THE SOIL PROFILE AS A NATURAL RESERVOIR[1]

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The present study has been undertaken (a) to test out the validity of the concept that the soil profile has a definite measurable storage capacity for water and a definite regulating effect on ground-water discharge, and (b) to demonstrate that these functions of the soil profile are analogous to those of detention-type storage basin structures used in flood control and to retention and equalizing reservoir structures employed for water resources conservation.

In the application of irrigation water to growing crops and in the practice of water spreading for underground storage in dry climates, it has been necessary to consider the whole soil profile as a single functioning unit. Here principles of soil hydrology have been made the basis of effective and economical field practices. A recognition of two types of water storage in the soil profile is required. One type of storage is represented by the water required to satisfy initial soil moisture deficiency and bring the current capillary water content up to field capacity. The second type of storage is represented by noncapillary or gravitational water, free to move vertically to the water table or to drain away laterally. In theory, gravitational water is not considered to exist until after capillary moisture deficiencies of the entire profile have been satisfied. In irrigation, gravitational water that drains to the water table may be considered as being lost or wasted. Consequently, a knowledge of moisture equilibrium constants for the different soil horizons is imperative to efficient irrigation practice.

It is conceivable that some of these same principles of soil hydrology that are basic to irrigation practices in arid regions are also of first-line importance to a better understanding of the soil profile in its relation to water storage and to ground water depletion contributing to streamflow in humid regions. For example, if the soil profile can be considered to function as an underground storage reservoir whose capacity and rate of discharge can be estimated, this will facilitate forecasting both storm runoff and base flow of streams. This concept requires that storage be expressed as a volume such as area inches. Thus, storage may be expressed as area inches of retention and detention storage opportunity in the soil profile, or as inches of water in storage. Not only would these values be usable for forecasting groundwater discharge in streams, but they would also serve as a basis for comparing the effects of different land use practices on soil-water relationships.

SELECTION OF DRAINAGE AREA FOR STUDY

Continuous soil moisture determinations made throughout the profile are known to furnish a usable index of the moisture changes that are taking place in capillary water due to rainfall, evaporation, transpiration and capillary movement. Gravitational water may be more difficult to follow through the soil profile because it may have both a rapid lateral and vertical movement. However, after it has become a part of ground water, a continuous record of the height of the water table should indicate the changes in amount of groundwater that are taking place in the soil profile.

In the present study the main interest has been to correlate changes in a water table with actual ground water discharge from a known watershed area. It has been desirable to eliminate factors of channel precipitation and channel storage. Also, it appeared desirable to select an area in which groundwater discharge is conceivably being derived from a single groundwater aquifer of reasonably well-known dimensions. These experimental requirements were found in a small drainage area on the Coweeta Experimental Forest in Macon County, North Carolina. The Coweeta Experimental Forest is located in the high rainfall belt of the Southern Appalachian Region and lies in the headwaters of the Little Tennessee River. It is a land use and hydrological research project of the Division of Forest Influences, Branch of Research, U. S. Forest Service, U. S. Dept. of Agriculture.

The drainage of 6.88 acres is a high mountain cove in the general shape of a Greek theater (Fig. 1). The elevation ranges from 3,020 to 3,190 feet above mean sea level. The present vegetative cover is a growth of yellow poplar (*Liriodendron tulipifera* L.), the area having once been cleared for a short period. The soils are relatively deep in the basin of the cove where the depth to the country rock is about 12 feet.

The surface horizon is classed as an excellent coarse mull. Decomposition of organic material at the surface is extremely rapid. Litter is scarce to almost lacking in the autumn before leaf fall. The more steeply sloping sides of the cove show frost creep soils ranging in depth from 3 to 6 feet. Colluvial action and local disturbances have resulted from wind thrown trees.

