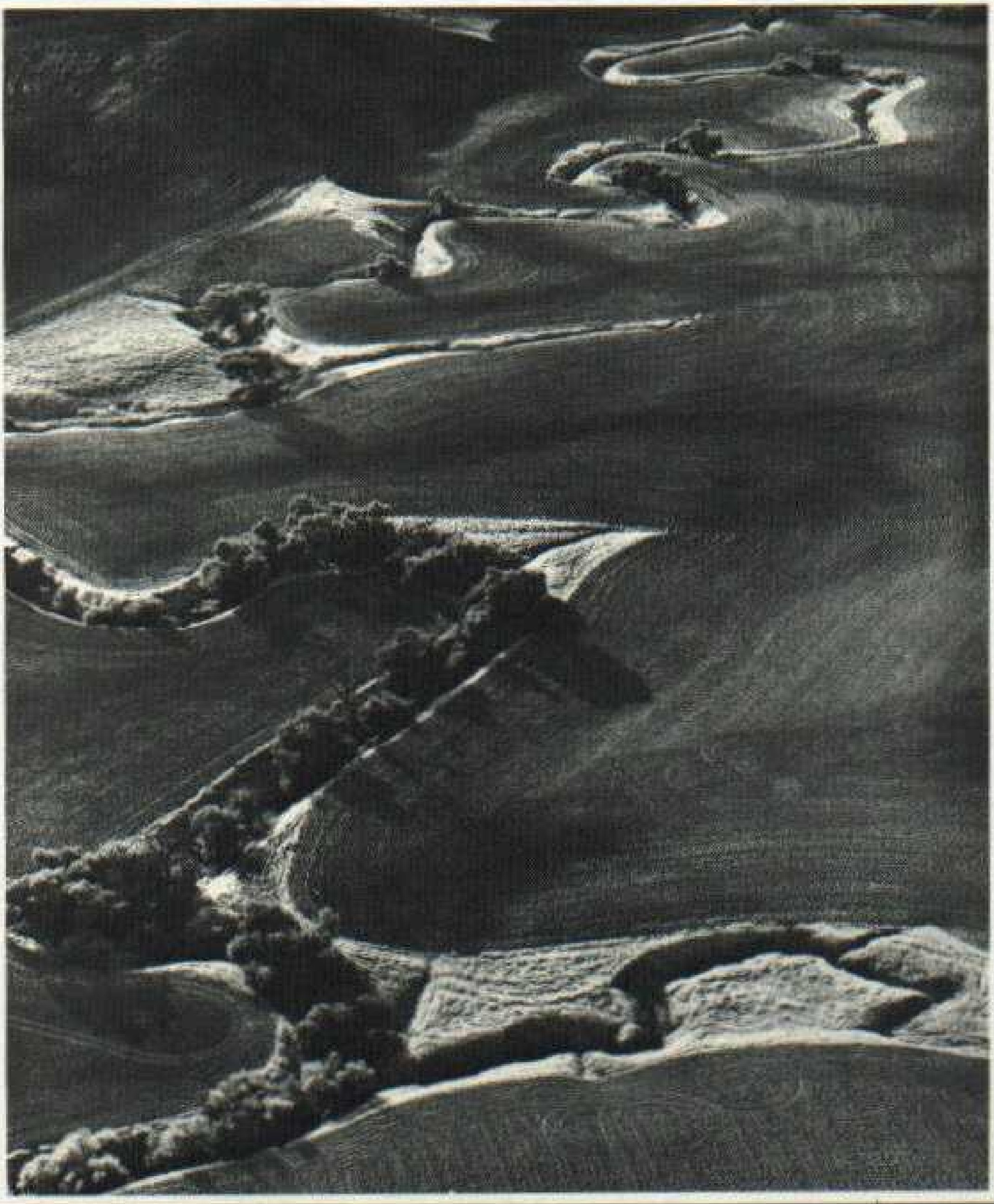
Water in Environmental Planning

Thomas Dunne and Luna B. Leopold



8

The Water Balance

Usefulness

Previous chapters have treated hydrologic processes more or less separately. We are now in a position to draw together hydrometeorology, soil physics, and groundwater hydrology by means of a very useful tool known as the *water balance*. The term water balance was used in 1944 by the meteorologist C. Warren Thornthwaite to refer to the balance between the income of water from precipitation and snowmelt and the outflow of water by evapotranspiration, groundwater recharge, and streamflow. The budget can be computed for a soil profile or for a whole drainage basin. The method allows the planner to compute a continuous record of soil moisture, actual evapotranspiration, groundwater recharge, and streamflow from a meteorological record and a few observations on the soil and vegetation. Its use will be illustrated by means of examples and by reference to published accounts from various areas of the world.

The power of such a technique in planning is obvious. The water balance has been used for computing seasonal and geographic patterns of irrigation demand, the soil moisture stresses under which crops and natural vegetation can survive, the prediction of streamflow and water-table elevations, the flux of water to lakes, and therefore the variations of water level and salinity. Because commonly available meteorologic records are the usual basis of the method, long periods of data on soil moisture, groundwater, and streamflow can be generated and subjected to probability analysis for studying the economic and ecologic feasibility of various schemes for using or manipulating land and water resources.

The water balance is also useful for predicting some of the human impacts on the hydrologic cycle. The hydrologic effects of weather modification or changes of vegetation cover can be quickly estimated at a very early stage in the planning. Although the predictions may be approximate, they are sufficiently accurate to indicate whether a scheme is hydrologically sound or foolhardy. Also the water balance can be refined to meet the most sophisticated design needs if sufficient time and money for instrumentation are available. Finally, the method is valuable for helping to phrase precise questions about the chances of success, mode of operation, and environmental impact of proposed changes. It is, therefore, a valuable tool in the analysis of water problems in a region.

