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INTERNAL REPORT 2

MODELING THE HYDROLOGICAL ASPECTS OF THE FERN LAKE WATERSHED

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ABSTRACT

Data collected from the Fern Lake watershed between 1958 and 1971 include measurements of the rate of flow of water into the lake through a single inlet stream. The objective of the work presented here is to develop a model of this flow using the climatological data available from the watershed. Measurements of air temperature, wind movement, air pressure, relative humidity, insolation, and precipitation were used to estimate the potential evapotranspiration through the use of the Penman equation (Penman 1948). A model based on relationships found in the published literature and some empirical relationships was developed to simulate the dynamics of the soil water. This submodel was incorporated into the larger model to link the climatological input variables to streamflow. Output from the computer program developed for the model includes soil water content, underground flow, evaporation, transpiration, and streamflow. In its tentative form, the model is sufficiently realistic to be used for further modeling of the dynamics of other aspects of the watershed involving water flow.

INTRODUCTION

The Fern Lake watershed is situated at the southern end of the Kitsap Peninsula in Washington State (Figure 1). Geologically the watershed is a ground moraine, the soils being very porous (50% gravel, 30% sand, 15% silt, and 5% clay, Olsen and Olson 1966). These soils cover to a depth of about 1 meter an underlying basal fill that is impervious to water and root penetration (Stephens 1959). As indicated in Figure 2, the lake itself comprises about 1.23% (9.65 ha) of the area of the watershed (7.87 km^2), which drains into the lake by way of the inlet creek. Figure 3 shows the lake, the location of the inlet stream and the positions of the data recording and measuring instruments.

Since 1958, through support from the Atomic Energy Commission, the University of Washington College of Fisheries, Laboratory of Radiation Ecology, in cooperation with the Washington State Department of Game, has carried out extensive ecological studies within the Fern Lake watershed. In 1969 the watershed was chosen as a site for continued work within the framework of the International Biological Program. This work was to involve mathematical modeling and to be considered as a type of pilot project in ecosystem modeling for the Coniferous Forest Biome. The work was to be oriented toward the use of the existing data collected during the past decade in the development of a simulation model involving the lake in its setting within the watershed. Initial efforts have been directed toward the simulation of the physical properties of the system, to be used later as dynamic input into the lake model complete with its biological components. The modeling work that forms the basis for this paper has been restricted to the period beginning on 1 January 1965 and ending on 31 December 1965. Other time periods for which there are data available for the same type of simulation work will be used for the purpose of validation.

CLIMATOLOGICAL AND STREAMFLOW DATA

Climatological data that have been collected for the Fern Lake watershed include measurements of wind speed, air temperature, air pressure, relative humidity, insolation, and precipitation. Air movement was recorded with a Green 323-E anemometer located at the field station headquarters. Data from the charts were transcribed, put on punch cards, and summarized for the year 1965. Figure 3-A shows weekly means of total daily air movement across the Fern Lake watershed as measured in kilometers for the same year. Wind data prior to 1971 are available for the period beginning September 1962 and ending August 1966.

Air temperatures were recorded with a Honeywell combination hair hygrometer-thermometer also located at the station headquarters. Means for eight-day periods were derived from the hydrothermograph charts by planimeter readings. These data, with the dates corresponding to the first day of each period, were used to produce the weekly means plotted for 1965 in Figure 3-B. Similar data are available for the period of October 1957 to the present.

Relative humidity has been measured and recorded for the Fern Lake area from 1952 to the present through the use of the Honeywell combination hygrometer-thermometer. Means were determined for weekly periods for 1965 and are shown in Figure 3-C.

Measurements of the air pressure were made on a Belfort recording barometer and are available from 1963 to the present. This instrument was located at the field station headquarters. Planimeter readings of the charts were made for 1965 approximately on a weekly basis. These data have been summarized and are shown in Figure 3-D where the average air pressure in millimeters of mercury is plotted for each week.

A Belfort pyrheliometer located at the end of a dock located near the field station headquarters was used to measure incoming solar energy to the Fern Lake watershed. Charts from this instrument were read with a planimeter for the year 1965. Charts are available from 1959 to present. The 1965 data are shown in Figure 3-E as the average number of langleys per day by weekly time period.

Precipitation falling on the Fern Lake watershed has been monitored for a period beginning in late 1957 and continuing to the present. Several measurement instruments have been used in combination or singly throughout this period. Table 1 shows the location and dates of each rain gage as well as the type of rain gage used. Figure 3-E shows the total weekly precipitation for 1965 as determined from the data available for the year.

Finally, a weir installed in the inlet stream just above the lake has been used to measure the rate of inlet flow from 1961 to the present. The head of water behind this weir was recorded on a Stevens type A-35 continuous water level recorder. Swank (1972) developed a conversion formula that converts the water head to flow rate as influenced by time, temperature, and weir characteristics. A computer program was written to convert the raw data (water head) to dated daily flow volume. These data were then totaled by weeks for 1965. Fiugre 3-G shows the streamflow pattern for 1965 as expressed in equivalent precipitation on the watershed. In other words, the values on the ordinate of Figure 3-F are equivalent to the depth to which the volume of flow for that week would cover the watershed.

In each case, the data described above were characterized by periods in which data were missing. In these cases it was necessary to determine a realistic value to be used for the purposes of modeling. Where data were available on a daily basis (as in the case of insolation) and only a few days (fewer than seven)were missing from any weekly period, the mean for that week was based on the data from those days for which there were data available. In other cases where existing data are representative of a longer period (such as in the case of precipitation and temperature), means taken from the same time period over several years were substituted.

