STUDIES IN THE BALANCED WATER-ECONOMY OF EXPERIMENTAL DRAINAGE-AREAS

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Watershed-management studies require drainage-areas that are independent hydrologic units having distinctive land-use patterns. Such studies are in progress on the Coweeta Experimental Forest in Macon County, North Carolina, by the United States Department of Agriculture, Forest Service. This 4,600-acre experimental area was selected specifically for the study of the hydrologic cycle in relation to the practical problems of land-management for water-yield. The area contains 30 small drainages with continuous flow. The average annual rainfall of 70 inches is distributed throughout the year. Mean annual temperature is 55°F. Soils are deep and permeable, but water-tables are sufficiently high to be observed in shallow wells. The natural growth is composed of deciduous trees with abundant shrubs and minor vegetation. Topography and stream-pattern favor the establishment of independent experimental units.

Evaluating the effects of land-use on water-cycle factors, although difficult for large areas, becomes more feasible on small experimental drainages. Hydrologic measurements are first made over a period of five years or more under natural forest-vegetation before changes in land-use are made. Records are compared before and after the change. Also, because half of the total number of drainage-areas are held as controls, comparative checks may be made with similar drainages selected as controls for each study.

For practical purposes, the most important single measurement is that of seasonal yield of ground-water and storm-runoff. However, to understand water-yield it is necessary to evaluate other factors of the water-cycle that relate specifically to the drainage-area. These include the amount of soil-moisture and ground-water in storage, together with current evaporation and transpiration.

The present paper discusses the problem of keeping accounts of the essential water-cycle factors for experimental drainage-areas. It is recognized that for practical purposes water-accounts should be kept storm by storm and this is the ultimate objective of the study. However, for a general consideration of the problem, monthly and annual balances are more suitable than are individual storm-values.

To illustrate methods, data from a representative experimental drainage-area of approximately 40 acres at an elevation of 2,200 to 3,200 feet are used. The vegetative cover is a hardwood forest not grazed, cut, or burned for at least 20 years.

Water-cycle measurements--In general, water-cycle measurements relate to the circulating water-capital of a drainage-area within a single water-year. This capital may be only a portion of the total amount of water on the drainage as there is always a base quantity of water present. Current balances are considered to account for water above this unmeasured base. Nevertheless, there is always the possibility that a part of this base-quantity of water can enter into the yearly balance. For this reason solution of unknowns by residuals alone may be unsatisfactory. The problem is to devise checks on those values known occasionally to draw upon the base water-capital of the drainage. With these checks, though they be only approximate, it may be possible to interpret plus or minus residual accumulations, and thus carry forward usable balances from one year to the next. The principal checks used for this purpose are the amount of ground-water and soil-moisture in storage within the soil-profile. These measurements, combined with independent estimates of evaporation and transpiration both by physical constants and by the use of mean yearly values also serve as a basis for studying the continuous water-economy of the experimental drainage-area. For temperate humid climates, it is also conceivable that the seasonal relationships of precipitation, runoff, and storage are so definite that they in themselves furnish a good basis for checking the water-cycle.

The water-year--For temperate climates, a study of the relationship of rainfall to runoff over long periods indicates that the times of minimum flow generally succeed each other by approximately 12 months. These periods are considered as the end of one water-year and the beginning of the next. Similarly, a period of annual maximum stream-flow can be recognized, which, if based on ground-water discharge, represents a value of maximum ground-water storage. PARKER [see 1 of "References" at end of paper] expresses his opinion "if the period at which the water stored up in the ground is at a maximum could be definitely observed, the relations of the rainfall to runoff for the intervals between these maxima would be more constant than for any other period."He recognizes, however, the difficulties of observing periods of maximum ground-water storage, and also that such periods may be more irregular in time than are periods of low flow.