Direct Measurement of the Water Balance

The water balance of a small drainage basin underlain by impervious rock at depth can be represented by Figure 8-1 and expressed in the following equation:

$$P = I + AET + OF + \Delta SM + \Delta GWS + GWR \qquad (8\text{-}1)$$

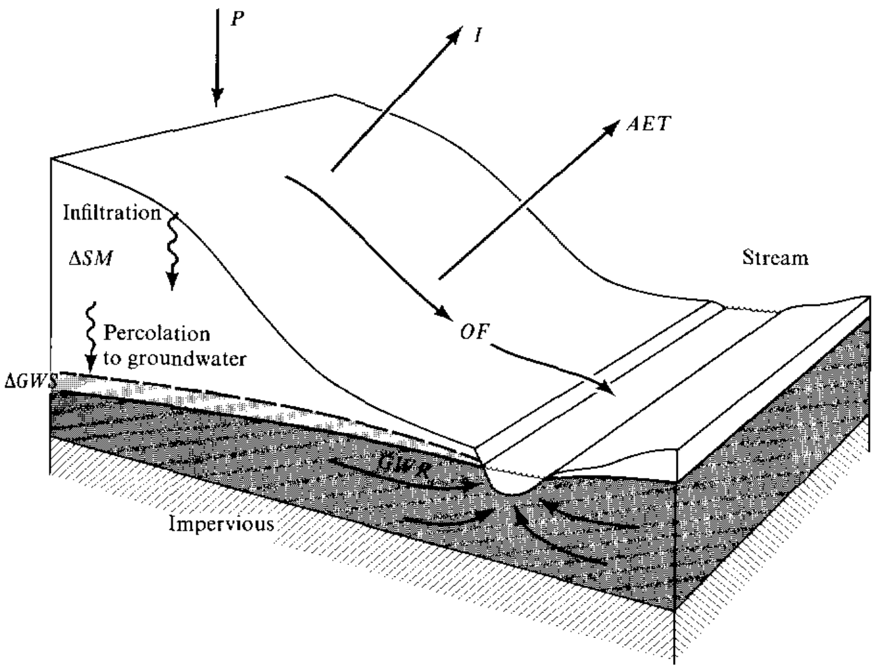


Figure 8-1 Components of the water balance on a hillside or a small catchment. P = precipitation; I = interception; AET = actual evapotranspiration; OF = overland flow; ΔSM = change in soil moisture; ΔGWS = change in groundwater storage; GWR = groundwater runoff.

where the symbols, expressed as equivalent depths of water for some time interval, represent precipitation, interception, evapotranspiration, overland flow, change of soil moisture storage, change of groundwater storage, and groundwater runoff.

If time and funds are available, each of these terms can be evaluated directly in the field by techniques that have already been discussed. Precipitation gauging and the measurement of interception are straightforward. Actual evapotranspiration can be evaluated from Equation 8-1 if all the other elements are measured. Small troughs below hillside plots would catch overland flow, or this component could be estimated from the streamflow hydrograph by methods described in Chapter 10. Soil moisture changes can be monitored with soil moisture blocks, a neutron meter, or a weighing-type lysimeter; and groundwater storage changes are reflected in fluctuations of the water table. Groundwater runoff can be calculated from Darcy's Law or from the streamflow hydrograph (see Chapter 10 on hydrograph separation). If calculations are made on an annual basis, it is often assumed that there is no net change of soil moisture or groundwater storage over the year and that the right side of Equation 8-1 reduces to the sum of interception, evapotranspiration, and streamflow.

Field measurements of this kind are valuable if the rural planner needs a detailed understanding of moisture regimes and their controls. They also allow the direct measurement of transpiration and the definition of the functional relationship between potential and actual water loss as expressed in Equation 5-13 and Figures 5-6, 5-7, and 5-8. A few weeks or years of direct measurement of the water balance can yield a large amount of hydrologic information about the interrelationships of climate, land use, groundwater, and runoff. Lewis and Burgy (1964) have given an excellent description of their field measurements of the water balance. During the International Hydrological Decade (1965–1974), the water agencies of many countries initiated water-balance studies in their main climatic regions, and a great deal of useful information was generated by these studies. In urbanized regions, the method can be extended to incorporate processes such as pumping and artificial recharge of groundwater and many other factors. Franke and McClymonds (1972), for example, present an analysis of the effects of urbanization on the water budget of Long Island.

Calculation of the Water Balance

A method for calculating the water balance was introduced by Thornthwaite in the early 1940's. It has been used for a great variety of purposes and has been modified many times. We will describe Thornthwaite's original method, as outlined in a very useful handbook by Thornthwaite and Mather (1957). We suggest that the reader who wishes to use the water balance extensively obtain this valuable publication. In the following discussion we suggest modifications of the basic technique that may be necessary or prudent under some circumstances.

The method is best explained by means of a worked example. The area under discussion is Kericho in the highlands of western Kenya. The problem may be phrased as follows. The area is relatively dry from December through February but especially wet in April and May. What is the magnitude of the evapotranspiration demand that is not satisfied by rainfall during the dry part of the year? When would one expect runoff derived from the excess of moisture over the demand of evapotranspiration, and what is the magnitude of this excess, if any exists? The results are summarized in Figure 8-2 and Table 8-1.

Monthly *precipitation* values for Kericho are listed in row 1 of the table. The next row contains values of *potential evapotranspiration,* calculated by the Penman method, though any other method, including pan evaporation data, could be used where appropriate. In row 3 the differences between precipitation and potential evapotranspiration define two seasons: a 9-month wet season when rainfall exceeds evapotranspiration and a 3-month dry season when the meteorologic demand is not satisfied by precipitation that has fallen in the same month. The severity of the dry season increases during the sequence of months with excessive potential evapotranspiration, and this is expressed in row 4 as the *accumulated potential water loss,* which is the cumulation of negative values of ($P - PET$) for the dry season only. The summation begins at the end of the wet season.