DEVELOPING THE MODEL

In modeling an ecosystem (or portion of an ecosystem) salient processes must be chosen, but not isolated, from the system. These processes must be characterized by being members of a relatively small set of processes that exert a great influence over the behavior of the total ecosystem. Modeling must then proceed to account for the dynamics of these processes and, as the modeling progresses, the influence of other processes may be included to gain further realism and precision. The first aspect of the Fern Lake system chosen for such consideration was the hydrological component of the ecosystem. Water and its influence on the ecosystem probably may be rated with energy in importance. Hence the first modeling effort in the Fern Lake system was directed at simulating the streamflow based on the climatological data available (Figure 3).

Between the time precipitation falls on the watershed and the time it flows into the lake it will come under the influence of several major factors. The water content of the soil will determine to a great extent the destiny of incoming precipitation. There will be greater amounts of surface runoff when the soil is moist than when dry. The soil water content, in turn, is controlled to a great extent by evapotranspiration. Estimating the potential evapotranspiration for the watershed was the first modeling work to be undertaken in the Fern Lake modeling program.

Penman (1948 and elsewhere) developed an equation for estimating the potential evapotranspiration under specific climatological conditions. Federer (1970) discusses the rationale and development of this and other approaches to the estimation of potential evapotranspiration. Because the Penman equation accounts for more of the variables potentially influential in the processes involved in evaporation and transpiration than do other estimation methods such as the Thornthwait method (Thornthwait and Mather 1957) already applied to the Fern Lake watershed (Swank 1972), and since the necessary data were available, this equation was chosen to be used for the Fern Lake model.

The Penman equation may be expressed as:

$$E_p = \frac{(d/C_p) \quad (R_n - S - M) + ph(q - q_{t^2})}{1 + (dL_v/C_r)} \qquad (1)$$

where

$$h = \frac{K^2 V_2}{[\ln (\frac{Z_z - D}{Z_0}) - Y]^2}$$

Here Ep is the estimated potential evapotranspiration. The remainder of the terms in (1) are defined in Table 2. As this equation was used for the Fern Lake watershed it was assumed that each day of a given week was equivalent to the average day for that week with respect to all of the climatological variables involved. Thus the estimated potential evapotranspiration for one such day was multiplied by seven for an estimate of the total evapotranspiration potential for any given week.

The data presented in Table 3 for air pressure, relative humidity, temperature, wind, and insolation were used as input to a computer programmed version of equation (1), and the estimated weekly potential evapotranspiration values shown in Figure 4 were calculated and presented in the output. The values in

Figure 4, as in the case of streamflow, are expressed in units equivalent to precipitation or the depth of water as spread over the watershed, which is equivalent to the estimated evapotranspiration.

F. R. Stevens has analyzed soil samples taken at various locations within the Fern Lake watershed as part of his graduate work in the College of Forestry at the University of Washington. The limited number of such samples and the time span covered by the study does not permit dêvelopment of the functional relationships mentioned above. The study does, however, present some useful information concerning the soil's field capacity and water content at saturation. Based on this study, it was assumed that the average depth of the soil above the hardpan is 1 m, that the soil has a field capacity of 35%, and that it has a saturation capacity of 60%. Under these assumptions the water content of the soil at field capacity would be equivalent to a layer of water 35 cm in depth spread over the watershed, and at saturation a layer of water 60 cm deep. For purposes of brevity and for utility in modeling, similar units of depth will be used from this point forward in this paper.

Factors that are influential in determining how much of the potential evapotranspiration is actually realized include the soil water content. This, in turn, is a variable influenced by the realized evapotranspiration, precipitation, and subsurface flow. Conceptually, the soil was considered to behave as a container from which water would escape through subsurface flow at a rate that can be expressed as a function of the total water content of the soil. This escape rate, as subsurface flow, would become zero at some minimum soil water content because of the physical adhesion of the water to the soil particles. It was also assumed that the soil has a fixed capacity such that at that capacity any additional precipitation would flow into the stream as surface water runoff.

Using 35 cm as the soil water capacity, then, for soil water content greater than 35 cm it was assumed that underground flow would bring the level back to 35 cm during a week's period. Hence, during any week in which precipitation brings the soil water content to a level greater than 35 cm, the underground flow F is expressed as:

$$F_1 = W_1 - 35 \tag{2}$$

where W_1 is the soil water content in centimeters. For soil water levels between saturation capacity and field capacity it was assumed that only a small portion of the water would leave the soil as subsurface flow. In this case, without the necessary data, it was found that for soil water levels between 20 and 35 cm a realistic portion was 0.005 of that in excess of 20. Hence:

$$F_1 = 0.005\ (W_1 - 20) \tag{3}$$

Below these levels water was assumed no longer to leave the soil as subsurface flow:

$$F_1 = 0 \qquad \text{for} \qquad W_1 < 20 \tag{4}$$

The soil in the Fern Lake watershed is porous, as mentioned above. Hence it was assumed that the surface layers of soil would allow a certain amount of water to penetrate even at or near saturation levels. Again, no data are available to substantiate or measure such a quantity and through the original manipulation of the model it was found that about 5 cm of water in addition to that present at capacity could realistically infiltrate into the soil in one week. Precipitation that reaches the soil in excess of this amount becomes surface runoff.

The amount of precipitation that actually reaches the soil to become part of the soil water is assumed to be that remaining after direct evaporation occurs. The process of evaporation is assumed to occur in the vegetation and litter above the soil and cannot exceed the precipitation that falls in any one week. In other words, the precipitation that falls in a week's period is assumed to be a potential evaporation estimate in that no more than this amount may actually evaporate. That portion of the potential which is actually realized will depend on the potential evapotranspiration and the process of transpiration in the vegetation, which will be considered shortly. The water from the precipitation that actually reaches the soil surface, called surface water here (W_2), is the precipitation less that portion which escapes as vapor:

$$W_2 = P - E_1 \tag{5}$$

The difference between the existing soil water content and that which would occur at saturation plus the transient water admitted because of the porosity of the soil is the amount that can be transferred across the soil surface to become part of the soil water. This will be called the surface deficit D, and we now express the new soil water as:

$$W_3 = \min\ (W_2,\ D) \tag{6}$$

Any surface water in excess of that which may be taken in by the soil flows toward the lake as surface runoff:

$$F_2 = W_2 - W_3 \tag{7}$$

The Fern Lake watershed cannot be treated as a basin with no loss of water due to underground flow. Some water may actually penetrate the hardpan, although it probably would be realistic to assume that no water actually leaves the drainage basin in this manner (Stephens 1959). Water most likely does flow around or under the lake as subsurface flow that is never accounted for in the inlet stream. Once again there are no data available for determining a relationship between the portion of water that is never measured as subsurface flow and other variables such as streamflow or soil water content. In the work presented here it was found that 0.4 of the subsurface flow generated by the model, when added to the streamflow, produced very realistic behavior in all variables involved:

$$F_3 = 0.4\ F_1 \tag{8}$$

As mentioned earlier, the factors that influence the level of water content in the soil include transpiration, which is influenced by the potential evaporation and realized evaporation. Concerning the interaction between evaporation and transpiration, it was assumed that, given an estimated potential transpiration (in the absence of evaporation) and an estimated potential evaporation (in the absence of transpiration), each would be realized in proportion to their relative magnitudes with an upper limit established by the potential evaporation, as estimated by the Penman method, or fraction thereof. As stated above, it was assumed that potential evaporation was equivalent to the precipitation for any one week. Following this the objective was to determine an estimate of potential transpiration.

Denmead and Shaw (1962) discuss the relationship between realized transpiration and soil water content. In general their study indicates, as would be expected, that there is an increase in transpiration with increase in soil water content until some maximum is realized. This maximum is determined by the field capacity of the soil in conjunction with the potential evapotranspiration. The maximum transpiration rate is not realized unless the soil water content is at or above the field capacity. Below field capacity only a certain fraction of the potential evapotranspiration is realized and this fraction decreases with decreasing soil water content. Denmead and Shaw present data taken under three different circumstances indicating this kind of relationship. In an attempt to make the present model general, the assumption was made that a single line could be used to fit these data and in so doing one could estimate the fraction of the estimated potential evapotranspiration at field capacity that may be realized. Thus, using the work presented by Denmead and Shaw and by transforming the relationship to units comparable to those used so far in this modeling work, we derived the following relationship:

$$T_1 = \left\{ \begin{array}{ll} 0 & \text{for } W < 9 \\ \min\,[5/9\ (W_1 - 9),\ 0.9E_p] & \\ & \text{for } W_1 > 9 \end{array} \right\} \qquad (9)$$

Nine cm of water was assumed to remain in the soil at that point when the vegetation is no longer capable of extracting moisture.

As reported by Denmead and Shaw (1962), there is probably only a certain portion of the potential evapotranspiration that may be realized at field capacity. In their case it was reported that the transpiration could be estimated from the equation:

$$Y = 0.13 + 0.73\ X \qquad (10)$$

where Y is the realized transpiration and X the estimated potential evapotranspiration by the Penman equation. For situations where more water may be available for evaporation and more vegetation for transpiration it was assumed that a maximum of 0.9 of the potential as estimated by the Penman equation could be realized.

Now, under the assumptions outlined above, we may express the estimated realized transpiration (T_2) and evaporation (E_2) as:

$$\left.\begin{aligned} T_2 &= T_1 \\ E_2 &= E_1 \end{aligned}\right\} \qquad \text{for } T_1 + E_1 < 0.9E_p$$

$$\left.\begin{aligned} T_2 &= \left(\frac{0.9E_2}{T_1 + E_1}\right) T_1 \\ E_2 &= \left(\frac{0.9E_p}{T_1 + E_1}\right) E_1 \end{aligned}\right\} \qquad \text{for } T_1 + E_1 > 0.9E_p \qquad (11)$$

Now, the soil water content may be calculated each week by subtracting the subsurface flow for that week, subtracting the transpiration for that week, and adding the available precipitation remaining after evaporation has been removed. That is, for week i,

$$W_1(i+1) = W_1(i) - T_2(i) + W_3(i) \qquad (12)$$

It remains only to calculate the streamflow (F_4):

$$F_4 = F_3 + F_2 \qquad (13)$$

The relationships discussed above (1-13) were incorporated into a computer program that used the climatological data (Figure 3) as input. The variables involved were calculated on a week-by-week basis based on the previous week's soil water level and the current week's climatological input. The output generated by the model is shown in Figure 5, which compares the simulated streamflow with the observed streamflow, and Figure 6, which shows the dynamics of the other simulated variables, which have no real observed counterparts with which they could be compared.

It is of interest to note that transpiration is at a minimum late in the summer when the soil water content is also at a minimum. Evaporation is dependent on the precipitation and potential evapotranspiration, being bounded by the latter during the winter and the former during the summer. It is also during summer that the trees and other vegetation must depend most heavily on the incoming precipitation for water necessary for transpiration. Significant runoff occurs only during periods of heavy precipitation. Subsurface flow occurs only when the soil contains sufficient water to allow water to percolate through, or where there is inadequate adhesion due to large quantities of water.

At this point in time the hydrological model is tentative and is undergoing revision. Because of a lack of data concerning some of the important hydrological aspects of such a system, it is difficult to evaluate the model other than to compare its behavior in terms of the streamflow (Figure 5) with the observed streamflow and subjectively evaluate the behavior of the other variables in the system.

REFERENCES

DENMEAD, O. T., and R. H. SHAW. 1962. Availability of soil water to plants as affected by soil moisture content and meteorological conditions. Agron. J. 45:385-390.

FEDERER, C. A. 1970. Measuring forest evaporation--Theory and problems. USDA For. Serv. Res. Pap. NE-165. 25 p.

OLSEN, S., and P. OLSON. 1966. Limnology of Fern Lake, Washington, U.S.A. Proc. Int. Soc. Theor. Appl. Limnol. 16:58-64.