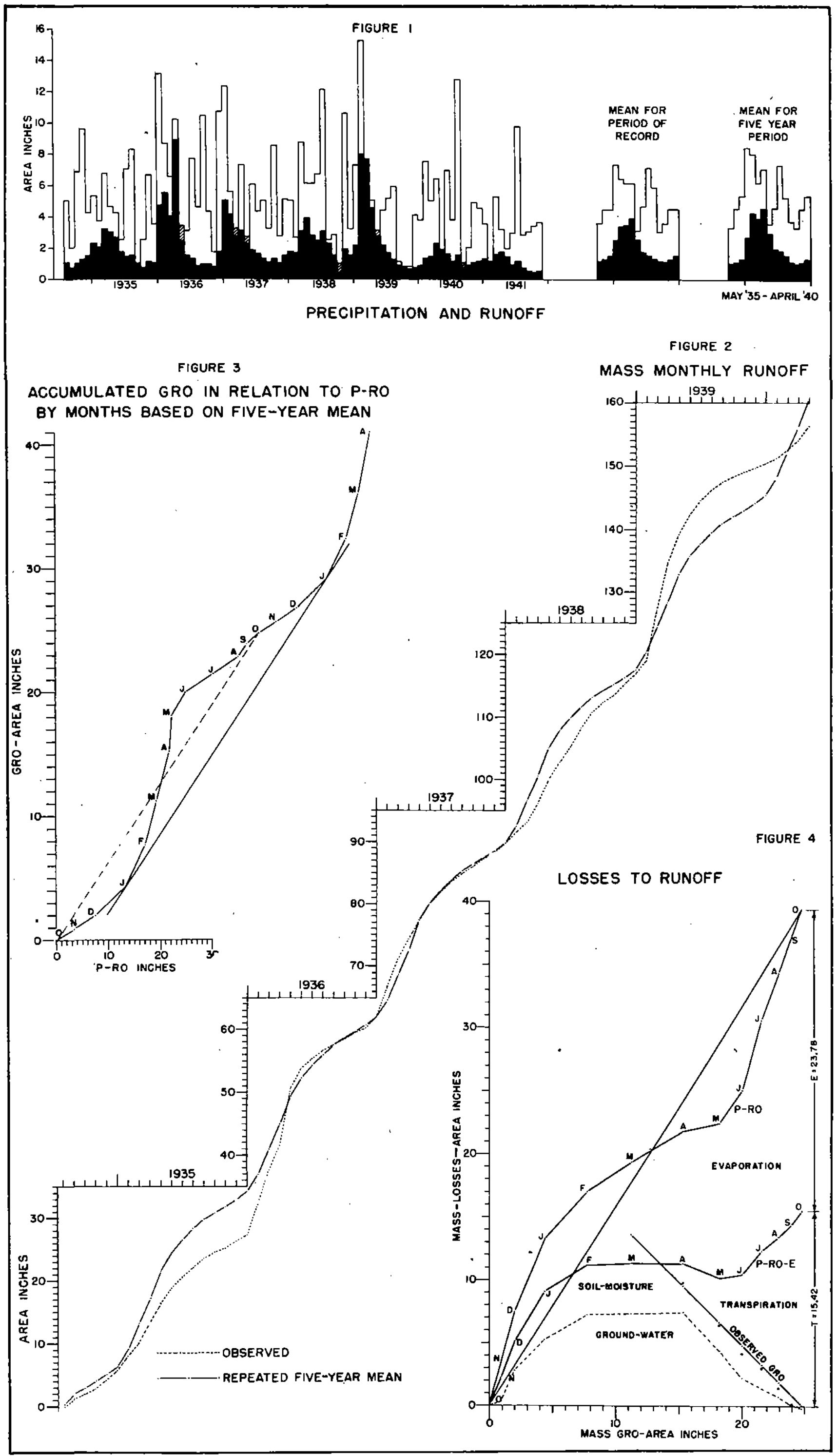
Both RAFTER [2] and HOUK [3] have recognized the water-year as divided into three periods, namely, replenishment of soil-moisture, storage of ground-water, and the growing period. The actual months covered by these essential divisions of the water-year will depend on the local climatic conditions. RAFTER used November 30 as the end of his water-year, and as the end of the replenishing period begun in September. He then considered December to May as the storage-period, which indicates that this division is made for a region of cold winters and heavy snow. For the Miami Valley, HOUK thought it more feasible to consider the months from October to December as the replenishing period, and January to April as the storage-period. HOYT [4] et al, reporting data for the Skunk River Basin in Iowa, derived approximate changes in soil-moisture by months, and recognized the month of September as beginning the replenishment-period. Their computations, covering a five-year period [Table 61], show [Column (9)] that the residual soil-moisture values when carried as a summation, tend to balance out to zero during the early autumn for the years of normal precipitation. It is also apparent in Columns (8) and (10), Table 61, that the total accretion to ground-water tends to balance ground-water runoff. VERMEULE [5] in his early classic on monthly and seasonal runoff-characteristics of streams summarized his data into the four seasons and then combined them into two periods, one from December to May, the other from June to November.

Runoff-precipitation relationships--A lineal relationship of plotted precipitation-summations and annual runoff has been frequently discussed. Values for individual months are known to fluctuate around the general slope of the mass-trend in a fairly regular pattern. The integrated hydrograph of monthly flow used in computing seasonal discharge is an expression of this fairly regular pattern of the monthly departure from the general slope of the line representing the summations of runoff.

Using the values shown in Figure 1, the summation of runoff has been expressed by months for a five-year period in Figure 2. Attempts to draw a straight trend line through the monthly values for different years indicate that the best fit comes during early fall or late spring months. It is believed that these are significant points in the water-year indicating fundamental changes in the seasonal relationships. Although periods of minimum or maximum storage will not be reached in every water-year, it is probable that the high precipitation and relatively high summer temperatures of the Coweeta Experimental Forest produce a more nearly uniform range of storage within the water-year than occurs in many other sections of the country.

Figure 2 shows also a repetition of the monthly means for the five-year period. The monthly sequence for 1937 is quite similar to the mean year monthly sequence. The two lines were approximately fitted for this year and used as a basis for comparing the remaining years. Considerable difference occurs between the mean and the monthly sequence for other years. However, both lines tend to coincide at least for a portion of the year, most commonly in the winter or spring months.

It is reasonable to expect that transpiration and other factors of the water-cycle controlled by biological activities remain fairly constant on a drainage-area where a natural vegetative cover has become established. The amount of plant-growth tends to be the same each year. Consequently, it may be expected that the mean annual transpiration-requirements over a period of years will remain the same. The physical constants that govern evaporation from the soil do not change rapidly under undisturbed natural conditions of a drainage-area. Neither do soil--profile-storage opportunities change from year to year unless some unusual disturbance takes place at the surface.



