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Estimation of Yields from River Basins by a modification of the Water Balance Procedure of Thornthwaite*

B. SUBBA RAO and V. P. SUBRAHMANYAM

Geophysics Department, Andhra University, Waltair

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1. Introduction

Stream-flow is one of the most important of hydrologic measurements, for, it represents the total runoff from a basin and is the residual of precipitation after the demands of evapotranspiration and soil storage are met. The need for runoff data in different parts of the world is increasing so rapidly that the existing network of stream-gauge stations is either too sparse or has an inadequate period of record. An alternative approach from meteorological data was, therefore, suggested by Thornthwaite (Thornthwaite 1948) whose book-keeping procedure for water balance offers a method for the determination of runoff on a monthly basis. The basis of this method as well as other water balance methods is that closed chain of events representing the circulation of water in the atmosphere and over the earth, known as the hydrologic cycle, which constantly redistributes water between the earth's surface and the atmosphere, tending to maintain a long term balance. For continental areas, this balance is represented by the basic hydrologic equation,

$$P = E + \triangle S + G + R$$

where P is precipitation, E is evaporation, $\triangle S$ is change in storage on or below the surface of the earth within the region, G is subsurface leakage from the region and R is runoff. If the region under consideration is large and free from unusual geological formations, leakage G can be neglected. The hydrologic equation then reduces to

$$P = E + \triangle S + R$$

Precipitation P can be measured directly and runoff R obtained from stream-gauging. The change in storage $\triangle S$ is a variable quantity and for short periods of time can be as large as any other item in the equation. However, over a long period, $\triangle S$ shows irregular positive and negative variations but remains comparatively small and, therefore, can be neglected. Omitting $\triangle S$, then, the long period hydrologic balance can be written as,

$$P = E + R$$

Therefore, the water balance of any region can be worked out with the help of the above expression. In India, measured runoff data are very scanty; information about evaporation too is meagre but intensive work in other countries is enabling us to estimate this element with reasonable accuracy from other climatic factors like air temperature, relative humidity, wind speed, solar radiation etc.

The term "evaporation" in hydrology is used in a general sense but a more precise term is "evapotranspiration" which includes all the processes by which water is transported back to the atmosphere in the vapour state from the earth's surface and vegetation and suspended water in the atmosphere. The actual amount of water that evaporates and transpires, called the Actual Evapotranspiration AE, is rather difficult to measure since it depends upon such uncertain factors as soil moisture, atmospheric humidity and so on.

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2. Thornthwaite's procedure

To overcome such difficulties, Thornthwaite developed the concept of 'Potential Evapotranspiration' *PE*, which is a climatic parameter depending for its magnitude on air temperature and latitude of the place under consideration. He defines *PE* as the maximum amount of water that would evaporate and transpire from a densely vegetated land area having no deficiency of moisture at any time for full use.

While *PE* depends upon the total amount of energy available for the process, *AE* is dependent, in addition, upon the amount of water available in the ground. To estimate *AE*, Thornthwaite developed in 1948 a book-keeping procedure wherein he assumed that the soil mantle has a capacity to hold 10 cm of water for purposes of evapotranspiration and whenever precipitation falls short of water need, *i.e.*, *PE*, the shortage can be made good from the stored soil moisture as long as it is available. When precipitation is in excess of *PE*, the excess will first go to recharge the soil to its field capacity and the surplus will be available for runoff; for converting this surplus into runoff, a factor of ½ was used with month as a unit. In 1955, Thornthwaite introduced certain changes in his earlier assumptions regarding the moisture holding capacity of the soil and the rate of utilization of the soil moisture for evapotranspiration. The field capacity of the soil was increased, in the light of fresh evidence, from 10 cm to 30 cm and the rate of depletion of this stored moisture was found to follow an exponential decay law. Tables were prepared by him for the soil moisture utilization with different moisture-holding capacities of the soil. These, in brief, are the essentials of Thornthwaite's latest method and further details can be obtained from the original papers (Thornthwaite and Mather 1955a and 1955b).

3. Khosla's method

Khosla (1951) earlier suggested a method for estimating yields from river basins, wherein he considered that air temperature takes cognizance of all other factors responsible for the loss of water from the ground to the atmosphere. On this basis, he developed a formula connecting air temperature and water loss as

$$L_m = \frac{T_m - 32}{9 \cdot 5}, \text{ for } T_m > 40°\text{F}$$

where L_m = monthly water loss in inches depth and T_m = monthly mean temperature in °F.

For $T_m < 40$°F, the loss was assured as follows—

T_m	40	30	20	10	0	°F
L_m	0·84	0·70	0·60	0·50	0·40	inches

Monthly runoff (R_m) was computed from the relation

$$R_m = P_m - L_m$$

where P_m is precipitation in inches and L_m is water loss in inches for the month, obtained as above.