The groundwater table ranges from 3 to 10 feet below the soil surface in the lower portion of the drainage area. The geologic formations under this basin apparently are sufficiently dense to direct groundwater outflow into a single discharge outlet. Consequently, this drainage must be viewed as a natural lysimeter that permits observation of both the water table and groundwater discharge. In this sense it is also a natural model for the study of water relations within the soil profile in which gravitational water drains directly to

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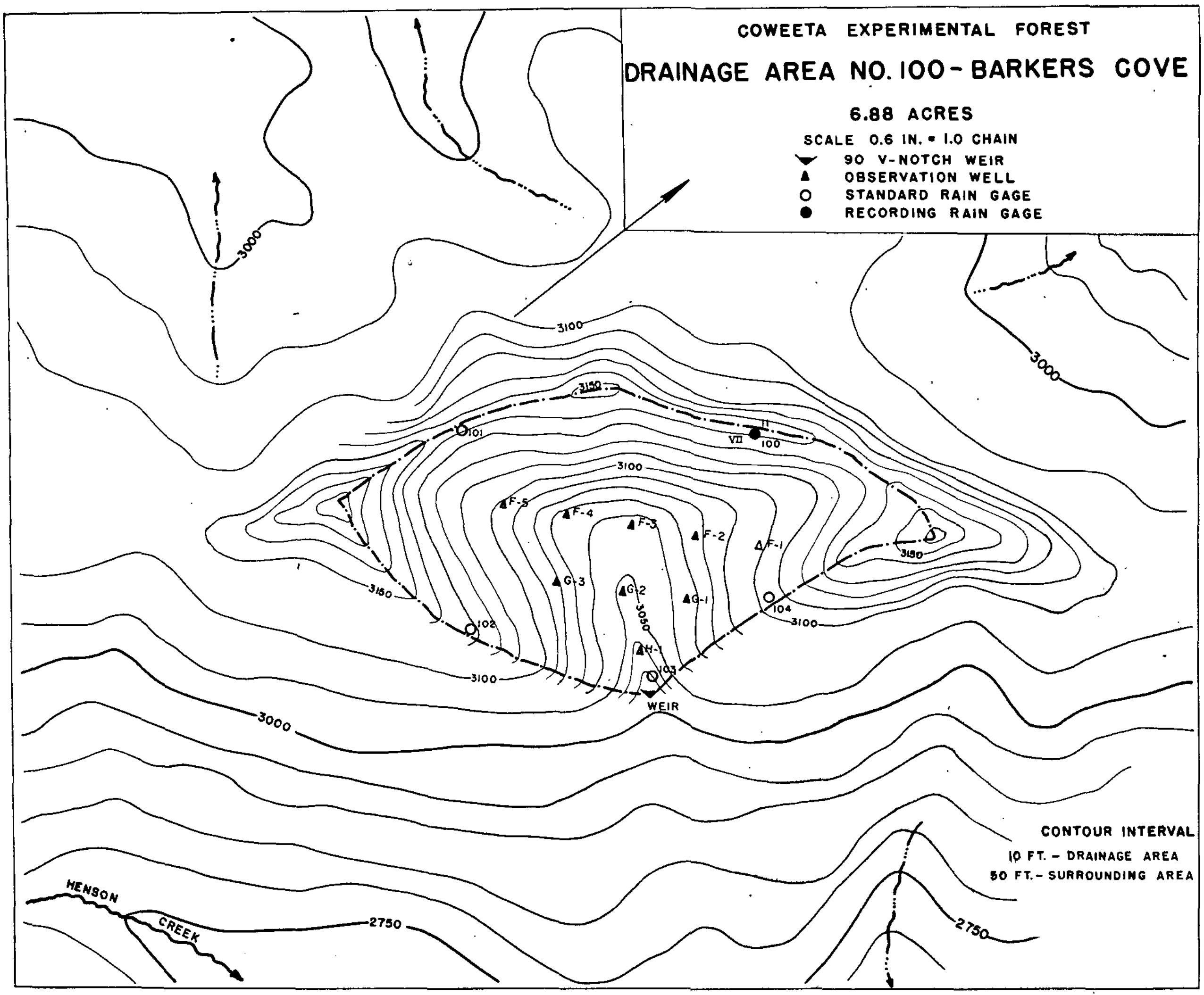

FIG. 1.—Topographic position of selected drainage area. This 6.88 acre ridge cove is considered to be an independent hydrologic unit which functions as a natural lysimeter.

the water table before appreciable lateral movement takes place.