Figs. 1-4--Coweeta Drainage-Area No. 1: (1) Monthly precipitation and runoff; (2) summation of runoff by months; (3) relation of ground-water runoff to ground-water storage; (4) graphic water-cycle analysis for mean year

Consequently, there are numerous reasons why water-accounts for a small drainage-area in a region of high precipitation should tend to balance annually for years of normal precipitation. When the water-accounts do not balance, the plus or minus water in storage at the end of the water-year is an expression of the annual deviation from the normal in precipitation or temperature.

The integrated hydrographs, Figure 2, have been drawn on a basis of runoff over months. This general diagram of runoff does not change greatly for the Coweeta Experimental Forest drainages when the summations of runoff are expressed over summations of either total rainfall or net effective rainfall. Here the slope-relationships show the uniform monthly deviations from the mean yearly slope. This type of diagram serves chiefly to indicate possible relationships not otherwise apparent, but may also serve for the indirect solution of unknown monthly values.

If the water-cycle does tend to balance annually in a region of high rainfall, it would be expected that the trend of the mean annual slope of such a relationship as the sums of GRO/net rainfall is characteristic for the individual drainage-area. Monthly changes occur in such a uniform pattern around the yearly slope of this relationship for Coweeta experimental drainages as to suggest that marked seasonal changes may serve as a check in water-cycle balances. A graphic expression of a monthly storage-discharge relationship is furnished by plotting GRO over an expression of losses to runoff such as P-SRO-E or P-RO, as shown in Figure 3.

Figure 3 shows the summation of the mean values of GRO expressed in relation to the summation of P-RO for the same month. These are from the same values of RO as shown in the mean curve of Figure 2. A plotting of GRO over P-RO for the preceding month may give a more significant curve. By deviation from the yearly mean slope, the monthly slopes show the degree to which GRO is greater or less than P-RO.

The values for the month of May indicate that GRO is almost independent of storage as expressed by P-RO. Storage opportunities are normally at a minimum and ground-water runoff becomes more directly related to precipitation than at any other period of the year.

To indicate exact seasonal storage-periods for the high rainfall-belt of the Southern Appalachians is an arbitrary procedure insomuch as replenishment of soil-moisture and also storage of ground-water will take place in any of the summer months when high rainfall results from tropical hurricane influences from the Gulf or South Atlantic. However, the concept of seasonal storage-periods is imperative to interpreting water-cycle problems.

The GRO/P-RO relationship shown in Figure 3 becomes the familiar mass-curve of P-RO when GRO becomes the X-axis (Fig. 4), or when P-RO is plotted over a uniform time-scale (Fig. 5).

Data for the mean curve on Figure 2, and for Figures 3, 4, and 5 are given in Table 1. The mass-expressions of Figures 4 and 5 are exactly the same as the tabulations of sums in the monthly accounting system used in Tables 1 and 2.

Of a number of methods for carrying forward a monthly record of water in storage on experimental drainage-areas, the one shown in Table 1 appears to be most practical. The ground-water storage-curve as described by SNYDER [6] is the basis for separating ground-water, Column (8), from soil-moisture, Column (12). The area-inches of ground-water storage given in Column (8) is an amount above the base of the storage-curve which for this drainage-area was drawn beginning 0.50 csm equals zero inch. The permanent base soil-moisture on the drainage-area is not known. Column (10) gives the sum of transpiration (P-RO-E) corrected for temperature through the use of MEYER'S [7] curve of transpiration. These values are redistributed as indicated by Columns (11) and (12).

The values given in Table 1 represent only the circulating water-capital furnished by current precipitation. No gain or loss is shown over the amount of precipitation for the mean year, although Column (8) and Column (12) are out of balance by 0.17 inch. Table 2 shows a trial-balance for seven years in which there is always a plus or minus carry-over of ground-water in storage and soil-moisture from one year into the next.

Figure 4 shows the essential water-cycle components that must be accounted for in keeping current records of circulating water-capital. The GRO storage-base [Column (8), Table 1], is continuous from one year into the next and constitutes a measurable reference that may be quickly determined by the use of the storage-curve. The observed GRO of Figure 4 comes from Column (2) of Table 1. For this mean year GRO from May to October may be considered to come largely from ground-water stored before May 1. Consequently, the depletion of observed GRO (Fig. 4)

Table 1--Mean monthly balances of sub-surface storage for 5-year period, May, 1935, to May, 1940, Coweeta Experimental Forest, Drainage-Area No. 1
(All values in area-inches)