This formula was applied by Khosla to different river basins in different parts of the world for the estimation of runoff and was found to give fairly good estimates on an annual basis compared to the measured values.

4. Modification of Thornthwaite's method

(a) *Reduction factor*—Estimates of evapotranspiration for the Damodar basin were obtained from long period normals of rainfall and runoff using the hydrologic equation and were graphically compared with the values of actual evapotranspiration computed according to the 1955 book-keeping procedure of Thornthwaite. It became evident from the statistical analysis that almost all the observed data were about 65 per cent of the computed values and that the latter should, therefore, be reduced in the same proportion in order to obtain the actual basin evapotranspirations. Reduction of computed *AE* values is not appropriate, for, this would result in differences between the *PE* and *AE* every month including the monsoon season when the *AE* should be expected to be identical with the *PE* because of the adequacy of available moisture. Application of the reduction factor to the *PE* data, on the other hand would eliminate this difficulty, for, in the book-keeping procedure for water balance, *AE* too would automatically be reduced by the same proportion and the final figures for *AE* and *PE* would remain identical in rainy periods. It is thus that this conversion factor of 0·65 has been applied to the *PE* data; it would be interesting to see if the so-reduced *PE* values would lie anywhere close to the actual evaporation data from open water surfaces in the basin or those obtained from evapotranspiration installations when such data may become available in future.

(b) *Soil moisture*—The actual amount of moisture available for potential water loss was assumed by Thornthwaite in 1948 to be 10 cm and as stated earlier, with the accumulation of further information, he changed this figure to 30 cm. This, however, is a general value valid, perhaps, only for American soils but in regular computational work, actual values of field capacity of the soil should be used. With 30 cm as the water-holding capacity of the soil in the present water balance investigation, the resultant annual surpluses for runoff were found to be about 100 mm less than the actual measured values. Since the water-holding capacity cannot be the same for all types of soils, it was felt that these two runoff values could be empirically made to agree with each other by choosing a figure of 200 mm for the field capacity of the soil in question. A set of tables was prepared after Thornthwaite's procedure for the determination of the soil moisture utilization, with this field capacity of 200 mm.

(c) *Detention factor*—To convert the monthly surplus into runoff, it is essential to have an idea of the fraction of the surplus that is obtained in the watershed as percolation water. This fraction depends upon such factors as the length of the period chosen, antecedent state of the soil prior to precipitation, intensity of rainfall, rate of infiltration, slope of the catchment etc. In small basins and basins with steep slopes, practically all the surplus can be expected to go as runoff. In large catchments, of the size of Amazon, it has been reported that upto about 75 per cent of the surplus in any month may be held in detention (Carter 1955). If instead of a month, the length of the period chosen were a day, as much as over 90 per cent of the daily surplus could appear as runoff leaving less than 10 per cent as percolation water. For Indian river basins whose catchments are quite extensive with somewhat steep gradients (particularly in Peninsular India) a detention of 1/3 has been felt to be appropriate on a monthly basis.

To sum up, in the present study, the empirical modifications that were incorporated on the Thornthwaite method of 1955, are (*i*) reduction of *PE* to 0·65 of its computed value, (*ii*) choice of 200 mm as the field capacity of the soil and (*iii*) basin detention of a third of the water surplus in any month for contribution to the subsequent month's surplus.

5. Results and discussion

With a view to make a comparative study of the water balances according to the modified Thornthwaite method proposed and those according to Khosla's above formula, runoffs were worked out for three river basins, the Mahanadi, the Kosi and the Ashni for which the estimates were formerly made by Khosla. The results are presented in Table 1 [(*a*)—(*c*)]. On an annual basis agreement between measured and computed values according to the two methods is good in all the three cases studied whereas on a monthly basis wide divergences are observed according to Khosla's method. This is evidently due