PENMAN, H. L. 1948. Natural evaporation from open water, bare soil, and grass. Proc. Roy. Soc. (London) A 193:120-146.

STEPHENS, F. R. 1959. The soil of the Fern Lake watershed. M.F. thesis, Univ. Washington, Seattle.

SWANK W. T. 1972. Water balance, interception and transpiration at Fern Lake. Ph.D. thesis, Univ. Washington, Seattle.

THORNTHWAIT, C. W., and J. R. MATHER. 1955. The water budget and its use in irrigation. U.S. Dep. Agric. Yearb. Agric. 1955: 346-358.

Table 1. The location of rain gages and the corresponding dates for the precipitation data collected in the Fern Lake watershed.

Date	Type of rain gage*	
(mo-day-year)	Lake†	Burn‡
12-17-57 to 5-31-61	3	
6-1-61 to 10-17-62	1(two)	
10-18-62 to 12-31-62	1	1
3-2-63 to 8-15-66	1	1
8-16-66 to 9-27-65	1+2	1
8-28-65 to 12-30-70	1+2	

* 1 = tipping bucket, 2 = standard ruler gage, 3 = weighing gage.

† At the field station headquarters.

‡ Approximately 274 m west of headquarters in a cleared area.

Table 2. Definitions of terms used in equation (1).

d = slope of the saturation specific temperature-humidity curve

C_p = specific heat of air (= 0.24 cal g^{-1}°K)

D = zero-plane displacement (cm)

k = 0.42 (Von Karman constant)

L_v = heat of vaporization (= 580 cal g^{-1})

M = heat of metabolism (cal cm^{-2} sec^{-1})

p = air density (= 0.0012 cm^{-3})

P = air pressure (mm Hg)

q = specific humidity

q_{t2} = saturation specific humidity at temperature t_2

R_n = net radiation (langleys)

S = change in soil or vegetation heat storage (cal cm^{-2} sec^{-1})

t = temperature

V = wind velocity (cm sec^{-1})

Y = integrated dinbatic correction

Z = height (cm)

Z_0 = height of theoretical surface (zero plane)

Table 3. Data corresponding to the information shown in Figure 3.

Week of year	Streamflow (cm)	Insolation (ly)	Air temperature (°C)	Relative humidity (%)	Wind movement (km/day)	Air pressure (mm Hg)
1	2.911	39.0	1.67	94	105.1	761.0
2	0.942	37.0	3.33	92	60.9	771.5
3	0.211	66.0	3.33	92	40.0	759.6
4	1.743	64.0	5.56	94	151.3	765.9
5	2.290	73.8	4.44	92	74.3	761.0
6	2.664	82.0	3.33	91	89.7	771.5
7	0.565	98.7	5.56	92	112.9	767.3
8	0.220	166.5	4.44	89	65.5	764.8
9	1.079	262.3	6.11	78	82.3	767.8
10	0.181	323.9	6.67	76	68.5	766.3
11	0.059	323.7	3.89	74	81.2	770.3
12	0.043	295.2	3.33	79	61.2	761.5
13	0.048	243.0	6.11	82	66.2	761.2
14	0.042	268.0	5.56	81	39.1	759.4
15	0.037	300.7	7.78	85	56.6	761.5
16	0.606	255.0	9.44	84	72.9	766.8
17	0.261	319.7	8.33	82	72.7	765.9
18	0.049	386.4	7.22	78	69.2	768.1
19	0.036	433.2	9.44	81	35.4	764.9
20	0.044	366.7	10.00	73	70.8	764.1
21	0.027	363.2	10.56	80	24.8	765.6
22	0.024	446.0	13.33	73	22.3	763.5

Table 3. Data corresponding to the information shown in Figure 3 (continued).

Week of year	Streamflow (cm)	Insolation (ly)	Air temperature (°C)	Relative humidity (%)	Wind movement (km/day)	Air pressure (mm Hg)
23	0.021	496.9	12.78	76	5.5	763.0
24	0.026	408.7	12.78	79	24.1	764.4
25	0.022	450.4	13.33	70	14.5	764.0
26	0.022	594.7	15.56	77	14.7	764.9
27	0.009	467.3	14.44	83	13.7	764.5
28	0.000	383.4	13.89	81	6.4	765.1
29	0.000	415.7	16.11	76	17.5	763.3
30	0.000	560.2	18.33	72	22.5	763.9
31	0.000	305.4	15.56	80	34.2	763.0
32	0.000	485.0	17.78	80	45.9	763.3
33	0.000	548.3	15.56	81	27.1	762.0
34	0.000	301.7	16.11	79	24.7	765.6
35	0.000	295.7	13.33	83	17.9	763.8
36	0.000	368.0	12.78	82	39.0	764.3
37	0.000	316.7	12.22	84	36.5	766.5
38	0.000	353.5	10.00	89	17.9	761.3
39	0.001	227.5	11.11	86	15.6	764.7
40	0.003	228.1	11.11	85	33.5	763.4
41	0.000	184.0	10.56	90	50.7	762.4
42	0.015	273.9	8.33	90	21.6	766.7
43	0.004	194.3	10.00	93	43.8	767.3
44	0.008	142.9	9.44	91	66.0	762.3

Table 3. Data corresponding to the information shown in Figure 3 (continued).