Although the mean yearly rainfall is about 70 inches, there is no surface stream channel on the drainage area. However, a source for groundwater discharge is present at the natural drainage outlet for the area and this source has been continuously measured through a right-angled, V-notch weir since March 14, 1938. The mean annual discharge from the area has been in excess of 1.5 c.s.m. (cubic feet per second per square mile), which compares favorably with the yield of larger drainage areas on the Coweeta Experimental Forest.

Infiltration at the soil surface has been in excess of precipitation intensity for the period of observation. Recorded rainfall intensities of 2.70 inches per hour for a maximum 10 minute interval have produced no storm water accumulation on the surface.

EXPERIMENTAL DATA

In Table 1 are given summaries of the groundwater discharge and water table changes that are associated with all storm periods of more than 1 inch of precipitation for a 6-month period of November 1938 to April 1939. The total precipitation for the period amounted to 48.76 inches and the total groundwater discharge was 28.55 inches. The table is self-explanatory. It should be observed that the 5.52 inches of precipitation on November 4 to 5 was associated with only 0.08 inch of groundwater discharge. Conceivably, most of this precipitation was required to satisfy initial soil moisture deficiency and did not reach the groundwater table as gravitational water. These values should be contrasted with those for storms of February and March for which 50 to 60% of the precipitation appeared as groundwater discharge. It is believed that deep seepage during storm periods amounts to a negligible quantity for this watershed.

TABLE 1.—*Summary of groundwater discharge and water table elevation for all storms over 1 inch, Nov. 1, 1938 to Apr. 30, 1939.*

Date	Precipitation, inches	Groundwater discharge				Water table elevation				
		Rate			Amount inches*	Well G-2 (3,047.53 feet)				
		Prior, c.s.m.†	Max., c.s.m.	Change, c.s.m.		Prior, feet	Max., feet	Change, feet	48 hrs. after max., feet	Soil surface to max., feet
	(1)	(2)	(3)	(4)	(5)	(11)	(12)	(13)	(14)	(15)
					1938					
Nov. 4–5	5.52	0.48	1.70	1.22	0.08	36.07	37.74	1.67	36.94	9.79
Nov. 6–8	2.02	0.57	3.12	2.55	0.17	36.94	38.03	1.09	37.92	9.50
Nov. 16–19	2.82	0.55	5.77	5.22	0.49	36.96	39.18	2.22	38.12	8.35
Dec. 26	1.67	0.89	3.98	3.09	0.26	36.97	38.34	1.37	38.12	9.19
					1939					
Jan. 4–5	1.48	1.00	3.12	2.12	0.28	38.08	38.27	0.19	38.20	9.26
Jan. 11–13	1.67	1.46	2.17	0.71	0.23	38.13	38.20	0.07	38.19	9.33
Jan. 24	1.10	1.73	3.78	2.05	0.32	38.19	38.32	0.13	38.24	9.21
Jan. 29–30	2.67	2.20	12.18	9.98	0.86	38.20	41.65	3.45	38.73	5.88
Feb. 2–3	2.89	3.93	30.18	26.25	1.49	38.39	43.00	4.61	40.27	4.53
Feb. 6	1.36	6.92	8.90	1.98	0.83	39.52	40.37	0.85	39.25	7.16
Feb. 9–12	3.68	6.35	21.07	14.72	1.79	39.25	43.20	3.95	40.90	4.33
Feb. 14–15	3.74	8.18	26.39	18.21	2.06	40.09	43.96	3.87	41.10	3.57
Feb. 25–28	3.94	4.97	18.17	13.20	2.00	38.87	42.79	3.92	40.48	4.74
Mar. 4–5	2.95	7.64	19.85	12.21	1.47	39.87	42.95	3.08	40.73	4.58
Mar. 26–27	1.05	3.83	4.08	0.25	0.42	38.47	38.57	0.10	38.46	8.96
Mar. 29–30	1.58	3.58	8.90	5.32	0.80	38.46	40.49	2.03	39.38	7.04
Apr. 25–26	2.24	2.82	6.92	4.10	0.77	38.27	39.62	1.35	38.67	7.91

*From beginning of change in groundwater discharge to 48 hours after maximum rate for storm period.
†Cubic feet per second per square mile.