Month	P	GRO	RO	Meyer's E	(P - RO - E)		Storage							t
							Ground-water change from storage-curve		Soil-moisture change					
									Soil-moisture + T	T		Soil-moisture		
					Month	Sum	Month	Sum	(6)-(8)	Month	Sum	(9)-(11)	Month	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
														°F
Nov.	4.50	0.90	1.09	1.23	2.18	2.18	0.39	0.39	1.79			1.79	1.79	45.7
Dec.	5.34	1.10	1.29	1.14	2.91	5.09	2.43	2.82	2.27			2.27	0.48	38.1
Jan.	8.43	2.38	2.67	1.79	3.97	9.06	2.40	5.22	3.84			3.84	1.57	37.7
Feb.	7.91	3.34	4.11	1.71	2.09	11.15	2.12	7.34	3.81			3.81	-0.03	40.7
Mar.	6.15	3.52	3.87	2.09	0.19	11.34	0.05	7.39	3.95			3.95	0.14	47.5
Apr.	7.02	4.08	4.54	2.54	-0.06	11.28	0.08	7.47	3.81	1.45	1.45	2.36	-1.59	53.3
May	3.56	2.85	2.94	1.77	-1.15	10.13	-3.03	4.44	5.69	2.14	3.59	2.10	-0.26	61.6
June	4.56	1.84	1.94	2.36	0.26	10.39	-2.20	2.24	8.15	2.67	6.26	1.89	-0.21	68.6
July	7.26	1.54	1.81	3.55	1.90	12.29	0.18	2.42	9.87	2.91	9.17	0.70	-1.19	71.2
Aug.	5.24	1.38	1.48	2.66	1.10	13.39	-1.62	0.80	12.59	2.78	11.95	0.64	-0.06	71.4
Sep.	3.74	0.98	1.08	1.72	0.94	14.33	-0.71	0.09	14.24	2.20	14.15	0.09	-0.55	66.2
Oct.	6.28	0.88	0.97	1.22	1.09	15.42	-0.26	-0.17	15.59	1.27	15.42	0.17	0.08	56.2
Total	66.99	.....	27.79	23.78	.....	....	.....	.....	....	15.42	....	.....	.....	.....

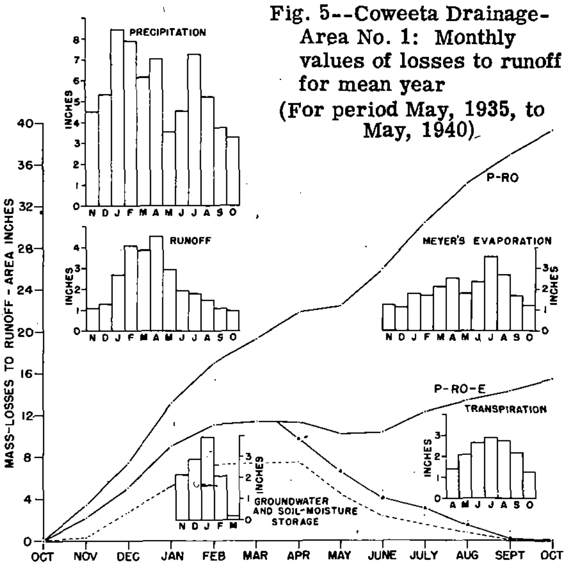


Fig. 5--Coweeta Drainage-Area No. 1: Monthly values of losses to runoff for mean year (For period May, 1935, to May, 1940)

may be used as the approximate base for taking off sums of transpiration from the (P-RO-E) curve of a mean year. However, the values obtained must be redistributed on the basis of temperature. This may be done by the use of MEYER'S [7] curves of transpiration in Column (10), the summation values of which are shown as heavy triangles along the curve of observed GRO depletion. In Figure 5, only this adjusted base for scaling off summations of transpiration is shown.

For other than the mean year, the sums in Column (10) of Table 2, for months of April to October when redistributed as transpiration, Column (11), give a residual which is carried over into the following year as a summation of soil-moisture, Column (15). At the beginning of Table 2 no soil-moisture was carried over from water-year 1933-34, but residual values of soil-moisture appear in all other years. These residuals are no more accurate than the estimates on which they are based, but with few exceptions they are in good agreement with field-observations.

Table 2--Monthly accounts of circulating water capital for the 7-year period, November 1934, to October 1941, Coweeta Experimental Forest, Drainage-Area No. 1

(All values in area-inches)