Week of year	Streamflow (cm)	Insolation (ly)	Air temperature (°C)	Relative humidity (%)	Wind movement (km/day)	Air pressure (mm Hg)
45	0.012	87.9	8.89	94	40.8	760.4
46	0.001	98.7	7.78	94	21.2	756.9
47	0.011	82.0	7.78	93	40.9	760.7
48	0.002	73.8	3.89	94	24.5	763.2
49	0.611	64.0	6.11	85	3.2	762.2
50	0.278	66.2	3.89	84	2.1	767.2
51	0.731	37.2	0.00	95	10.9	759.8
52	2.679	39.3	1.67	93	0.0	750.9

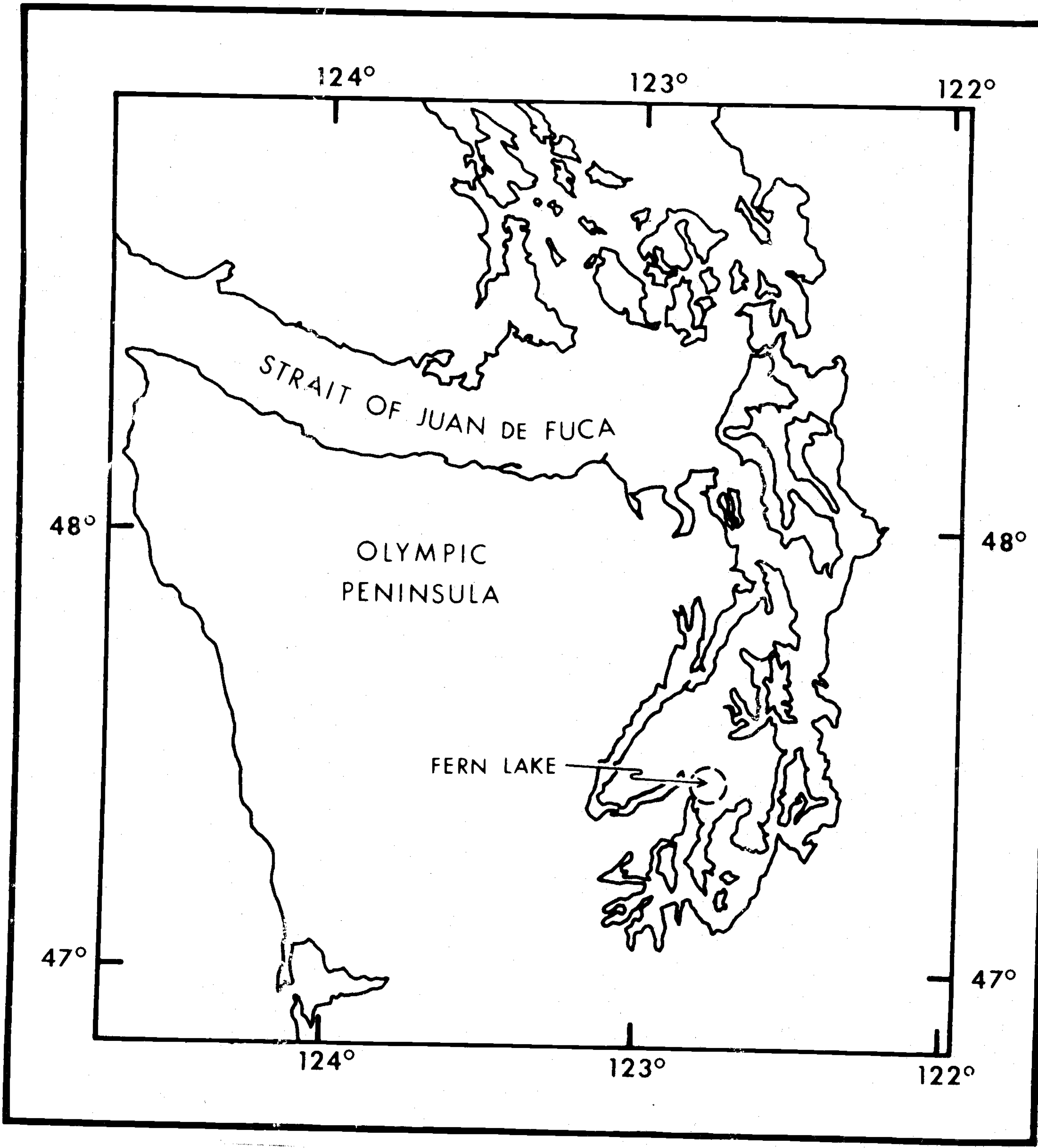

Figure 1. Map of northwestern Washington State showing the location of the Fern Lake watershed.