41.38 14.31 34%

STORM DISCHARGE WITH AND WITHOUT DETENTION STORAGE

The relationships of precipitation, groundwater discharge, and water table given in Table 1 are illustrated for a series of three consecutive storms in Fig. 2. The bar diagrams shown with diagonal shading represent rainfall intensities which occurred in excess of 0.30 inch per hour. These bar diagrams illustrate roughly the appearance of the hydrograph of surface stormflow discharge if infiltration at the surface of the soil were limited to a rate of 0.30 inch per hour. This is not an uncommon rate for a soil profile that has been altered through trampling of livestock or destructive cultivation. By way of contrast with this hypothetical storm runoff, the hydrograph at the weir shows the manner in which discharge from the drainage area has actually taken place.

It is obvious for the storms shown in Fig. 2 that a portion of the precipitation for these storms is reaching the water table as gravitational water and is appearing after a definite period of detention as subsurface stormflow. This discharge, however, reaches the stream after several hours have elapsed, depending upon the nature of the storm and prior storage opportunities within the soil profile. In Fig. 2 it appears that the soil profile is functioning as a detention type storage basin in that it does not store the gravitational storm water except for a very temporary period. This storage process, however, is sufficient to reduce the peak of the discharge appearing as subsurface stormflow to a small fraction of that which could logically take place if no detention storage were present.

WELL ELEVATION AND STORM DISCHARGE

Fig. 3 illustrates the elevation of the water table and the groundwater discharge drawn on the same time scale for the period January 29 to February 21, 1939. It should be noticed that the two graphs shown in Fig. 3 have no scale in common other than that of time. Conceivably, however, both graphs represent a form of discharge, one through the weir and the other through the soil. The coincidence of the rise and fall of the water table with the change in discharge at the weir indicates that there is a definite relationship between the two. Consequently a test has been made for the constancy of this relationship.

