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Soil-Moisture Budget Analysis and Regional Groundwater Recharge Estimation for the Solomon Watershed, Kansas

by

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Abstract

For the Solomon watershed the mean annual precipitation during the 1964–1988 period was 23.29 in., whereas the mean annual potential evapotranspiration (ET) for a typical meterological station, such as Kirwin, was 27.8 in. Average streamflow and baseflow at the stream gaging stations of the watershed have been declining over time, but precipitation patterns have not changed. Thus at the Glade station average streamflow was approximately 40,000 acft/yr and baseflow approximately 10,000 acft/yr during the 1950's and 1960's, whereas during the 1970's and 1980's they were approximately 10,000 and 4,000 ac-ft/yr, respectively. Water-balance diagrams for the area show that precipitation increases during the warm months, as do potential and actual ET. At the western portion of the watershed, potential ET is always greater than precipitation. As one moves eastward, precipitation occasionally exceeds potential ET, and at the eastern end of the watershed precipitation almost equals potential ET. Two methods were employed to estimate regional groundwater recharge for the watershed. One is based on streamflow record analysis and the other on soil-moisture budget analysis. Assuming that the long term average recharge equals the long term average groundwater outflow under equilibrium conditions, such as what existed in the early 1960's in the area, it is estimated that 0.73 in. per year (in./yr) of recharge occurred. Based on the soil-moisture budget analysis for the same period, the estimated recharge was 1.15 in./yr. Thus the average recharge based on the two estimation methods is estimated to be 0.94 in./yr, which represents only 4% of the average annual precipitation. During the early 1980's, groundwater appropriations at the Glade subwatershed amounted to 4.7 times the estimated recharge.

Components of the water balance in the Solomon watershed

Precipitation and temperature

There are 19 meteorologic stations in or near the Solomon watershed that have precipitation records of sufficient length and completeness for analysis (National Oceanic and Atmospheric Administration, various years). The locations of these stations are shown in fig. 1. All stations measure precipitation and temperature; in addition, the Kirwin, Webster and Glen Elder stations measure pan evaporation. However, these data are not complete (numerous missing values).

The mean annual precipitation over the entire watershed for 1964–1988 ranges from 18.5 in. at the west end of the watershed to 30 in. at the east end. The mean annual precipitation during the 1964–1988 period was 23.29 in. The monthly precipitation and temperature records for the last 25 years (1964–1988) for all 19 stations are shown in tables 1 and 2, respectively (National Weather Service data tapes).

Evapotranspiration

Evapotranspiration is the combined process of evaporation from free water and bare soil surfaces and transpiration by plants. Potential evapotranspiration is defined as the evapotranspiration that would occur from a vegetation-covered soil surface that is never short of water. Because moisture is never restricted, potential evapotranspiration is limited solely by available energy, primarily solar energy. If there is a shortage of moisture, actual evapotranspiration will fall short of potential evapotranspiration.

No direct measurements of evaporation or evapotranspiration are available in the Solomon watershed. As an approach to the problem of estimating potential evapotranspiration, the empirical method of Thornthwaite (1948) was applied to the data of all 19 stations shown in fig. 1. The minimum amount of meteorologic data required for this method and the method's simplicity were the factors considered in choosing this method, although the results are only a rough approximation of evapotranspiration.