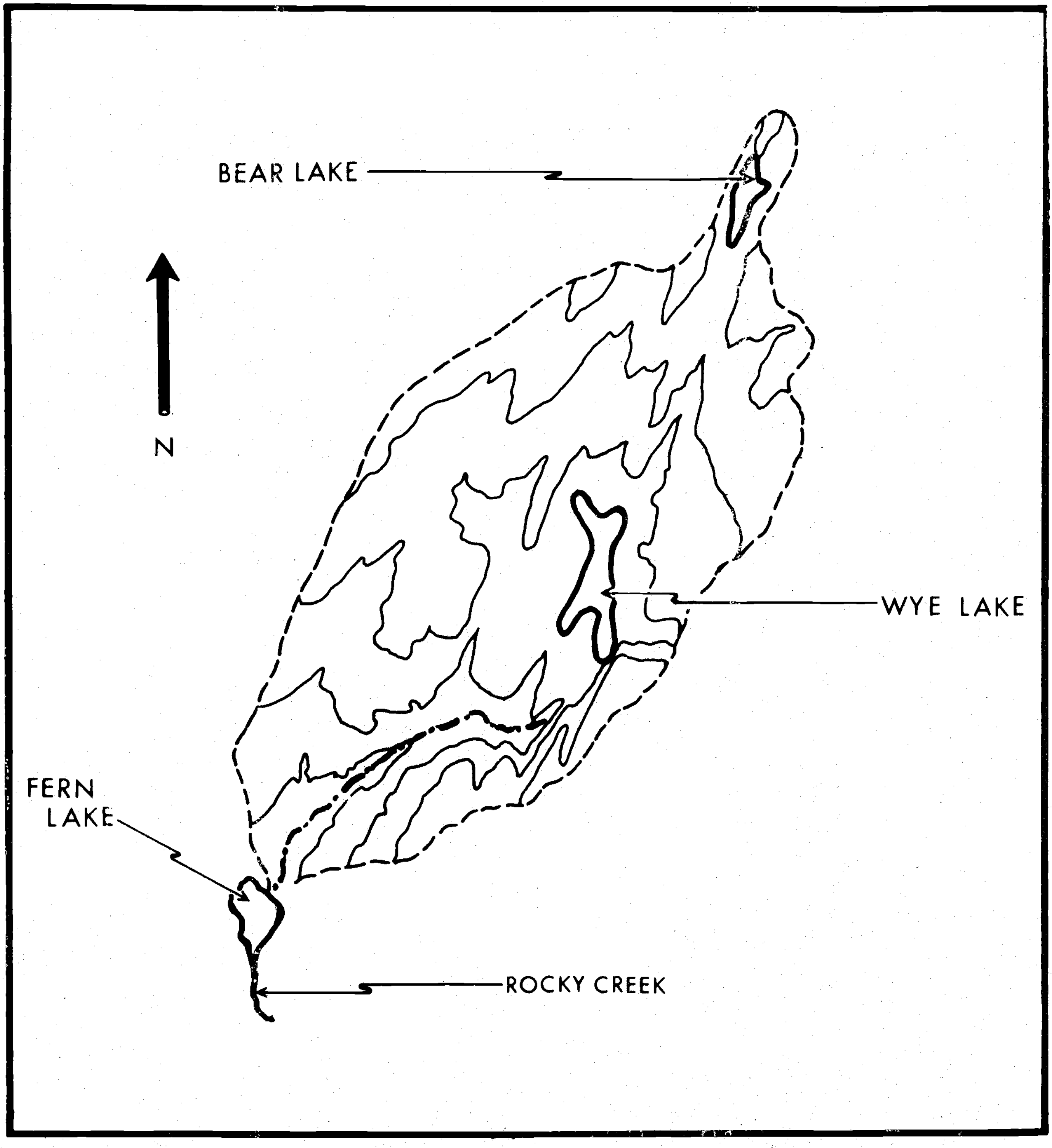

Figure 2. The Fern Lake watershed. The elevation of Fern Lake is 64 m and the contour intervals represent 12 m.

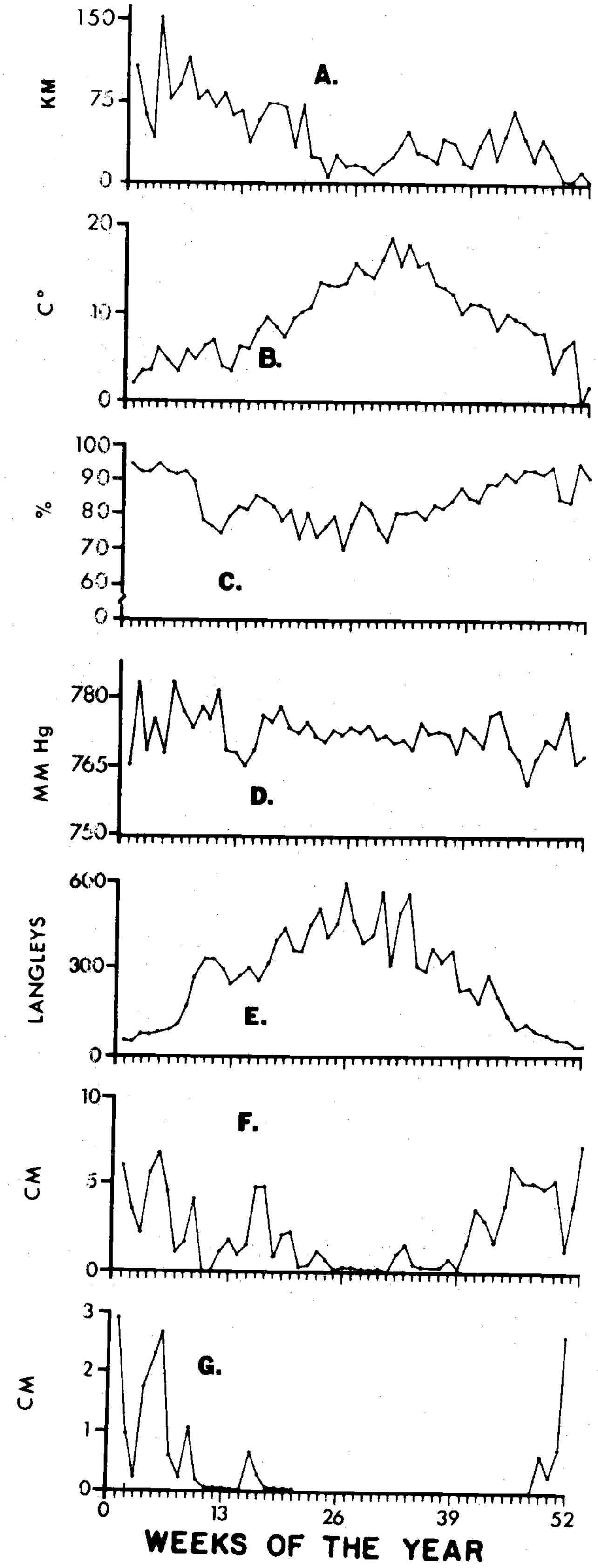

Figure 3. The data used in modeling the hydrological aspects of the Fern Lake watershed for 1965. A. The total daily movement of air across the watershed plotted as weekly means in kilometers. B. Mean weekly air temperature in degrees Celsius. C. Mean weekly relative humidity. D. Mean weekly air pressure. E. Daily insolation plotted as weekly means. F. Total weekly precipitation in centimeters. G. Total weekly streamflow plotted as equivalent precipitation.