Month	P	GRO	RO	Meyer's E	(P-RO-E)		Storage									t
							Ground-water			Soil-moisture						
							Change from storage-curve		Total	Soil-moisture + T	Transpiration		Change		Total	
	(1)	(2)	(3)	(4)	Month (5)	Sum (6)	Month (7)	Sum (8)	Sum (9)	(6)-(8) (10)	Month (11)	Sum (12)	(10)-(12) (13)	Month (14)	Sum (15)	(16)
1934-5									1.49[b]							°F
Nov.	9.62	0.94	1.24	2.10	6.28	6.28	4.13	4.13	5.62	2.15			2.15	2.15	2.15	45.7[a]
Dec.	4.21	1.38	1.52	1.00	1.69	7.97	-1.36	2.77	4.26	5.20			5.20	3.05	5.20	38.1[a]
Jan.	5.34	1.88	2.33	1.50	1.51	9.48	0.61	3.38	4.87	6.10			6.10	0.90	6.10	37.7[a]
Feb.	3.70	1.92	2.02	1.25	0.43	9.91	0.17	3.55	5.04	6.36			6.36	0.26	6.36	40.7[a]
Mar.	6.78	2.93	3.22	2.25	1.31	11.22	2.95	6.50	7.99	4.72			4.72	-1.64	4.72	47.5[a]
Apr.	4.63	2.87	3.00	1.90	-0.27	10.95	-0.99	5.51	7.00	5.44	1.45	1.45	3.99	-0.73	3.99	53.3[a]
May	4.23	2.55	2.65	2.05	-0.47	10.48	-2.06	3.45	4.94	7.03	2.14	3.59	3.44	-0.55	3.44	61.6[a]
June	2.52	1.73	1.76	1.50	-0.74	9.74	-1.99	1.46	2.95	8.28	2.67	6.26	2.02	-1.42	2.02	67.0
July	7.03	1.27	1.41	3.50	2.12	11.86	-1.08	0.38	1.87	11.48	2.91	9.17	2.31	0.29	2.31	72.0
Aug.	8.25	1.24	1.49	3.75	3.01	14.87	0.41	0.79	2.28	14.08	2.78	11.95	2.13	-0.18	2.13	71.4[a]
Sep.	1.02	0.99	1.00	0.60	-0.58	14.29	-1.71	-0.92	0.57	15.21	2.20	14.15	1.06	-1.07	1.06	66.2[a]
Oct.	2.50	0.72	0.76	1.10	0.64	14.93	0.13	-0.79	0.70	15.72	1.27	15.42	0.30	-0.76	0.30	55.7
1935-6																
Nov.	6.65	0.86	1.09	2.00	3.56	3.56	0.70	0.70	1.40	2.86			2.86	2.86	3.16	48.7
Dec.	3.52	0.97	1.01	0.70	1.81	5.37	0.32	1.02	1.72	4.35			4.35	1.49	4.65	31.0
Jan.	13.75	3.46	4.70	1.45	7.60	12.97	5.83	6.85	7.55	6.12			6.12	1.77	6.42	33.6
Feb.	8.66	4.86	5.53	1.65	1.48	14.45	2.45	9.30	10.00	5.15			5.15	-0.97	5.45	36.3
Mar.	6.56	3.79	3.98	2.20	0.38	14.83	0.34	9.64	10.34	5.19			5.19	0.04	5.49	47.8
Apr.	10.22	7.96	8.90	3.40	-2.08	12.75	0.63	10.27	10.97	2.48	1.45	1.45	1.03	-4.16	1.33	53.8
May	2.40	3.20	3.41	1.35	-2.36	10.39	-5.45	4.82	5.52	5.57	2.14	3.59	1.98	0.95	2.28	62.4
June	3.13	1.39	1.53	1.85	0.25	10.14	-3.76	1.06	1.76	9.08	2.67	6.26	2.82	0.84	3.12	69.7
July	7.70	1.13	1.33	3.80	2.57	12.71	0.29	1.35	2.05	11.36	2.91	9.17	2.19	-0.63	2.49	73.2
Aug.	4.58	0.75	0.81	2.35	1.42	14.13	-1.84	-0.49	0.21	14.62	2.78	11.95	2.67	0.48	2.97	[illegible]
Sep.	10.45	0.55	0.95	4.25	5.25	19.38	1.91	1.42	2.12	17.96	2.20	14.15	3.81	1.14	4.11	
Oct.	4.33	0.90	0.98	1.75	1.60	20.98	-1.60	-0.18	0.52	21.16	1.27	15.42	5.74	1.93	6.04	56.8
1936-7																
Nov.	1.70	0.76	0.77	0.60	0.33	0.33	0.26	0.26	0.78	0.07			0.07	0.07	6.11	45.8
Dec.	10.77	1.30	1.75	1.95	7.07	7.40	9.56	9.82	10.34	-2.42			-2.42	-2.49	3.62	43.9
Jan.	12.33	4.39	4.92	1.80	5.61	13.01	0.42	10.24	10.76	2.77			2.77	5.19	8.81	37.7
Feb.	5.58	3.84	4.09	1.60	-0.11	12.90	-0.96	9.28	9.80	3.62			3.62	0.85	9.66	39.0
Mar.	2.78	3.04	3.24	1.10	-1.56	11.34	-2.27	7.01	7.53	4.33			4.33	0.71	10.37	45.3
Apr.	7.31	2.71	3.11	2.65	1.55	12.89	0.83	7.84	8.36	5.05	1.45	1.45	3.60	-0.73	9.64	53.3
May	2.34	2.70	2.72	1.35	-1.73	11.16	-3.45	4.39	4.91	6.77	2.14	3.59	3.18	-0.42	9.22	62.4
June	6.08	1.73	1.83	3.00	1.25	12.41	-0.86	3.53	4.05	8.88	2.67	6.26	2.62	-0.56	8.66	69.6
July	4.37	1.60	1.64	2.35	0.38	12.79	-1.07	2.46	2.98	10.33	2.91	9.17	1.16	-1.46	7.20	69.9
Aug.	5.02	1.26	1.30	2.55	1.17	13.96	-0.65	1.81	2.33	12.15	2.78	11.95	0.20	-0.96	6.24	71.6
Sep.	3.22	1.00	1.05	1.50	0.67	14.63	-1.22	0.59	1.11	14.04	2.20	14.15	-0.11	-0.31	5.93	63.4
Oct.	8.57	1.01	1.34	2.70	4.53	19.16	0.94	1.53	2.05	17.63	1.27	15.42	2.21	2.32	8.25	53.4
1937-8																
Nov.	2.75	1.00	1.04	0.80	0.91	0.91	0.07	0.07	2.12	0.84			0.84	0.84	9.09	43.3
Dec.	5.09	1.17	1.44	1.20	2.45	3.36	2.37	2.44	4.49	0.92			0.92	0.08	9.17	37.9
Jan.	5.03	1.56	1.74	1.50	1.79	5.15	0.18	2.62	4.67	2.53			2.53	1.61	10.78	38.6
Feb.	2.66	1.55	1.60	1.10	-0.04	5.11	-1.03	1.59	3.64	3.52			3.52	0.99	11.77	46.0
Mar.	8.75	2.29	3.07	2.90	2.78	7.89	4.11	5.70	7.75	2.19			2.19	-1.33	10.44	51.6
Apr.	6.12	3.57	3.89	2.40	-0.17	7.72	0.35	6.05	8.10	1.67	1.45	1.45	0.22	-1.97	8.47	54.6
May	6.11	2.68	2.79	2.70	0.62	8.34	-1.49	4.56	6.61	3.78	2.14	3.59	0.19	-0.03	8.44	62.0
June	6.70	2.23	2.41	3.10	1.19	9.53	-1.81	2.75	4.80	6.78	2.67	6.26	0.52	0.33	8.77	66.5
July	12.07	2.13	3.04	5.30	3.73	13.26	4.12	6.87	8.92	6.39	2.91	9.17	-2.78	-3.30	5.47	70.7
Aug.	2.45	2.49	2.51	1.50	-1.56	11.70	-4.87	2.00	4.05	9.70	2.78	11.95	-2.25	0.53	6.00	72.8
Sep.	2.85	1.53	1.57	1.45	-0.17	11.53	-1.68	0.32	2.37	11.21	2.20	14.15	-2.94	-0.69	5.31	65.7
Oct.	0.18	1.09	1.09	0.15	-1.06	10.47	-0.80	-0.48	1.57	10.95	1.27	15.42	-4.47	-1.53	3.78	55.8