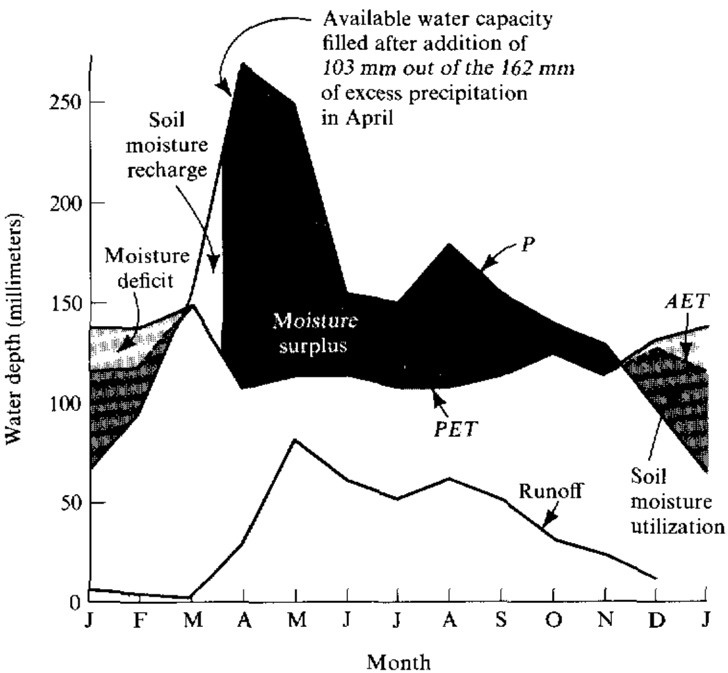


Figure 8-2 Results of the monthly water balance calculation for a catchment with a clay loam soil under woodland at Kericho, Kenya. Available water capacity of the root zone is 200 mm.

Table 8-1 Long-term average monthly water balance at Kericho, Kenya, for a soil with an available water capacity of 200 mm. The soil is a clay-loam under brushy regenerating woodland with a rooting depth of 0.80 m. All values in the table are in millimeters.

(MM)	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.	YEAR
1. P^*	65	95	155	270	250	155	150	180	155	140	130	95	1840
2. PET	138	138	150	108	114	114	108	108	114	126	114	132	1464
3. $P - PET$	−73	−43	5	162	136	41	42	72	41	14	16	−37	376
4. $Acc\ Pot\ WL$	−110	−153										−37	
5. SM	115	92	97	200	200	200	200	200	200	200	200	166	
6. ΔSM	−51	−23	+5	+103	0	0	0	0	0	0	0	−34	
7. AET	116	118	150	108	114	114	108	108	114	126	114	129	1419
8. D	22	20	0	0	0	0	0	0	0	0	0	3	45
9. S	0	0	0	59	136	41	42	72	41	14	16	0	421
10. Total avail. for runoff	13	7	3	59	165	124	104	124	103	65	49	25	
11. RO	6	4	2	30	82	62	52	62	52	32	24	12	420
12. Detention	7	3	1	29	83	62	52	62	51	33	25	13	

*P = precipitation; PET = potential evapotranspiration; $P - PET$ is difference by subtraction; $Acc\ Pot\ WL$ = accumulated potential water loss derived by accumulating negative values in row 3; SM = soil moisture; ΔSM = change in soil moisture during the month; AET = actual evapotranspiration; D = soil moisture deficit; S = soil moisture surplus; RO = runoff.

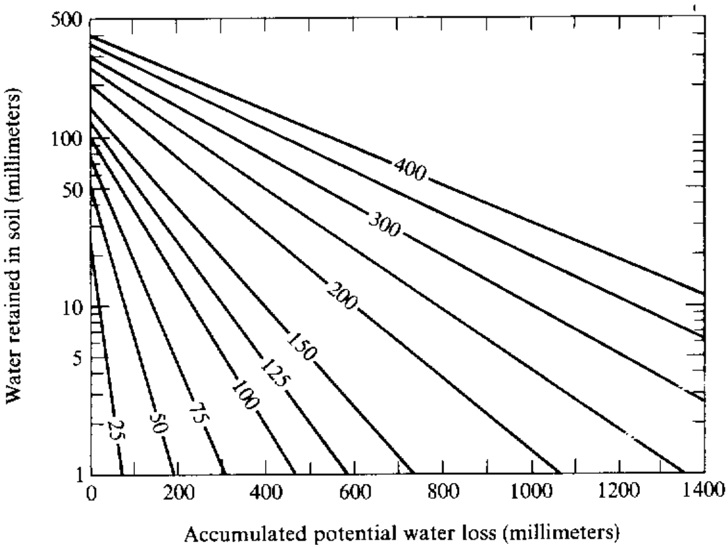


Figure 8-3 Water retained in the soil against an accumulated potential water loss. The number on each curve is the available water capacity for the soil in millimeters. (Data from Thornthwaite and Mather 1957.)

The difference between P and PET will be at least partly made up by the withdrawal of soil water. In Chapter 5, however, we described how evapotranspiration falls below the potential rate as the soil dries, and here it is necessary to choose which functional relationship to use in Equation 5-13. The earlier discussion of this subject will help the user with his choice. We have decided to use the method given in the original instruction manual by Thornthwaite and Mather. Their tabulated information is summarized in Figure 8-3, which shows how much water will be retained in the soil after various amounts of accumulated potential water loss. The lines represent soils with different available water capacities, which in turn depend upon the texture of the soil and the rooting depth of the vegetation. The available water capacity can be measured, or it can be estimated from Figure 6-9 or Table 8-2. In humid regions, however, the rooting range of crops can be much less than those indicated in the table, and therefore field observations are preferable. The table tells us that the available water capacity of a clay loam is approximately 25 percent (250 mm of water per m depth of soil). The depth of root penetration under the brushy regenerating woodland that we observed in the field was 0.80 m, indicating that the root zone could hold (0.80 m $\times$ 250 mm/m =) 200 mm of water at field capacity.

Using Figure 8-3, we find that if a soil with an available water capacity of 200 mm is subjected to a potential water loss of 37 mm, the amount of water that will be retained by the soil is 166 mm. This value of *soil moisture* is entered for December in the fifth row of Table 8-1, and the process is repeated for the other dry-season months. Soil moisture values for the wet

Table 8-2 Suggested available water capacities for combinations of soil texture and vegetation. (From Thornthwaite and Mather 1957.)