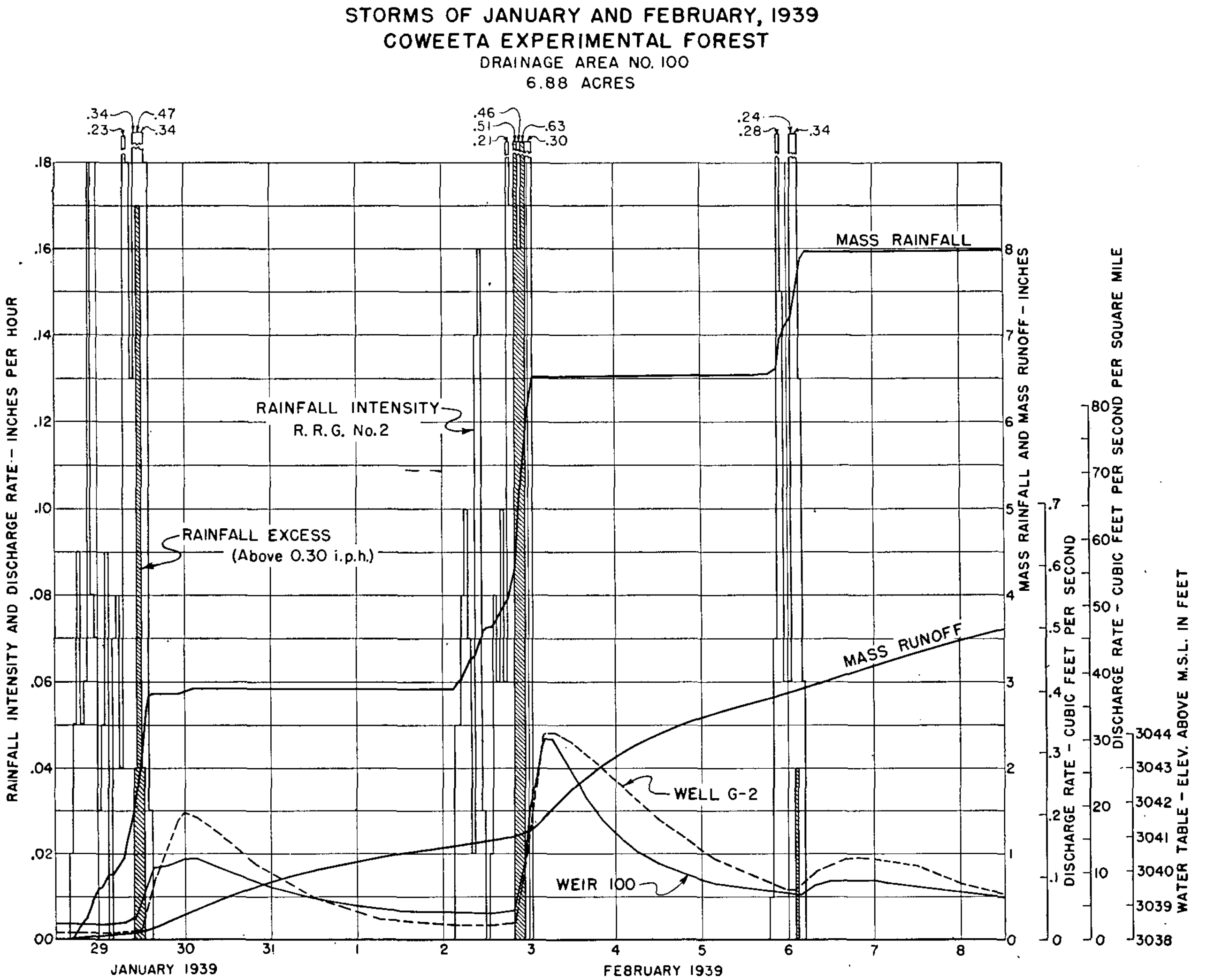

FIG. 2.—Effect of precipitation on groundwater discharge and water-table level. Detention storage effect of the soil profile is apparent both in the pronounced reduction of peak and delayed discharge.

Fig. 4, which is based on 18 major storms taken over a period of several years, illustrates a curve that is defined by plotting peak storm discharge at the weir against the maximum height of the water table at the time of this peak. This curve was then strengthened by further plotting each successive 1-foot drop during the water table recession against the weir discharge at the time each 1-foot drop was completed. The resulting curve indicates that throughout the range of water table movement shown, the discharge at the weir is reasonably constant for any given well elevation. It is recognized that the drainage area is specially adapted to this type of study. However, the principles that govern the groundwater movement observed must be considered to be universally applicable.

DETERMINATION OF POROSITY REQUIREMENTS FOR DETENTION STORAGE

On the basis of Fig. 4 it is logical to expect that the total discharge at the weir during the time required for the water table to recede 1 foot should represent the volume of detention storage within the given foot of profile. By converting this volume of discharge to watershed area inches it should then be possible to determine a per cent by volume of detention storage within each foot of the soil profile for which data are available. Such a volume also represents the macroporosity of the foot of profile. This volume has been obtained by using the smoothed curve of Fig. 4 and taking the time in hours for the water table to drop each foot directly from the original well hydrograph.

