 6	.67	1.282	1	.25	2.76
Hemlock	Apr. 14	.37	Apr. 17	.20	1.851	3	.20	3.45

Longer periods of ground-water regimen than were here available are of course desirable in determining k_g. It has been found from studies of other drainage-basins that reasonably close determination of these quantities can often be made, as in this instance, from observations for a single period with ground-water regimen.

Except for Ackerman Run the conditions were favorable to good determination of k_g. The "half-time" given in Column (9) of Table 1 is the time in days required for depletion of one-half of the initial ground-water storage, starting at any given date, if no accretion occurs meanwhile. This quantity is similar to the "half-time" of radioactive decay. These are numerically small half-times as compared with those obtained for most larger drainage-areas and indicate that because of steep slopes and relatively shallow permeable material comprising these aquifers, the ground-water is temporary or ephemeral and quickly drains out or becomes negligible in amount during periods with no accretion.

The integral of equation (1) from $t = 0$ to $t = \infty$ represents the total ground-water outflow, starting with an initial flow q_o and with no subsequent accretion. This quantity must also represent the total ground-water storage at the beginning of the period. This leads to the important result, which also follows directly from POISEUILLE-DARCY'S law, that for a hill-slope aquifer where the slope of the water-table remains sensibly constant while the flow-rate changes, the rate of ground-water flow at a given time is directly proportional to the amount of ground-water storage Q_g or

$$q_g = k_g Q_g \quad \text{.......................... (3)}$$

where k_g has the same value as in equation (1). This simple relation makes it possible to determine the ground-water flow-rate q_g at any time if the ground-water storage Q_g is known. Also if q_g is known at a given time, then

$$Q_g = (q_g/k_g) \quad \text{........................ (4)}$$

From the known ground-water flow for a few days after the end of the snow-melt, values of Q_g for a given date have been fixed for each drainage-basin, as in Table 2.

Table 2--Determination of terminal ground-water storage (inches)

Area (1)	k_g (2)	Date (3)	q_g (4)	Q_g (5)
Gilfoyle	.23	Apr.16	.10	0.434
McKee	.14	Apr.17	.11	0.79
Ackerman	.25	Apr.17	.16	0.64
Hemlock	.20	Apr.16	.23	1.15

Subsurface storage and flow--The line marked "Storage-increment" on each of Figures 1 to 4 was obtained as follows. The measured precipitation was corrected for rainfall-interception, using percentages derived from previous observations of interception by HORTON [4] and others. This gives the ground-rainfall. The mass ground-rainfall from the beginning of melting to the end of any given day of record was determined and added to the gain or loss of surface-storage, determined from the snow-surveys. Subtracting from this quantity for each day the mass-runoff during the same period, starting with the beginning of snow-melt, the remainder represents water unaccounted for either as runoff or as storage above ground and which therefore represents an increment or decrement of storage within the soil, either as ground-water storage below the water-table or capillary storage above the water-table, or both.

Temperatures were unusually low throughout the preceding winter, and with heavy snow-cover no water had entered the soil for several weeks. At the beginning of the melting-period the ground-water flow was low and, as shown later, there was some deficiency of capillary moisture in the soil above the water-table on three of the areas.

The values of ground-water storage Q_g previously given for a particular date on each area permit a datum-line of zero ground-water storage to be added to each diagram. The ground-water flow on any given date will then be equal to the intercept between this datum-line and the ground-water storage-increment line multiplied by the constant $(1/k_g)$ for the given area.