TABLE 1

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
(a) Water Balance of the Mahanadi river at Sambalpur for the year 1932													
PE	29	31	94	116	133	130	105	106	101	93	46	23	1007
P	0	21	3	8	14	123	502	280	286	53	31	0	1321
AE	14	25	31	29	28	124	105	106	101	86	41	13	703
D	15	6	63	87	105	6	0	0	0	7	5	10	304
S	0	0	0	0	0	0	259	174	185	0	0	0	618
R	2	1	0	0	0	0	173	173	181	61	20	7	618
MR	7	5	4	3	2	2	172	215	143	51	41	10	655
KR	0	0	0	0	0	0	371	146	148	0	0	0	665
(b) Water Balance of the Kosi river at Dam site for the year 1947													
PE	1	12	23	35	40	52	59	57	38	22	16	16	371
P	3	4	46	33	66	173	422	315	222	53	3	3	1343
AE	1	10	23	35	40	52	59	57	38	22	16	13	366
D	0	2	0	0	0	0	0	0	0	0	0	3	5
S	0	0	0	0	20	121	363	258	184	31	0	0	977
R	3	1	1	0	13	85	271	262	210	91	30	10	977
MR	20	14	17	20	28	76	211	229	168	107	36	25	951
KR	0	0	12	0	16	108	350	241	168	20	0	0	915
(c) Water Balance of the Ashni river at Dochi Dam site for the year 1947													
PE	7	14	27	52	73	75	70	59	47	33	23	14	494
P	41	42	80	5	50	56	291	259	564	39	0	26	1453
AE	7	14	27	43	64	66	70	59	47	33	21	14	465
D	0	0	0	9	9	9	0	0	0	0	2	0	29
S	25	28	53	0	0	0	159	200	517	6	0	0	988
R	22	26	44	15	5	1	107	169	401	137	46	15	988
MR	35	31	36	28	26	24	112	144	335	83	30	25	909
KR	13	0	21	0	0	0	193	168	479	0	0	0	874

Note—*D* is deficiency, *S* is surplus, *MR* is measured runoff and *KR* is runoff according to Khosla's method and all values are in millimetres

TABLE 2

Runoff in millimetres from Mahanadi river basin

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
1926	*C*	3	1	1	0	0	0	36	328	255	86	29	9	748
	M	10	7	8	7	4	2	40	258	203	78	18	11	646
1927	*C*	3	1	1	0	0	0	169	291	149	49	17	5	685
	M	7	5	7	2	2	2	134	254	177	63	15	10	705
1928	*C*	2	1	0	0	0	0	195	153	94	59	19	7	530
	M	6	5	2	2	2	24	164	81	94	83	20	9	492
1929	*C*	2	1	0	0	0	0	227	287	122	57	19	6	721
	M	4	5	3	1	1	3	198	342	163	77	26	13	836
1930	*C*	2	1	0	0	0	0	165	154	119	40	24	8	513
	M	11	5	3	2	2	5	135	170	102	49	43	15	542
1931	*C*	3	1	0	0	0	0	14	281	142	104	44	15	604
	M	0	7	8	2	1	2	2	217	138	89	49	15	530
1932	*C*	5	1	1	0	0	0	201	171	181	61	20	7	648
	M	9	6	4	2	2	2	157	193	133	48	45	14	615
1933	*C*	2	1	0	0	0	81	219	303	228	76	25	9	944
	M	10	14	11	4	6	70	171	323	183	68	35	18	913
1934	*C*	3	1	0	0	0	0	157	269	237	79	26	9	781
	M	12	8	5	3	3	12	159	234	220	101	37	18	812
1935	*C*	3	1	0	0	0	0	197	148	135	45	15	5	549
	M	12	9	8	6	4	3	184	166	118	37	15	10	572
1936	*C*	2	1	0	0	0	156	229	283	189	73	24	8	966
	M	8	8	5	3	3	126	168	244	197	90	43	16	911
1937	*C*	3	1	0	0	0	8	249	254	185	62	21	7	790
	M	10	8	9	5	6	13	187	299	172	54	21	11	795
1938	*C*	2	1	0	0	0	1	143	207	166	81	27	9	637
	M	9	7	4	2	1	37	89	151	192	91	21	11	615
1939	*C*	3	1	0	0	0	0	161	322	187	68	23	7	772
	M	9	6	5	3	1	10	150	248	286	56	33	12	819
1940	*C*	3	1	0	0	0	15	294	271	90	30	10	3	717
	M	8	6	5	2	1	38	309	249	74	29	14	9	744
1941	*C*	1	1	0	0	0	0	83	106	61	20	7	2	281
	M	8	6	3	2	2	15	103	111	56	32	10	6	354

NOTE—*C* is the runoff computed according to the modified method and *M* is the actually measured runoff to the fact that Khosla has considered neither the moisture-holding capacity of the soil nor a detention factor in estimating runoffs in individual months. The modified Thornthwaite method takes into account both of them and hence the computations based on this method are found to be in good agreement, on annual as well as monthly bases.

The reason why run values were computed for the Mahanadi river basin for 1932 and for the Kosi and the Ashni basins for the year 1947 is that it is only for these years that Khosla worked out the runoff data earlier. As a matter of fact, computations for individual years for other basins also gave highly coincident values. Data for the Mahanadi catchment for 16 years from 1926—1941, for which reliable measured stream-flow records are available, are presented in Table 2 and the agreement between the two sets of data is extremely interesting.

6. Conclusions

It should be emphasized that the parameters used in the present study were arrived at empirically but surprisingly they appear to be of the right order of magnitude. The method at present cannot be said to be perfect from a theoretical point of view and may need further and more intensive work for confirmation. The agreement, however, between the computed and measured data of runoff is more than convincing to lend strong support to the approach.

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