Column (9) has also been introduced in Table 2 to carry forward a continuous value of total ground-water. The sum of Columns (9) and (15) represents the amount of circulating water in storage at the end of each month after evaporation and transpiration have been accounted for. During the course of the month both transpiration and evaporation have been a part of soil-moisture. Consequently, the values given in Column (15) must be thought of as being one to four inches higher than actually shown to account for transient evaporation and transpiration not appearing in final monthly balances.

Table 2--Monthly accounts of circulating water capital for the 7-year period, November 1934, to October 1941, Coweeta Experimental Forest, Drainage-Area No. 1--Concluded
(All values in area-inches)

Month	P	GRO	RO	Meyer's E	(P-RO-E)		Storage									t
							Ground-water			Soil-moisture						
							Change from storage-curve		Total	Soil-moisture + T	Transpiration		Change		Total	
	(1)	(2)	(3)	(4)	Month (5)	Sum (6)	Month (7)	Sum (8)	Sum (9)	(6)-(8) (10)	Month (11)	Sum (12)	(10)-(12) (13)	Month (14)	Sum (15)	(16) °F
1938-9																
Nov.	10.57	1.24	1.91	2.15	6.51	6.51	1.30	1.30	2.87	5.21			5.21	5.21	8.99	47.0
Dec.	3.19	1.40	1.54	0.80	0.85	7.36	0.11	1.41	2.98	5.95			5.95	0.74	9.73	38.6
Jan.	7.30	1.73	2.13	2.00	3.17	10.53	5.18	6.59	8.16	3.94			3.94	-2.01	7.72	39.9
Feb.	15.20	5.48	7.98	2.35	4.87	15.40	7.97	14.56	16.13	0.84			0.84	-3.10	4.62	44.4
Mar.	7.61	7.13	7.65	2.50	-2.54	12.86	-2.88	11.68	13.25	1.18			1.18	0.34	4.96	48.8
Apr.	5.03	4.35	4.53	2.00	-1.50	11.36	-3.75	7.93	9.50	3.43	1.45	1.45	1.98	0.80	5.76	52.7
May	2.74	3.13	3.15	1.40	-1.81	9.55	-2.68	5.25	6.82	4.30	2.14	3.59	0.71	-1.27	4.49	59.9
June	4.39	2.11	2.18	2.40	-0.19	9.36	-2.60	2.65	4.22	6.71	2.67	6.26	0.45	-0.26	4.23	70.3
July	5.15	1.58	1.65	2.80	0.70	10.06	-1.38	1.27	2.84	8.79	2.91	9.17	-0.38	-0.83	3.40	70.1
Aug.	5.91	1.18	1.27	3.15	1.49	11.55	-1.15	0.12	1.69	11.43	2.78	11.95	-0.52	-0.14	3.26	69.7
Sep.	1.16	0.85	0.85	0.75	-0.44	11.11	-0.83	-0.71	0.86	11.82	2.20	14.15	-2.33	-1.81	1.45	66.8
Oct.	0.82	0.69	0.70	0.45	-0.33	10.78	0.00	-0.71	0.86	11.49	1.27	15.42	-3.93	-1.60	-0.15	57.4
1939-40																
Nov.	0.83	0.65	0.66	0.35	-0.18	-0.18	-0.36	-0.36	0.50	0.18			0.18	0.18	0.03	43.6
Dec.	4.13	0.66	0.73	1.05	2.35	2.17	-0.21	-0.57	0.29	2.74			2.74	2.56	2.59	38.9
Jan.	3.75	0.75	0.85	0.85	2.05	4.22	0.41	-0.16	0.70	4.38			4.38	1.64	4.23	24.8
Feb.	7.47	0.99	1.34	1.80	4.33	8.55	2.17	2.01	2.87	6.54			6.54	2.16	6.39	37.6
Mar.	5.03	1.33	1.43	1.70	1.90	10.45	0.94	2.95	3.81	7.50			7.50	0.96	7.35	44.0
Apr.	6.41	1.80	2.28	2.25	1.88	12.33	2.36	5.31	6.17	7.02	1.45	1.45	5.57	-1.93	5.42	52.1
May	1.88	1.87	1.88	1.05	-1.05	11.28	-2.82	2.49	3.35	8.79	2.14	3.59	5.20	-0.37	5.05	58.3
June	6.95	1.43	1.59	3.15	2.21	13.49	-1.27	1.22	2.08	12.27	2.67	6.26	6.01	0.81	5.86	67.0
July	3.79	1.15	1.17	2.10	0.52	14.01	-1.10	0.12	0.98	13.89	2.91	9.17	4.72	-1.29	4.57	69.1
[illegible]	12.76	1.00	1.57	4.90	6.29	20.30	2.93	3.05	3.91	17.25	2.78	11.95	5.30	0.58	5.15	69.9
[illegible]	0.64	1.03	1.04	0.40	-0.80	19.50	-2.85	0.20	1.06	19.30	2.20	14.15	5.15	-0.15	5.00	62.4