Initial capillary moisture-deficiency--The daily ground-water flow determined in this way is shown by the line marked "Ground-water flow". This line lies under the runoff-line in the right-hand portion of the melting-period but crosses the runoff-line on April 4 for Ackerman and Hemlock areas and on March 28 for the Gilfoyle and McKee areas. Preceding these dates the ground-water flow-line as computed lies above the actual runoff-line and this portion of the computed ground-water flow-line represents ground-water as it would have been if there had been no initial capillary deficiency at the beginning of the melting-period, in which case the entire increment of subsurface storage would have been added to ground-water accretion. Ground-water accretion cannot occur in general until any existing capillary deficiency is made up by infiltration. The actual runoff for the part of the diagram where the computed ground-water line lies above the measured runoff-line was entirely ground-water flow. The fact that the computed ground-water flow exceeded the observed runoff shows that the ground-water flow was less than the amount corresponding to the total subsurface storage. The actual ground-water storage can be determined from the measured runoff at the beginning of the period by multiplying this quantity by ($1/k_g$). The difference between this and the total storage shown by the storage-increment line on any given date represents the remaining deficiency of capillary moisture. The total capillary deficiency determined in this way at the beginning of the melting-period for the different areas was as follows: Gilfoyle, 0.35 inch; McKee, 0.00 inch; Ackerman, 1.12 inches; and Hemlock, 1.00 inch. The increase of ground-water flow, as shown by the actual runoff during the period while capillary deficiency continued, shows that on these areas there was an accretion to ground-water storage before the capillary deficiency disappeared. This is easily understood from the fact that these are forested areas and underneath the protected crown-areas of trees, particularly needle-leaf trees, hemlock, spruce, and pine, much larger capillary deficiencies occur at the end of the growing season than in the open [5]. This is partly the result of interception, partly the result of exhaustion of soil-moisture within the root-zone of the tree. When infiltration occurs the capillary deficiency between trees will become zero and accretion to the water-table will take place while some capillary deficiency still remains under tree-crowns. Consequently in a mixed area both increase of capillary storage and accretion to the water-table may take place simultaneously without any violation of the rule that at a given spot they do not occur simultaneously.

Hydrologic balance-sheet--Using the methods of analysis described, the hydrologic balance-sheet was made up for each of the four areas, as shown by Table 3.

Table 3--Hydrologic balance-sheet, snow-melting period, streams in western Pennsylvania
(Data by United States Forest Service; analysis by Robert E. Horton; all quantities in inches or inches per day)

(1) Stream	Gilfoyle	McKee	Ackerman	Hemlock
(2) Cover	Thin	Thin	Good	Full
(3) Period	Mar. 27-Apr. 4	Mar. 29-Apr. 10	Mar. 28-Apr. 18	Mar. 28-Apr. 13
(4) Number of days	9	13	22	17
(5) Snow-storage	3.14	4.78	5.34	5.24
(6) Precipitation	2.00	3.33	5.01	4.16
(7) Total supply	5.14	8.11	10.35	9.40
(8) Interception, evaporation, etc., 10 per cent of (6)	10	10	10	10
(9) Loss	0.20	0.33	0.50	0.42
(10) Net supply	4.94	7.78	9.85	8.98
(11) Total runoff	3.20	6.70	9.06	7.77
(12) Ground-water: Total	1.53	2.31	6.82	6.47
(13) Ground-water: Average rate	0.17	0.18	0.31	0.38
(14) Surface-runoff =[(11) - (12)]	1.67	4.39	2.24	1.30
(15) Infiltration =[(10) - (14)]	3.27	3.39	7.61	7.68
(16) Time in hours	216	312	528	408
(17) Infiltration, average rate, inch per hour	0.015	0.011	0.014	0.019
(18) Ground-water-flow constant, k_g	0.23	0.14	0.25	0.20
(19) Storage, beginning of period	0.00	0.62	1.40	1.50
(20) Storage, end of period	1.25	1.14	1.55	1.97
(21) Δ_s	1.25	0.52	0.15	0.47
(22) Runoff (item 11)	3.20	6.70	9.06	7.77
(23) Δ, ground-water storage	1.25	0.52	0.15	0.47
(24) Moisture-deficiency	0.35	0.00	1.12	1.00
(25) Total	4.80	7.22	10.35	9.24
(26) Net supply (item 10)	4.94	7.78	9.85	8.98
(27) Difference, [(26) - (25)]	-0.14	-0.56	0.50	0.26

Lines 1 to 10 give the determination of the net supply available to produce either surface-runoff, ground-water runoff, or capillary or ground-water storage during the melting-period. It will be noted that the net available supply of water, line 10, ranged from 4.94 inches on the Gilfoyle Area to nearly ten inches on the Ackerman Area.