VEGETATION	SOIL TEXTURE	AVAILABLE WATER CAPACITY (% VOLUME)	ROOTING DEPTH (M)*	AVAIL. WATER CAP. OF ROOT ZONE (MM)
Shallow rooted crops (spinach, peas, beans beets, carrots, etc.)	Fine sand	10	0.50	50
	Fine sandy loam	15	0.50	75
	Silt loam	20	0.62	125
	Clay loam	25	0.40	100
	Clay	30	0.25	75
Moderately deep rooted crops (corn, cereals, cotton, tobacco)	Fine sand	10	0.75	75
	Fine sandy loam	15	1.00	150
	Silt loam	20	1.00	200
	Clay loam	25	0.80	200
	Clay	30	0.50	150
Deep rooted crops (alfalfa, pasture grass, shrubs)	Fine sand	10	1.00	100
	Fine sandy loam	15	1.00	150
	Silt loam	20	1.25	250
	Clay loam	25	1.00	250
	Clay	30	0.67	200
Orchards	Fine sand	10	1.50	150
	Fine sandy loam	15	1.67	250
	Silt loam	20	1.50	300
	Clay loam	25	1.00	250
	Clay	30	0.67	200
Mature forest	Fine sand	10	2.50	250
	Fine sandy loam	15	2.00	300
	Silt loam	20	2.00	400
	Clay loam	25	1.60	400
	Clay	30	1.17	350

*In some places where we have worked, the rooting depths given by Thornthwaite and Mather are too high. Field observations in the area for which the water balance is being computed are preferable to the use of this table.

season are obtained by adding the excess precipitation from row 3 to the soil moisture level at the end of the dry season. Thus, the 5-mm excess occurring in March will raise the soil moisture storage from 92 mm at the end of February to 97 mm at the end of March. In April 162 mm will be added to the 97 mm. Because the soil can only hold 200 mm of water, however, soil moisture values cannot exceed this value, and so for April and succeeding wet months the moisture content remains at field capacity. Surplus water which cannot be held in the soil by capillary and osmotic forces drains out of the root zone. This subject will be dealt with later.

From row 5 the *change in soil moisture* can be entered in row 6. When precipitation exceeds potential evapotranspiration, the *actual evapotranspiration* in row 7 equals the potential rate because the rainwater is considered to be easily available to the plant, even if the soil moisture of the whole root zone is not raised to the available water capacity. When the meteorologic demand must be partially satisfied from the stored soil water, actual evapotranspiration is the sum of precipitation and the amount of soil moisture withdrawn from storage (95 + 34 =) 129 mm in the case of December.

The amount by which the actual and potential evapotranspiration differ in any month is called the *soil moisture deficit*, and is listed in row 8. In this case, because the available water capacity is high and the dry season is short, evapotranspiration continues almost at the potential rate throughout the year.

Once a moisture deficit has developed, it can be reduced when excess precipitation is stored in the soil at the beginning of the wet season. The soil moisture will eventually attain field capacity, however, and further precipitation excess must leave the soil by gravitational drainage. The amount of water that cannot be stored (the excess from line 5) is termed the *moisture surplus* and is listed in row 9.

The moisture surplus drains to the groundwater body and eventually to streams. It cannot all drain out in the same month that it is generated, however, and a certain proportion remains in the soil and is carried over into later months. The fraction which will leave a river basin as *runoff* varies with the depth and texture of the soil and the physiography of the basin. Ideally this proportion should be evaluated for the region of application. It can be obtained by direct field measurement of the water balance for a few months of the wet season. A less exact estimate can be made by examining the relative amounts of streamflow during successive wet months. In some cases the use of widely differing proportions does not lead to very different answers, so there is not much reason to refine the estimate. For some applications of the water balance, however, such refinements are necessary. Thornthwaite and Mather give only the following advice: For large catchments approximately 50 percent of the surplus water that is available for runoff in any month actually runs off. The rest of the surplus is detained in the subsoil, groundwater, small lakes, and channels of the basin and is available for runoff during the next month. If the water balance is calculated for periods shorter than one month, or for catchments of only a few square kilometers, the proportion detained will often be less than 50 percent. In Table 8-1, however, we have used the 50 percent figure.

Beginning in April, 59 mm of moisture surplus were available and therefore 30 mm should run off. Twenty-nine millimeters will be detained in the catchment to be added to the moisture surplus of May for a total of 165 mm. Therefore, 82 mm of water will run off during May, and 83 mm will be detained until June. Repetition of this calculation completes rows 10, 11, and 12.

The results of this set of calculations are portrayed in Figure 8-2, which summarizes a great deal of information on the hydrology of Kericho. Besides showing the seasonal pattern of precipitation, evapotranspiration, and runoff, it indicates the times of moisture deficit, soil moisture recharge, and moisture surplus. The moisture deficit indicates that the plants are under some stress, and if the cover were a valuable crop, the calculations would indicate the timing and magnitude of irrigation necessary to remove the stress. The water balance is therefore valuable for understanding the ecology, agronomy, and economics of growing crops.

Figure 8-1 indicates a component of the water balance that is ignored in the Thornthwaite method, namely, storm runoff. In the region for which we have made the calculation, this problem is not an important one; storm runoff amounts to 3 to 5 percent of rainfall, and this abstraction is not sufficient to lower the evapotranspiration much below the potential rate. In other regions or other vegetation covers, however, the stormflow component is important. To take this into account, an additional step in the calculation should be added between rows 1 and 2 in the tables, in which storm runoff is subtracted from precipitation. Estimation of the volume of stormflow can be based on the infiltration capacity of the soil, or on the Soil Conservation Service method described in Chapter 10. This requires rainfall data from individual storms, but unfortunately, such data are often not available. If a few continuous streamflow records are available for small catchments in the region, monthly storm runoff can be separated from the hydrographs, as described in Chapter 10, and expressed as a fraction of the rainfall for each month. This method provides a rough idea of how much rainfall should bypass the calculation of the soil-water balance and be treated immediately as runoff.