Oct.	2.06	0.82	0.84	0.90	0.32	19.82	0.58	0.78	1.64	19.04	1.27	15.42	3.62	-1.53	3.47	55.3
1940-1																
Nov.	4.90	0.90	1.03	1.40	2.47	2.47	-0.16	-0.16	1.48	2.63			2.63	2.63	6.10	45.1
Dec.	4.48	1.03	1.12	1.20	2.16	4.63	0.72	0.56	2.20	4.07			4.07	1.44	7.54	42.7
Jan.	3.47	1.20	1.28	1.15	1.04	5.67	0.19	0.75	2.39	4.92			4.92	0.85	8.39	38.9
Feb.	1.55	1.08	1.10	0.70	-0.25	5.42	-0.27	0.48	2.12	4.94			4.94	0.02	8.41	34.9
Mar.	5.24	1.48	1.58	1.65	2.01	7.43	1.22	1.70	3.34	5.73			5.73	0.79	9.20	41.4
Apr.	3.19	1.62	1.69	1.50	0.00	7.43	0.12	1.82	3.46	5.61	1.45	1.45	4.16	-1.57	7.63	55.7
May	1.96	1.37	1.39	1.10	-0.53	6.90	-1.41	0.41	2.05	6.49	2.14	3.59	2.90	-1.26	6.37	61.1
June	2.95	0.87	0.89	1.70	0.36	7.26	-0.86	-0.45	1.19	7.71	2.67	6.26	1.45	-1.45	4.92	68.0
July	9.76	0.96	1.17	4.50	4.09	11.35	-0.25	-0.70	0.94	12.05	2.91	9.17	2.88	1.43	6.35	73.2
Aug.	2.83	0.67	0.69	1.60	0.54	11.89	-1.28	-1.98	-0.34	13.87	2.78	11.95	1.92	-0.96	5.39	72.5
Sep.	3.02	0.48	0.50	1.60	0.92	12.81	-0.12	-2.10	-0.46	14.91	2.20	14.15	0.76	-1.16	4.23	67.6
Oct.	3.39	0.38	0.42	1.50	1.47	14.28	-0.04	-2.14	-0.50	16.42	1.27	15.42	1.00	0.24	4.47	59.8

[a] Means for record period. [b] Observed ground-water October 31, 1934.

Use of Table 2--The accounting procedure shown in Table 2 will give a current value of ground-water and soil-moisture in storage in the absence of well-records and soil-moisture determinations. Where soil-moisture determinations are available they serve as a basis for correcting the tabular values. Frequently, however, in a region where periods of continuous daily rainfall occur, adequate moisture-sampling of the entire soil-profile becomes an impossible task. During such periods the values in Table 2 may be carried forward by days for special periods, or storm by storm, using computed corrections for evaporation and transpiration and other field-moisture losses. The feasibility of this procedure has been recently pointed out by LINSLEY and ACKERMANN [8].

The greatest practical value in Table 2 should be in showing actual circulating values of soil-moisture and ground-water in storage. The lack of sensitivity of ground-water levels to rainfall before soil-moisture replenishment has taken place shows up throughout the Table. Rapid rises in ground-water may be expected to take place only when soil-moisture is at a maximum. These comparative values of soil-moisture and ground-water will be generally used for computing current storage-opportunity in the soil-profile for forecasting runoff.

Because the monthly balance in Table 2 is made at the end of each month, the current values may be extended into a daily or storm-by-storm analysis by beginning with the last monthly balances. In any case monthly balances serve as a check on storm-analyses. Further studies using short-period analyses are now in progress for the Coweeta drainages.

The monthly values shown in Table 2 may be obtained directly without the use of sums. However, sums are advantageous as a constant check on errors of tabulation which are common in handling negative quantities. Sums lend themselves well to calculation by machine.