In lines 18 to 27 of Table 3, figures are given showing the balance between water available and water disposed of. If all the data were precise and the computation correct, these two quantities should be equal. The increment of ground-water storage is given by line 21. The runoff for the melting-period plus ground-water storage plus initial moisture-deficiency, if any, represents the total water accounted for. The difference between this and the net supply, line 10, represents water unaccounted for. These differences are in each case less than ten per cent of the net supply and may be due to any one of several different things: Error in determination of snow-storage; errors in rainfall or stream-gaging; or estimated water-losses, particularly in case of the Hemlock Area, some uncertainty as to ground-water storage and flow. The important point is that these differences are not sufficient to have any important effect on the determination of infiltration-capacity.

Infiltration-capacity--Infiltration-capacity is the maximum rate at which a given soil can absorb rain or melt-water at a given time. It is like the carrying capacity of a pipe or electrical conductor--a volume per unit of time and not a total volume. Lines 11 to 17 of Table 3 contain data for determination of the average infiltration-rate during the snow-melting period. The results show a substantial amount of infiltration throughout the snow-melting period, ranging from about 0.25 to 0.5 inch of water absorbed per day. These quantities are not infiltration-capacities because of the fact that during a large part of the time the supply-rate was less than the infiltration-capacity--as shown by the fact that there were alternate increases and decreases of storage. A close approximation to the infiltration-capacities of these areas, with unfrozen soil under snow-cover, is obtainable by using data for the day on which the infiltration-rate was the highest. On these days storage accumulated above ground, showing that the supply exceeded surface-runoff plus infiltration. The determination of infiltration-capacity is based on the fact that the total infiltration in any time-unit must equal the increment of ground-water storage plus the ground-water outflow. Both these quantities are given on Figures 1 to 4, and the results are given in Table 4, and indicate that for each of these areas the infiltration-capacity was approximately 0.05 inch per hour or about 1.2 inches per day. These figures are in line with other values of infiltration-capacity in central United States for winter conditions but with unfrozen soil. (It should be noted that the fact that storage attained a maximum on different dates on each of these areas does not indicate either that the soil became saturated or even that the supply-rate equalled the infiltration-capacity. It merely shows that at the times of maximum storage, ground-water storage was built up to a point where the ground-water outflow plus surface-runoff became equal to the supply-rate from rainfall and the snow-melt.)

Table 4--Infiltration-capacity

Area (1)	Date (2)	Δ_g (3)	q_g (4)	Total (5)	Infiltration capacity (6)
				in	in/hr
Gilfoyle	Apr. 17	1.05	0.18	1.23	0.051
McKee	Apr. 17	1.00	0.13	1.13	0.047
Hemlock	Apr. 3	0.75	0.57	1.32	0.055
Ackerman	Apr. 18	0.91	0.22	1.13	0.047

Snow-melting constant--A computation was also made of the rate of snow-melt in inches per degree-day on the different areas, using temperatures at Kane Forest Experiment Station. The results, given on Table 5, show a larger melting-constant for the areas with smaller forest-density and the figures for denser forest are in line with the values of the snow-melting constant, ranging from 0.05 to 0.06 inch per degree-day temperature-excess above 32° as determined from laboratory and field experiments in other localities by HORTON [6] and CLYDE [7], under nearly comparable conditions.

Table 5--Snow-melting characteristics, streams in western Pennsylvania

(1) Stream	Gilfoyle	McKee	Ackerman	Hemlock
(2) Cover	Thin	Thin	Good	Full
(3) Period	Mar. 28-Apr. 1	Mar. 30 Apr. 5	Mar. 28-Apr. 5	Mar. 28-Apr. 9
(4) Number of days	5	7	9	13
(5) Amount of melt-water, inches	2.60	3.50	3.35	4.65
(6) Rate of melt-water, in/day	0.52	0.50	0.37	0.36
(7) Degree-days above 32°F[a]	31	39	57	80
(8) Degree-days per day	6.2	5.6	6.3	6.2
(9) Melt-water, inches/degree-day	0.084	0.088	0.059	0.058

[a] Mean of maximum and minimum at Kane, Pennsylvania.