Another modification is necessary if the climate of a place is so dry that the soil never reaches field capacity, that is, if the available water capacity of the root zone is never filled. Under these conditions it is not obvious when the accumulation of potential water loss in row 4 should begin. Instead, the user must find a value of the potential water loss for the beginning of the first month when the precipitation falls below the rate of potential evapotranspiration (June in Table 8-3). This is done by successive approximations as follows.

The accumulated potential water loss is estimated for the first month with a negative value of $(P - PET)$ that is, for the beginning of the dry season. We first sum the negative values of $(P - PET)$ for the dry season; in Table

Table 8-3 Long-term average monthly water balance calculation for Nairobi, Kenya. The soil is a fine sandy loam, and the vegetation is woodland with a rooting depth of 1.33 m. AWC = 200 mm.

(MM)	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.	YEAR
1. P	59	51	126	219	160	51	21	23	29	57	143	91	1030
2. PET	140	140	116	120	100	99	96	90	118	88	145	126	1378
3. $P - PET$	−81	−89	10	99	60	−48	−75	−67	−89	−31	−2	−35	−348
4. $Acc\ Pot\ WL$	−446	−535			(−18)	−66	−141	−208	−297	−328	−330	−365	
5. SM	21	13	23	122	182	143	98	70	44	38	38	32	
6. ΔSM	−11	−8	+10	+99	+60	−39	−45	−28	−26	−6	0	−6	
7. AET	70	59	116	120	100	90	66	51	55	63	143	97	1030
8. D	70	81	0	0	0	9	30	39	61	25	2	29	348
9. S	0	0	0	0	0	0	0	0	0	0	0	0	0
10. RO	0	0	0	0	0	0	0	0	0	0	0	0	0

8-3 this total is −517 mm. Using Figure 8-3 with an available water capacity of 200 mm, we find the value of soil moisture that would be retained against this accumulated potential water loss by the end of the dry season. The value read from the ordinate of the figure is 15 mm, which is the moisture that would remain in storage at the end of the dry season if the soil had contained 200 mm of available water at the beginning of the dry period. The true value was less than 200 mm.

If we then add the sum of the positive $(P - PET)$ values to the 15 mm, we obtain a soil moisture value of $(15 + 169 =)$ 184 mm at the end of the wet season. Figure 8-3 indicates that the accumulated potential water loss up to the end of the wet season that would be necessary to result in a soil moisture storage of 184 mm is 16 mm. If the total negative $(P - PET)$ value for the dry season is then added to this value, we would have an accumulated potential water loss of $(16 + 517 =)$ 533 mm at the end of the dry period. Entering Figure 8-3 again gives us a value of 14 mm for the soil moisture value at the end of the dry season, and if the total positive $(P - PET)$ values are added, we estimate that the soil moisture would be 183 mm at the end of the wet season, which would be in equilibrium with an accumulated potential water loss (from Figure 8-3) of 17 mm. The negative $(P - PET)$ values are again added to this value, and the soil moisture retention at the end of the dry season is found to be 13 mm. Addition of the positive values gives a value of 182 mm at the end of the wet season, which would require an accumulated potential water loss of 18 mm up to that time. Therefore by the end of the dry season the accumulated potential loss would be 533 mm and the soil moisture retention would be 13 mm, the same as it was at the last estimate. Repetition will not change the figures, and we have determined that the correct value of the accumulated potential water loss at the end of the last month of the wet season is 18 mm. This value is entered in row 4 for May, the last month with a positive value of $(P - PET)$. From this point on the water balance calculation proceeds normally. The results are shown in Figure 8-4.

The Nairobi water-balance calculation indicates large moisture deficits and no runoff. When rainfall exceeds evapotranspiration, the excess simply recharges the soil moisture but does not exceed the field capacity so that no moisture surplus or runoff is generated. This does not mean that there is no streamflow around Nairobi. First of all, stormflow occurs. We have not included it in the computations because techniques for assessing the volume of storm runoff will not be introduced until Chapter 10. Under woodland in the Nairobi region, however, this component accounts for 10 to 15 percent of the rainfall, generating some streamflow but increasing the moisture deficit. A second source of runoff in the region is groundwater that migrates through lava beds from higher, wetter regions to the west. This should remind the planner that the hydrogeological conditions of an area should be examined before the local water balance is blindly used to predict runoff.

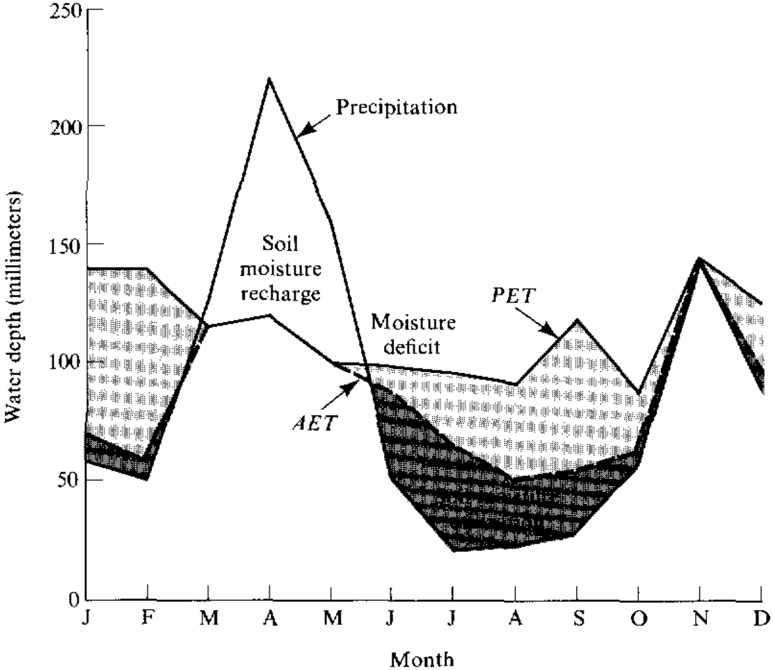


Figure 8-4 Results of a monthly water balance calculation for woodland on a fine sandy loam soil at Nairobi, Kenya.