The most outstanding error in the trial-balances given in Table 2 is that the storage-curve obtained directly from the normal curve of ground-water depletion, and used to derive the ground-water change, Column (7), apparently does not apply to the months of exceptionally high rainfall. Either this is the case, or else MEYER'S values of transpiration are too high for these months. Both may be true. As a result, negative values appear in Column (13) which cannot be explained. Nevertheless, these unexplained values serve as the clue for locating the inaccuracies in the estimates of Columns (7) and (4). An effort is being made to find and correct these errors.

So far as can be determined, serious errors appear chiefly for months of ten inches of precipitation or more. Elsewhere the Table appears to check well with field-observations. A close field-check upon such exceptional periods as September to December, 1939, when precipitation was far below normal, bears out the low values in Column (8). In August, September, and October, 1941, GRO actually fell below the 0.5 csm zero-point of the storage-curve, and the readings of ground-water storage were taken from an extended curve. As a whole, Table 2 in its present form is of more value in presenting a check-method of accounting for continuous hydrologic phenomena, rather than a completely accurate water-storage analysis for the drainage-area studied. In the latter sense it must be considered more as a progress-report and a trial-balance which requires numerous corrections.

References

[1] P. A. M. PARKER, The control of water, Geo. Routledge and Sons, Ltd., London, 1932.
[2] G. W. RAFTER, W.-S. Paper 80, U. S. Geol. Surv., 1903.
[3] I. E. HOUK, Rainfall and runoff in the Miami Valley, Miami Conservancy District Tech. Rep., Pt. 8, pp. 134-176, 1921.
[4] W. G. HOYT et al., Studies of relations of rainfall and runoff in the United States, W.-S. Paper 772, U. S. Geol. Surv., pp. 245-255, 1936.
[5] C. C. VERMULE, New Jersey Geol. Surv., v. 3, pp. 11-108, 1894.
[6] F. F. SNYDER, A conception of runoff-phenomena, Trans. Amer. Geophys. Union, pp. 725-738, 1939.
[7] A. F. MEYER, The elements of hydrology, John Wiley and Sons, 2d, ed. 1928.
[8] R. K. LINSLEY, JR. and W. C. ACKERMANN, Method of predicting the runoff from rainfall, Proc. Amer. Soc. Civ. Eng., v. 67 (6), pp. 1023-1033, 1941.

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DISCUSSION

L. K. SHERMAN (Chicago, Illinois)--The whole is equal to the sum of all of the parts. This axiom, referred to the volume of water falling on a drainage-basin, includes the storage-equation: Inflow = Outflow ± storage.

The whole is a known quantity and the equation may be used to determine any single residual part if the other parts are determinate. The residual here in question is the volume of ground-water storage. The authors have made a graphical presentation of the problem which is ingenuous and has the beauty of clearness and simplicity.

The authors' work is confined (perhaps fortunately) to a basin where the period of ground-water accretion does not coincide or conflict with the season of transpiration. Perhaps a similar methodology could be applied to other basins where transpiration and ground-water replenishment occur simultaneously, but the authors have not demonstrated this phase.

The authors have outlined one procedure based on the averages for several years. This is premised on the fact that in a series of years the cycles of precipitation, runoff, and losses must of necessity balance. Their evidence in Figure 2 shows very close agreement between the averaged and observed yearly cycles. For increased accuracy, the procedure which takes cognizance of the excess or deficiency of stored ground-water at the end of the year seems worth while.

The derivation of the depletion-curve of GRO in Figure 5 is not clear. Presumably, it represents the average of a number of observed hydrograph tails during periods when no surface-runoff existed. A depletion-curve could also be derived by subtracting MEYER'S transpiration values (T) from the mass-curve P-RO-E. This would also give a good smooth curve, but the two depletion-curves would not be in good agreement. MEYER'S derivations of evaporation and transpiration have generally given good results--at any rate, the best now obtainable, but in this case we would naturally expect that the observed depletion-curve would be the more reliable. Viewed in this light, the mass-evaporation plus transpiration of MEYER checks very well. In fact, the whole procedure, as presented by months, has its greatest value in this check of a composite depletion-curve.

The depletion-curve has been applied to the derivation of base-flow under flood-hydrographs. This is erroneous. Ground-water outflow at flood-stages is throttled and is frequently a negative quantity. After the flood-stage recedes, the rate of GRO is greater than that given by the normal depletion-curve until equilibrium takes place. The authors' use of a monthly grouping of rainfall and runoff cancels these effects of flood-peaks on the normal recession-curve.

The authors state that the month-by-month analysis is in the nature of a preliminary report or trial-balance. As such it is a valuable contribution.

Recently several studies have been presented on continuous records of hydrologic phenomena for a year or more. One of these studies was presented by LINSLEY and ACKERMANN [Proc. Amer. Soc. Civ. Eng., June 1941]. They presented the record storm by storm. Your critic sees no reason why the authors could not apply their procedure by storm-units as well as monthly units. Such a study might furnish better working factors than the rather crude empiricisms used by LINSLEY and ACKERMANN.

The quantitative effects of vegetal cover and agricultural works can now be definitely determined by the infiltration-theory for all conditions, storm by storm and season by season. An excellent check on the work would be obtained if the yearly cycle was completed and balanced by the authors' diagram.