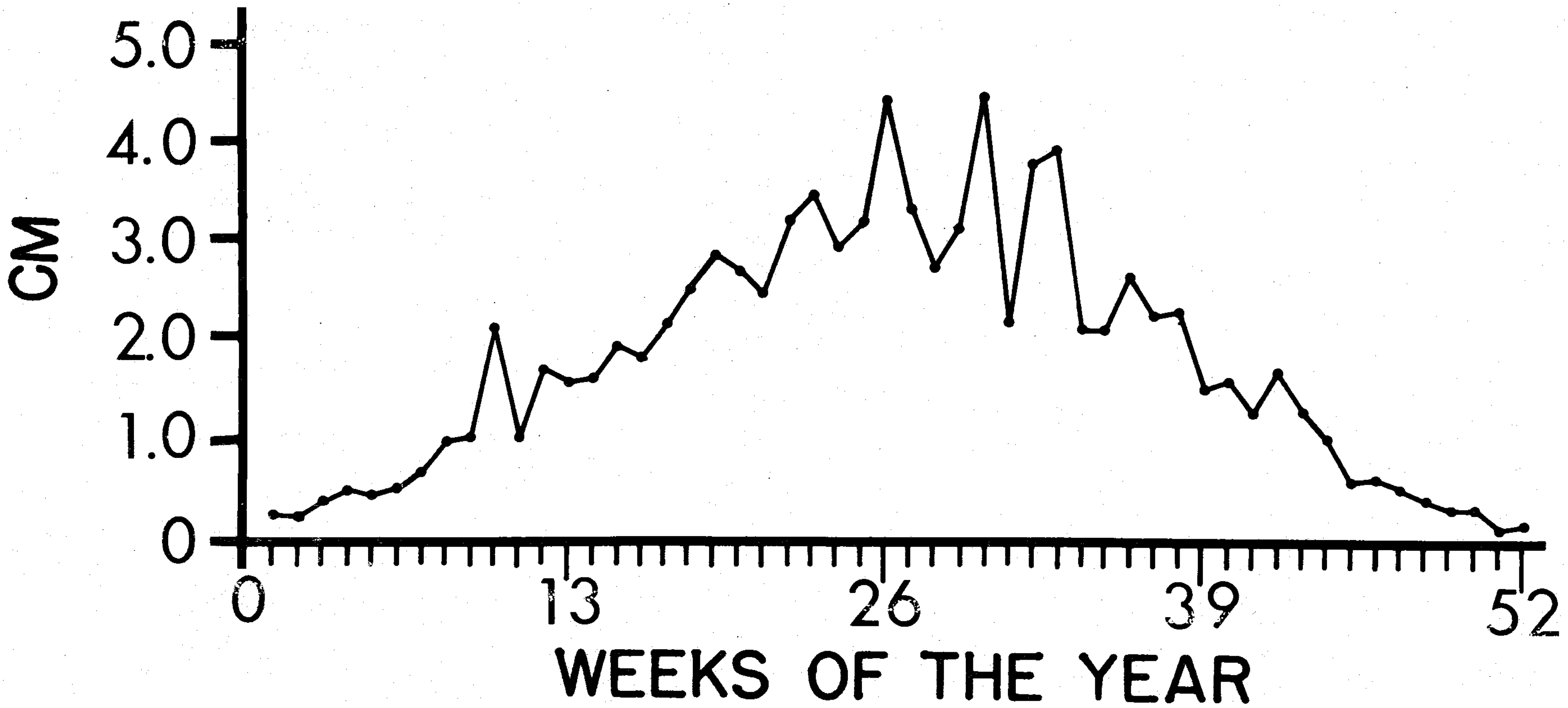

Figure 4. Calculated potential evapotranspiration for each week of 1965 for the Fern Lake watershed expressed as equivalent precipitation.