While the results of this study are informative, the main purpose of the paper is to describe a methodology which it is hoped will be extended and applied in other cases. With adequate data it is possible to trace the entire hydrologic history of the snow-melting period from the snow-surface downward to the water-table. As here given, the method can be applied only if (1) a ground-water curve is available, (2) if ground-water storage can be determined at the beginning and end of the period. The analysis would be greatly facilitated if suitable ground-water-level records were available within the drainage-basin. Such records, together with the depletion-curve, can be used to determine the ground-water storage at the beginning and end of the record and also the dates and amounts of ground-water accretion.

The author is indebted to Dr. H. L. SHIRLEY and E. N. MUNNS of the United States Forest Service and to Dr. A. L. PATRICK of the United States Soil Conservation Service for permission to use the field-data on which the paper is based, and for carefully reading the manuscript and offering valuable suggestions.

References

[1] PIERCE, MITCHELL, and TUTHILL, Snow survey report, Allegheny Watershed, 1940, Allegheny Forest Exp. Sta., Philadelphia, Pennsylvania, Mimeo., January 8, 1941.
[2] ROBERT E. HORTON, Suggestions for a comprehensive research on runoff phenomena: Deficiencies in hydrologic research, Nation. Res. Plan. Board, Washington, D. C., pp. 62-74, 1940.
[3] C. L. WICHT, Determination of the effects of watershed-management on mountain streams, Trans. Amer. Geophys. Union, Part II, pp. 594-606, 1943.
[4] ROBERT E. HORTON, Rainfall interception, Mon. Wea. Rev., pp. 603-623, September, 1919.
[5] VEIHMEYER and HENDRICKSON, Soil-moisture as an indication of root distribution in deciduous orchards, Plant Physiol., v. 13, pp. 169-177, 1938.
[6] ROBERT E. HORTON, The melting of snow, Mon. Wea. Rev., pp. 599-605, December, 1915.
[7] GEORGE D. CLYDE, Snow melting characteristics, Utah Agric. Exp. Sta., Logan, Utah, Bull. 231, 1931.

Horton Hydrologic Laboratory,
Voorheesville, New York

(Manuscript received June 21, 1944; presented by G. W. Musgrave at the Twenty-Sixth Annual Meeting, Washing- D. C., May 31, 1945; open for discussion until January 1, 1946.)

REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

(See also pp. 18, 58, 90, and 126)

ROBERT E. HORTON: Erosional development of streams and their drainage basins: Hydrophysical approach to quantitative morphology. Bull. Geol. Soc. Amer., v. 56, pp. 275-370, 40 figs., 1945.

In this paper HORTON has dealt quantitatively with the general problem of physical characteristics of stream-pattern and basin-drainage. Quantitative physiographic factors are described, objectively defined, and analyzed with respect to surface runoff, erosion, and sedimentation in the origin and development of stream-systems. The paper is well documented and well illustrated, and has considerable mathematical treatment combining theory with observations and many specific examples.

Four of the fundamental concepts are: (1) The law of stream-numbers--This expresses the relation between the number of streams of a given order (systematically and objectively determined by the degree of branching) and the stream-order in terms of an inverse geometric series. (2) The law of stream-lengths--This expresses the average length of streams of a given order in terms of stream-order, average length of streams of the first order, and the stream-length ratio, and takes the form of a direct geometric series. (3) Limiting infiltration-capacity--This is the maximum volume per unit-time which a soil in a given condition can absorb from falling rain. (4) Runoff-detention-storage relation--There is a definite functional relation between the depth of surface detention, or quantity of water accumulated on the soil-surface, and the rate of surface runoff or channel-inflow.

The most important single factor involved in connection with the development of stream-systems and their drainage-basins by aqueous erosion is the minimum length of overland flow required to produce sufficient runoff-volume to initiate erosion.

This important and valuable contribution by HORTON could have come only from a man of his varied and extensive experience and with his great breadth of vision.

WALTER T. WILSON