Finally, water balance calculations are usually made on long-term average climatic data in order to obtain a rough picture of the seasonal march of rainfall, evapotranspiration, soil moisture, irrigation need, and runoff. Long-term averages tend to underestimate extreme deficits and surpluses. In a wetter-than-average year, a moisture surplus is often developed around Nairobi and the groundwater receives some recharge. Even during an average year an increase in the wet-season rainfall can generate a moisture surplus at the expense of soil moisture storage during the dry season. In order to examine the probability of runoff generation and also the probability of various degrees of moisture deficit, a meteorological record of many years can be processed in sequence. Moisture deficits or surpluses developed in one year are simply carried forward into the next. The accumulation of potential water loss is initiated after some period when runoff is known to have occurred. The resulting long-term water balance can then be examined statistically, by counting the frequency of moisture deficits, moisture surpluses, or runoff greater than various levels. An example is shown in Figure 8-5. Such statistical statements are valuable for calculating the chances of irrigation demand or of crop failure. The methodology is discussed by Van Bavel (1953).

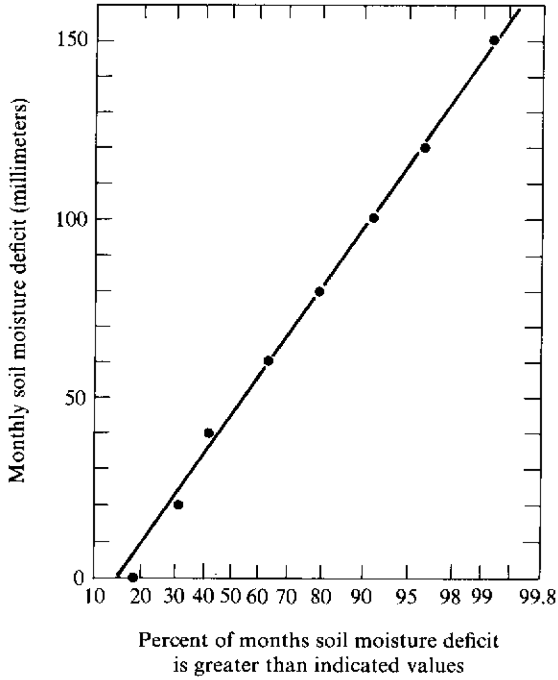


Figure 8-5 Results of statistical analysis of the water balance at Nairobi. The graph shows the frequency of soil moisture deficits for the period 1931–1940. Other results of the water balance calculations can be analyzed in the same way and are useful in agricultural planning.

The water balance can be refined in several other ways. The computations can be made on a daily basis to obtain better definition of short-term moisture deficit or surplus. Daily computations are particularly useful if deficit and surplus occur in the same month. These and other modifications to be made at stations with two dry seasons or a snowmelt input are described in the instruction manual of Thornthwaite and Mather, although their method of calculating snowmelt can be improved upon with the material in Chapter 13.

Applications

The most obvious use of the water balance is in a basic description of the hydrology of a place or region. Maps can be drawn of the annual extreme water deficit or surplus or of the total annual irrigation need or groundwater runoff. Spatial patterns within a region or a large river basin can be employed in planning the distribution of resources. Al-Khashab (1958) was

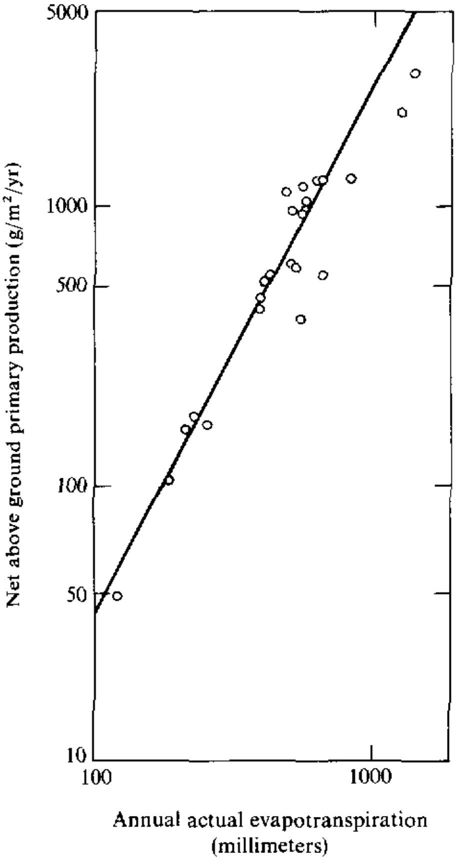


Figure 8-6 Relationship between net above ground primary productivity and actual evapotranspiration. (From M. L. Rosenswieg 1968, *American Naturalist,* published by the University of Chicago. Copyright © 1968.)

able to use the water balance to define the seasonal and geographical pattern of water supply and irrigation demand at an early stage in the planning for the development of the water resources of the 785,000-square-kilometer Tigris–Euphrates Basin in Iraq.

Actual evapotranspiration calculated from the water balance is correlated with primary productivity of vegetation and so with the value of rangeland or cropland (see Figure 8-6). Knowledge of the probable moisture deficit is useful for planning irrigation schemes and for predicting crop yields on lands that are not irrigated (Palmer 1964). Statistical maps of moisture deficit can be developed to indicate drought probabilities based on how much water is held in the soil rather than on the rainfall total. If, for example, a critical soil moisture deficit of 100 mm for two consecutive months in early summer is known to cause a catastrophic crop failure in a particular soil, then the long-term water balance can be examined and the frequency of years in which such a deficit occurred in that soil can be counted. These figures allow the construction of contour maps of the frequency of drought hazard. Such maps assist the rural planner in determining the economic viability of introducing new cash crops in a region, and the value of crops to be expected.

The calculated moisture surplus is also a useful planning tool for indicating regions and frequencies of useful runoff. A large moisture surplus may indicate conditions too wet for some crops that are susceptible to disease. Moisture surplus is also an index of the intensity with which plant nutrients are leached from the soil by excess precipitation. Nutrient-deficient, acid soils are often found in regions of high surplus, and fertilizers and liming are necessary but are leached relatively quickly in such areas. For other purposes the moisture surplus can be incorporated into a simple accounting technique for predicting the level of the water table (Boersma 1967).