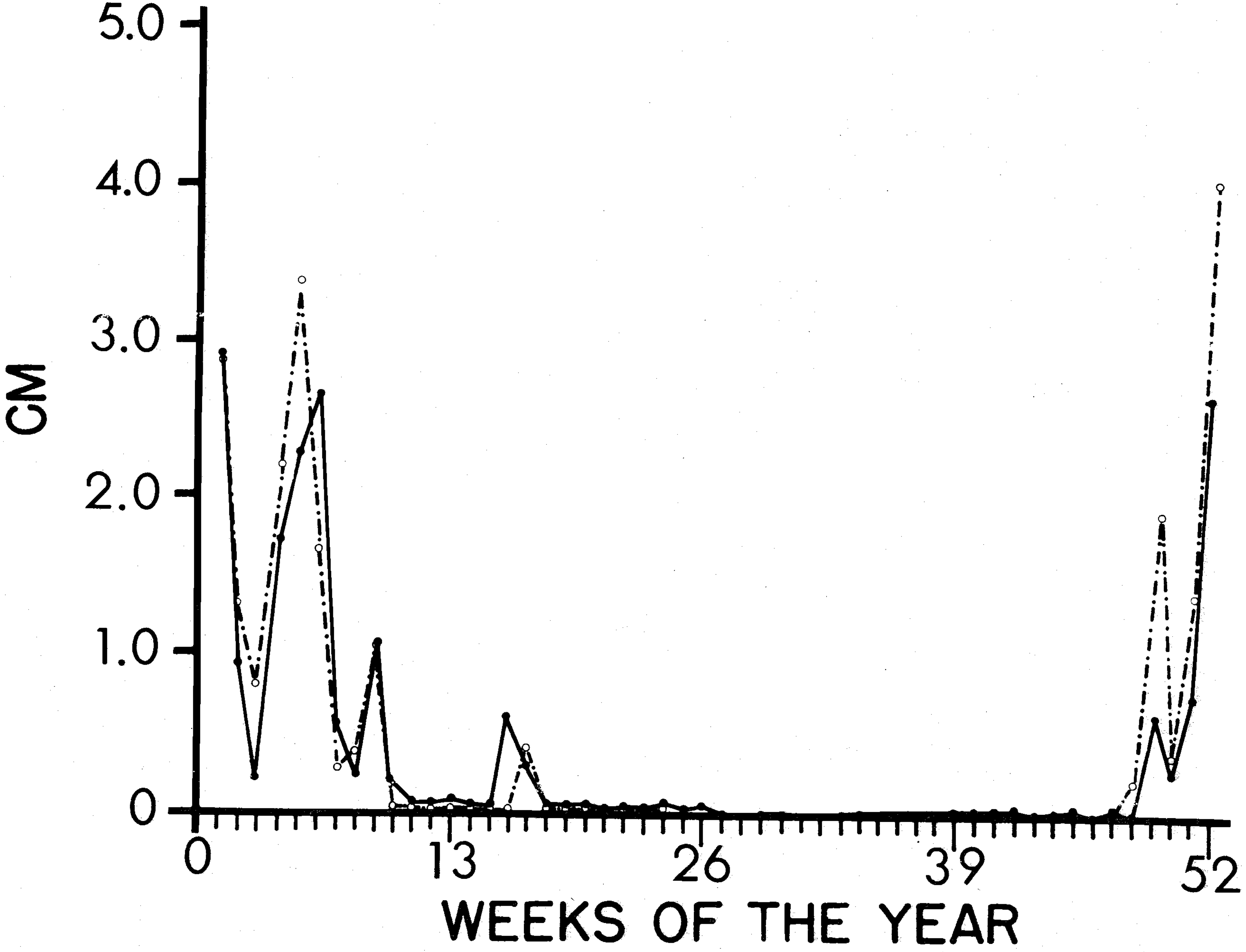

Figure 5. Comparison of the simulated streamflow with the observed streamflow for 1965, both being expressed as equivalent precipitation. Simulated (-·-·-) and observed (——) streamflow.

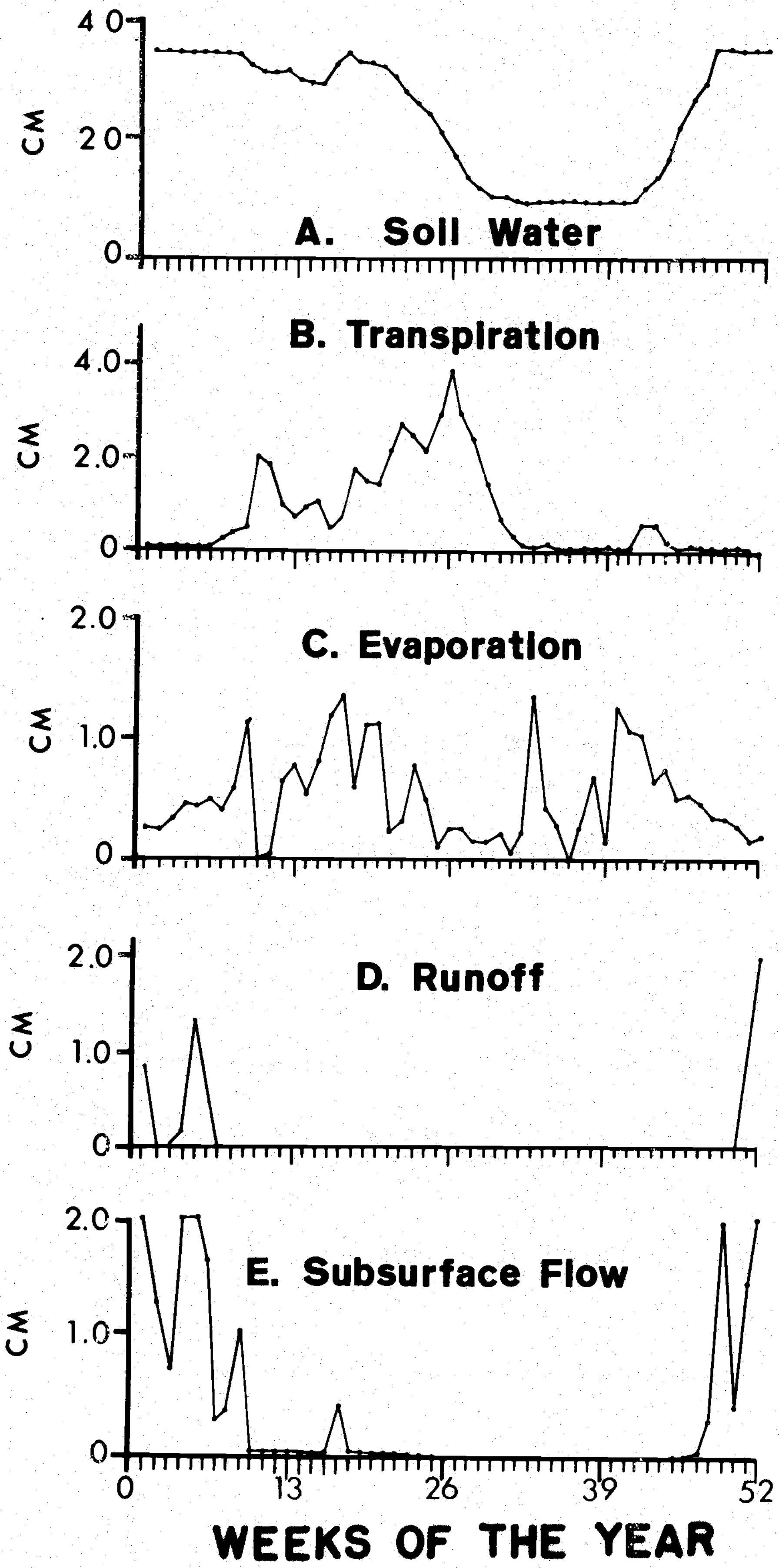

Figure 6. The dynamics of simulated variables associated with the hydrological aspects of the Fern Lake watershed for 1965 as expressed in equivalent precipitation.