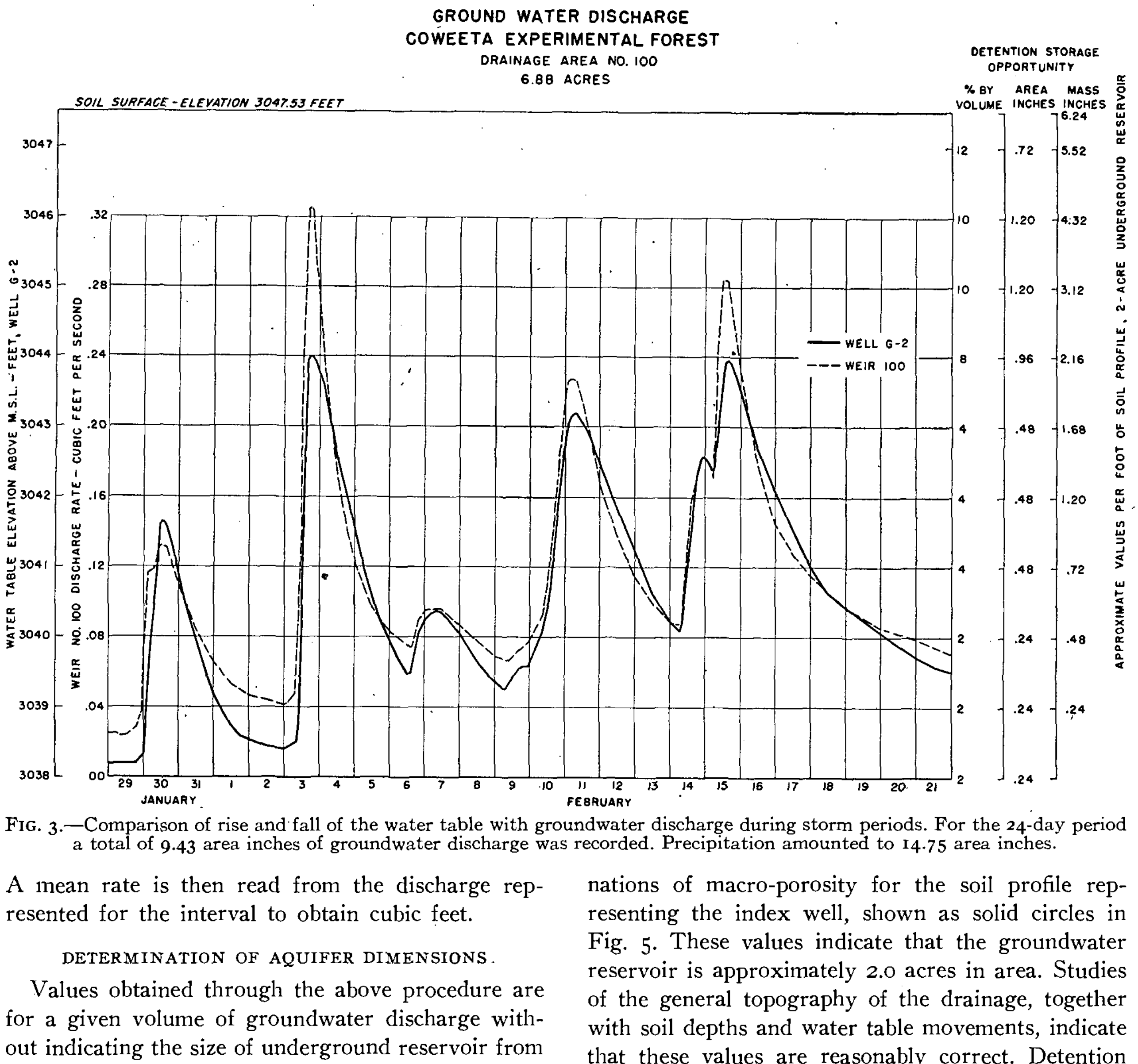

FIG. 3.—Comparison of rise and fall of the water table with groundwater discharge during storm periods. For the 24-day period a total of 9.43 area inches of groundwater discharge was recorded. Precipitation amounted to 14.75 area inches.

A mean rate is then read from the discharge represented for the interval to obtain cubic feet.

DETERMINATION OF AQUIFER DIMENSIONS.

Values obtained through the above procedure are for a given volume of groundwater discharge without indicating the size of underground reservoir from which it has been obtained. In Fig. 5 are shown four curves of the macro-pore space required for each foot of profile to yield the discharge recorded. The solid curve is defined by the group means of porosity values based on 18 storms. Values are computed from the weir discharge and time required for 1-foot recessions of the water table. For this computation the underground reservoir is considered to be the same size as the drainage area. The broken line curves represent porosity requirements if the reservoir is of 1, 2, and 3 acres in area. Further studies will be necessary to determine the real size of the aquifer. Conceivably the size may grow larger as the depth from the surface is increased. This is borne out by laboratory determinations of macro-porosity for the soil profile representing the index well, shown as solid circles in Fig. 5. These values indicate that the groundwater reservoir is approximately 2.0 acres in area. Studies of the general topography of the drainage, together with soil depths and water table movements, indicate that these values are reasonably correct. Detention storage in inches for this 2-acre reservoir may be computed by converting macro-porosity percentage values read from the curve to inches of detention per foot, and cumulating from bottom to top of the profile as illustrated on the right hand side of Fig. 3. Thus, using the 2-acre reservoir curve, 4.1 area inches of detention storage occur between the depths of 9 feet and 3 feet from the soil surface.