It is clear then that the water balance is a valuable planning tool, one that deserves further application and refinement.

Bibliography

AHLGREN, L., BASSO, E. AND JOVEL, R. (1969) Preliminary evaluation of the water balance in the Central American isthmus; *Proceedings of Symposium on the Water Balance in North America*, American Water Resources Association, pp. 288–298.

AL-KHASHAB, W. H. (1958) The water budget of the Tigris and Euphrates basin; *University of Chicago, Department of Geography Research Paper 54.*

BOERSMA, L. (1967) Water-table fluctuation in the soil series of the Willamette catena; *American Society of Agricultural Engineers, Transactions*, vol. 10, pp. 405–406, 510.

DUNIN, F. X. AND COSTIN, A. B. (1970) Analytical procedures for evaluating the infiltration and evapotranspiration terms of the water balance equation; *International Association of Scientific Hydrology, Symposium of Wellington, Publication No. 96*, pp. 39–55.

EAAFRO (1962) Hydrological effects of changes in land use in some East African catchment areas; *East African Agricultural and Forestry Journal*, vol. 27, pp. 1–131.

FRANKE, O. L. AND MCCLYMONDS, N. E. (1972) Summary of the hydrologic situation on Long Island, New York, as a guide to water management alternatives; *U.S. Geological Survey Professional Paper 627-F.*

HURSH, C. R. AND PEREIRA, H. C. (1953) Field moisture balance in the Shimba hills, Kenya; *East African Agriculture and Forestry Journal*, vol. 18, pp. 139–145.

LEWIS, D. C. AND BURGY, R. H. (1964) Hydrologic balance from an experimental watershed; *Journal of Hydrology*, vol. 2, pp. 197–212.

LIGON, J. T., BENOIT, G. R. AND ELAM, A. B. (1965) Procedure for estimating occurrence of soil moisture deficiency and excess; *American Society of Agricultural Engineers, Transactions*, vol. 8, pp. 219–222.

PALMER, W. C. (1964) Climatic variability and crop production; in *Weather and our food supply*, Centre for Agricultural and Economic Development, Iowa State University, Ames, IA.

PALMER, W. C. (1964) Meteorological drought; *U.S. Weather Bureau Research Paper 45.*

ROSENSWEIG, M. L. (1968) Net primary production of terrestrial communities: predictions from climatological data; *American Naturalist*, vol. 112, pp. 67–74.

THORNTHWAITE, C. W. AND MATHER, J. R. (1955) The water balance; *Laboratory of Climatology, Publication No. 8,* Centerton, NJ.

THORNTHWAITE, C. W. AND MATHER, J. R. (1957) Instructions and tables for computing potential evapotranspiration and the water balance; *Laboratory of Climatology, Publication No. 10,* Centerton, NJ.

VAN BAVEL, C. H. M. (1953) A drought criterion and its application in evaluating drought incidence and hazard; *Agronomy Journal,* vol. 45, pp. 167–172.

WARD, R. C. (1972) Checks on the water balance of a small catchment; *Nordic Hydrology,* vol. 3, pp. 44–63.

ZAHNER, R. (1967) Refinement in empirical functions for realistic soil moisture regimes under forest cover; in *Forest hydrology* (eds. W. E. Sopper and H. W. Lull), Pergamon Press, Oxford, pp. 261–274.

Typical Problems

8-1 Calculation of Monthly Runoff

Repeat the water-balance calculation of monthly runoff for Kericho, illustrated in the text, but assume that 80 percent of the surplus water available for runoff in any month runs off. This requires altering only the last three lines of Table 8-1. Plot your monthly runoff values on a tracing of the runoff curve from Figure 8-2, and describe the kinds of drainage basins to which the two calculations might apply. Suggest an application of the water balance for which the difference would be important and another application for which it would be unimportant.

8-2 Effect of Available Water Capacity on the Water Balance

From your local library, water resources agency, or atlas, obtain monthly values of precipitation and potential evapotranspiration.

1. Go out and look at a woodland near your home and measure (in a road cut) the average depth of the root zone, and note the soil texture. Estimate the available water capacity of the root zone from the local soil survey report or from Figure 6-9. Assume that the storm runoff is negligible.

2. Calculate the water balance of a small catchment underlain entirely by the single soil–vegetation complex and by impervious bedrock, so that all the soil moisture surplus leaves the basin as runoff.

Repeat the calculation for a grass cover whose potential evapotranspiration is equal to that of the forest, but whose root zone is only one-half as deep. Assume that storm runoff from the grass amounts to a constant ten percent of each month's runoff. Note that each of these approximations could easily be refined.

3. Plot an annual graph of moisture deficit, moisture surplus, and runoff for each cover type, and write a short essay interpreting your calculations.

8-3 Modification of Weather and Vegetation Cover

Advocates of particular technologies frequently make proposals for manipulating land and water resources. These proposals must be carefully reviewed before committing scarce resources or before raising hopes about quick solutions to land development problems.

Imagine an almost uninhabited 50-square-kilometer drainage basin covered with savanna woodland on a sandy loam soil having 200 mm of soil-moisture storage capacity in the root zone. A proposal is made to increase soil moisture levels (i.e., decrease soil moisture deficits) and increase runoff by a combination of weather modification and vegetation change. Bush clearance would allow the growth of grass for stock rearing or the cultivation of subsistence cash crops. The increased supply of precipitation should assist these developments by reducing soil moisture deficits. The increased runoff could be used for irrigation of crops along the floor of the main valley or for water spreading to improve pasture.

The proposal is one of those "very preliminary" ones that agencies frequently become committed to before they really know what is involved. This is particularly common if the funds for the weather modification are to be supplied for several years by another organization.