DISCUSSION AND CONCLUSIONS

The recognition of subsurface stormflow component of the stream hydrograph, as pointed out by Snyder (3)[3] and Barnes (1), requires further explanation of the manner in which this flow takes place.

[3]Figures in parenthesis refer to "Literature Cited," p. 486.

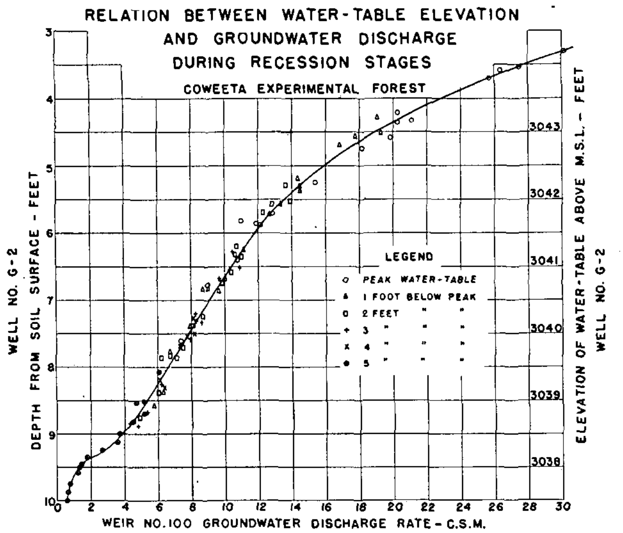

FIG. 4.—Water-table elevation and groundwater discharge rates during storm recession stages for 18 major storms. For a water-table recession between the sixth and seventh feet, requiring 12 hours as observed on the well hydrograph, a mean discharge rate may be taken as 10.5 csm. The 0.18 area inch, considered as specific yield, amounts to 1.5% macro-porosity for this horizon depth over the entire drainage area.

To obtain the volumes of subsurface stormflow reported, it appears that gravitational storm water must be transmitted at a rate much faster than has been generally considered to occur within the soil profile. Hursh and Brater (2) have presented evidence that subsurface stormflow may actually account for the major portion of the storm hydrograph on small forested drainages during prolonged storm periods. They have also indicated that a change in the water table of the aquifer associated with these streams describes a delayed storm hydrograph that can be related to the recession side of the stream hydrograph.

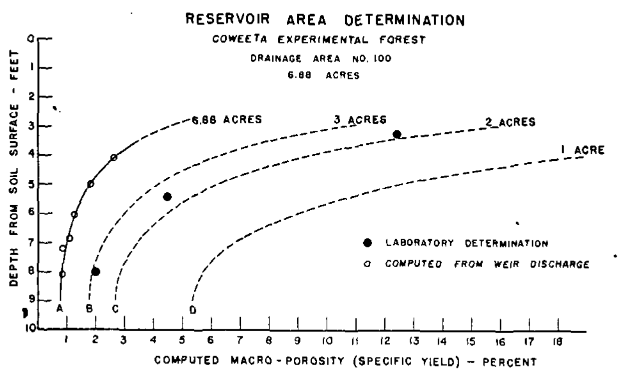

FIG. 5.—Curve A is based on macro-porosity for the entire watershed as determined from the weir discharge. Curves B, C, and D express comparable values for smaller areas. Laboratory tests of macro-porosity from volume soil samples indicate that the reservoir area for this drainage is about 2 acres at the depth of 4 feet, and probably 3 acres at the depth of 8 feet.

For agricultural drainages Riesbol (4) considers that gravitational water may be of significance in flood flows from river basins but states that, "the delay is sufficient to aid runoff control in smaller streams". Wenzel (5) has suggested a possible explanation of the rise of streams due to subsurface stormflow based on an increase in the saturated cross sectional area of the stream bank. This explanation applies particularly to areas of rough topography. For quite level drainages it has been pointed out that the stream rise may actually produce a throttling effect on groundwater seepage.