As a planner, you are asked to evaluate the feasibility and wisdom of the proposal. You decide to begin by making some hydrologic calculations of the degree to which soil moisture deficits would be changed and runoff increased. A survey of the literature in a variety of fields indicates that the following data are relevant for the region under study:

1. Weather modification can increase rainfall by perhaps 10 percent when atmospheric conditions are favorable during the 6-month wet season.

2. Changing the woodland to grassland would decrease the moisture storage capacity of the topsoil from 200 mm to 75 mm, because the root zone would be shallower. Under maize, the most likely crop, the soil moisture storage capacity would be 150 mm.

3. Under savanna woodland roughly 20 percent of the rainfall runs off as stormflow. This would be increased to about 30 percent with a grass cover and to 25 percent under maize.

4. Fifty percent of the land is cultivable, and 65 percent could be used for grazing.

5. Monthly rainfall values are published, and you are able to calculate potential evapotranspiration from evaporation pan data. The data are tabulated in Table 8-4.

Compute water balances for: (a) savanna woodland at present; (b) savanna woodland with weather modification; (c) grassland with weather modification; and (d) maize with weather modification. Plot annual graphs of your results. Summarize the effect of each scheme on the maximum soil moisture deficit.

Predict the mean monthly discharge of the main stream of the basin in m^3/sec if: (a) 65 percent of the basin is converted to grassland, the remainder being left in woodland; and (b) 50 percent of the basin is planted to maize, with woodland on the other half.

After making the hydrologic calculations,

Table 8-4 Precipitation and potential evapotranspiration values for a proposed region.

	JAN.	FEB.	MAR.	APR.	MAY	JUNE
P (mm)	52	34	17	19	38	37
PET (mm)	115	117	131	145	86	97

	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
P (mm)	165	175	165	155	85	135
PET (mm)	87	62	52	43	41	78

review all the other aspects of such a project that you can think of. List the kinds of information you would need to continue the review. This part of the problem may best be treated in a discussion by an interdisciplinary class with each person being assigned a particular aspect of the proposal to review. The problem could also be repeated with a different set of meteorologic data, and the results compared and interpreted in a class discussion.

Solution

For the savanna woodland under present weather conditions, storm runoff is first subtracted from the rainfall because it does not enter the soil moisture budget. The stormflow is added into the runoff total later in the computation. The net amount of infiltration should be entered as a second line in the water budget table. The third line includes the calculated potential evapotranspiration. On line 4 the difference between the water entering the soil and the potential evapotranspiration is entered. The total potential demand of evapotranspiration exceeds the amount of water entering the soil, and the soil moisture content does not reach field capacity. The successive approximation method must be used to find an accumulated potential water deficiency from which to start cumulating negative values of $(P - SRO - PET)$. The method, described in detail in the text, should lead the reader to find an accumulated potential water loss of about 77 mm for November, the last month of the wet season (i.e., the last month with a positive value of $(P - SRO - PET)$.

The calculation then proceeds as described in the text.

8-4 Water Balance for Various Soil Types

Using the data on precipitation and potential evapotranspiration from Table 8-1, calculate the water balance for a loam with an available water capacity of 150 mm. Instead of using the Thornthwaite and Mather curves from Figure 8-3, obtain the actual evapotranspiration rate by the method shown in Figure 5-8. Assume that storm runoff is negligible.

Solution

During months of excess rainfall, evapotranspiration occurs at the potential rate. When potential evapotranspiration exceeds precipitation, the rainwater is evaporated at the potential rate and the deficit is exerted as a demand upon soil moisture. As explained in Chapter 5, this demand is not exerted at the potential rate but at a rate that depends on the amount of soil moisture in storage. At the beginning of each month therefore the ratio of available water content (AW) to available water capacity (AWC) must be calculated and used to modulate the potential evapotranspiration that is unsatisfied by rainfall. Note that in Table 8-5 values of soil moisture content (SM) refer to the amount of water held at a level above the permanent wilting point, and thus SM is also the numerator AW on line 5 of the table.

Line 3 in Table 8-5 lists the unsatisfied transpirative demand as a negative value. At the end of the wet season (beginning of December) the soil moisture is at field capacity, the ratio AW/AWC is one, and evapotranspiration, occurring at the potential rate, withdraws 37 mm of water from the soil during December. This value is listed as the change of soil moisture for December on line 6. Actual evapotranspiration on line 7 is the sum of precipitation and the change of soil moisture.

The change of soil moisture for December yields the soil moisture content at the end of that month that will control the ratio AET/PET for January. In January the unsatisfied transpirative demand is 73 mm, and since the ratio AW/AWC is 0.75, Figure 5-8 indicates that evapotranspiration will continue at the potential rate. The change of soil moisture, therefore, is 73 mm.

By February 1, the soil moisture content will have declined to 40 mm, and the ratio AW/AWC to 0.27. After the month's precipitation has been evaporated, therefore, the ratio AET/PET will decline to 0.27 according to Figure 5-8, and the

Table 8-5 Calculating water balance for loam.

	JAN.	FEB.	MAR.	APR.	MAY	JUNE
P	65	95	155	270	250	155
PET	138	138	150	108	114	114
$P - PET$	−73	−43	5	162	136	41
SM	113	40	28	33	150	150
AW/AWC	0.75	0.27				
ΔSM	−73	−12	+5	+145	0	0
AET	138	107	150	108	114	114
D	37	110	122	127	0	0
S	0	0	0	17	136	41
	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
P	150	180	155	140	130	95
PET	108	108	114	126	114	132
$P - PET$	42	72	41	14	16	−37
SM	150	150	150	150	150	150
AW/AWC						1.0
ΔSM	0	0	0	0	0	−37
AET	108	108	114	126	114	132
D	0	0	0	0	0	0
S	42	72	41	14	16	0

decline of soil moisture will be (0.27 × 43 =) 12 mm. Actual evapotranspiration ($P + \Delta SM$) will be 107 mm. From March onward, precipitation exceeds the PET demand, evapotranspiration occurs at the potential rate and the calculation proceeds as indicated in Table 8-1.

The reader can obtain further understanding and practice by repeating this water balance calculation for the other soil types shown in Figure 5-8, and by using a set of data from some other area of interest.