Further studies will be required to explain completely the subsurface stormflow described in the present report. These studies will call for more detailed observation of storage and transmission of gravitational storm water over the whole drained area. Both movement and storage of gravitational water in the soil profile are governed by the volume, size, shape, and continuity of the noncapillary pore space. The exact nature of this macro-pore space occurring in different horizons of the soil profile has yet to be described. It includes all large underground channels formed from decayed roots, fractured rock, insect and animal burrows, and larger spaces that may exist. It also includes macro-pore spaces formed through the complex structural patterns created by the aggregation of soil particles in the presence of organic materials. In the upper horizons of natural soils these biological openings and structural patterns built up from lattice-like aggregates are far more important in determining noncapillary porosity than the single grain soil particle size. Root channels and animal burrows are of particular significance in the detention storage and draining of gravitational water. A single earthworm burrow may be far more important in draining through a block of heavy soil than the entire cross sectional area of the pore space. In like manner, it is conceivable that a few continuous void spaces may give rise to rapid discharge of groundwater through a soil profile which, when viewed as a uniformly pervious medium, would be expected to transmit water slowly.

These larger hydraulic pathways are most abundant where biological activity is greatest, generally in the upper soil horizons. Consequently, because channeling by roots, rodents, and insects is most active within a few feet of the surface, the lateral transmission rate that is dependent upon biological activity might well vary with depth from the surface.

Exposed soil profiles extending across narrow drainage lines in mountainous areas indicate the presence of continuous hydraulic pathways that permit the free movement of water. These pathways or continuous void spaces in some instances appear to be subterranean stream channels that have always been kept open, although buried under centuries of accumulation of angular rock talus, organic material, and soil. The overlying colluvial mass has been interspersed with burrows of rodents and insects and with channels left after the decay of roots. Many of these pathways are connected directly with the upper soil horizons. Consequently, the transmission of gravitational water is not governed in this case by the laws of a uniform pervious medium, but rather by a continuous network of noncapillary channels of various dimensions. The rate of water movement through such a soil would be expected to be far in excess of a computed rate based on the grain size of soil samples. The gradient of the water table under these mountainous conditions is unusually steep and this fact must also be kept in mind in visualizing transmission rates through the soil.

All of these biological channels and structural voids of noncapillary size are not only avenues for free water movement in the soil, but they must also be viewed as a part of the groundwater reservoir. In this sense they augment the storage in noncapillary pore space that may be computed on the basis of soil particle size. During the period it is in the soil, all gravitational water, even though it may contribute to subsurface stormflow, should be viewed as being in temporary detention storage. Because of the extensive biological activity on the drainage area for which studies have been reported, it is believed that there exists ample detention storage opportunity to account for the amount and rate of discharge of the subsurface stormflow observed. This extensive biological channeling combined with the steep gradient of the water table is considered to be the explanation of the rapid storage and depletion of the underground reservoir discussed in this report.

It is concluded from the present study that an analogy of the storage functions of the soil profile to storage in artificial reservoirs is entirely justifiable. Use of such an analogy is advantageous in evaluating land-use effects upon stream behavior in terms of area inches of storage and runoff. These values may be expressed in terms comparable to storage and runoff values from artificial structures called for in water resources conservation planning.

The following types of reservoir functions of the soil profile have been recognized:

1. Permanent retention storage resulting in a complete loss to runoff. This is exemplified by the water that becomes soil moisture. It is measured in terms of capillary pore space and has been defined as water of specific retention.

2. Groundwater detention storage resulting in an equalizing effect upon streamflow during nonstorm periods. This is the normal groundwater aquifer of the soil that may be measured in terms of noncapillary porosity.

3. Stormwater detention storage analogous to water held back temporarily during storm periods by detention-basin type structures. This storage is represented by the moving gravitational water that reaches the stream in sufficient time to contribute to the storm hydrograph. It may or may not proceed to the normal water table before being transmitted to the stream.

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