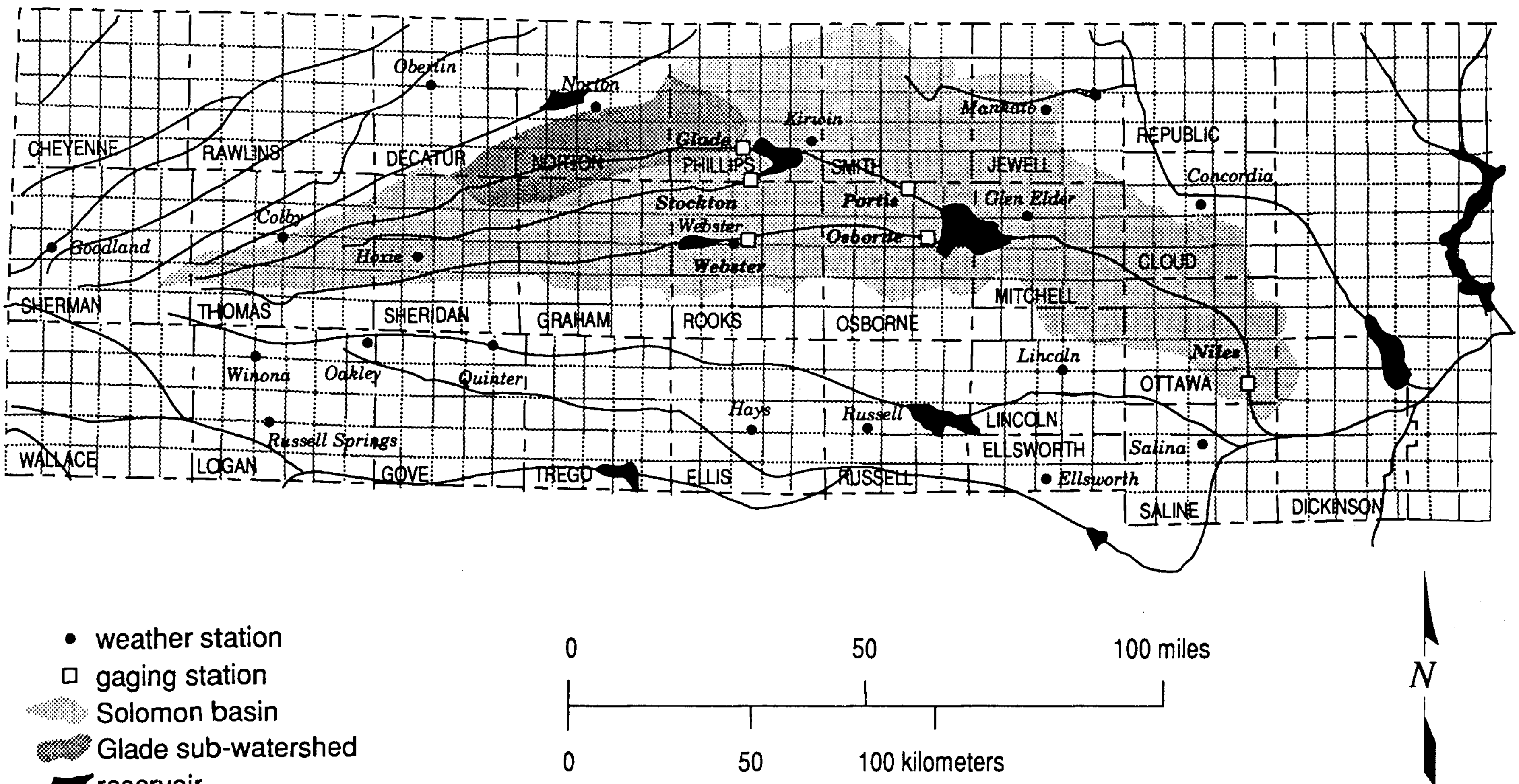


Figure 1: Precipitation and stream flow data stations for the Solomon basin

The formula developed by Thornthwaite for determining potential evapotranspiration from temperature data is:

$$E = 1.62\,(10T/I)^a, \qquad (1)$$

where E is the monthly evapotranspiration in centimeters, T is the mean monthly temperature in degrees centigrade, I is the heat index determined by adding for the expression $(T/5)^{1.514}$ 12 months, and

$$a = 67.5 \times 10^{-8} I^3 - 77.1 \times 10^{-6} I^2 + 0.0179 I + 0.492.$$

The computed potential evapotranspiration is adjusted for day length, which is determined by the latitude of the data-collecting station.

The average monthly and yearly values determined by the Thornthwaite approach for the Kirwin station is listed in table 3. The average (1964–1988) annual potential evapotranspiration from this station is approximately 27.8 in.

Table 1. Average monthly and yearly precipitation records in inches for the 25-year period (1964–1988) for all 19 stations in and around the Solomon watershed shown in Figure. 1

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly Total
Colby	0.30	0.37	1.15	1.72	3.61	3.08	3.08	2.01	1.62	1.13	0.62	0.37	19.05
Concordia	0.59	0.80	2.16	2.52	4.17	4.42	3.82	3.60	2.85	1.99	1.20	0.90	29.01
Ellsworth	0.60	0.80	2.19	2.54	4.11	3.92	2.86	3.35	3.18	2.35	1.11	0.86	27.89
Glen Elder	0.50	0.62	1.90	2.48	3.64	3.57	2.94	2.70	2.88	2.03	1.06	0.61	24.92
Goodland	0.42	0.43	1.18	1.43	3.53	2.96	2.86	1.74	1.50	1.00	0.70	0.44	18.18
Hays	0.35	0.58	1.84	2.09	2.72	3.37	3.22	2.54	1.86	1.54	0.99	0.58	21.68
Hoxie	0.38	0.52	1.42	2.14	3.36	2.74	2.80	2.41	1.60	1.27	0.85	0.48	19.97
Kirwin	0.34	0.60	1.90	2.35	4.01	3.20	2.71	2.46	2.56	1.74	0.97	0.47	23.31
Lincoln	0.67	0.84	2.23	2.50	4.16	3.21	3.11	3.34	2.88	2.23	1.35	0.88	27.39
Mankato	0.59	0.79	1.88	2.70	3.99	3.77	3.06	3.44	3.10	2.04	1.28	0.92	27.56
Norton	0.29	0.42	1.44	2.52	3.98	3.78	3.17	2.85	2.18	1.74	0.95	0.39	23.71
Oakley	0.39	0.48	1.09	1.78	3.23	2.70	3.02	2.29	1.57	1.10	0.82	0.48	18.96
Oberlin	0.42	0.54	1.57	2.23	3.59	3.84	3.58	2.14	1.98	1.33	0.88	0.53	22.63
Quinter	0.45	0.73	1.51	2.08	3.84	2.90	3.19	3.00	1.87	1.50	1.03	0.64	22.73
Russell FAA	0.57	0.74	2.17	2.95	3.46	3.19	3.07	3.75	2.73	1.77	1.13	0.83	26.36
Russell Springs	0.39	0.37	1.21	1.54	3.14	2.81	2.61	2.20	1.72	1.11	0.75	0.37	18.23
Salina	0.72	0.94	2.43	3.15	4.24	4.20	2.95	3.36	2.94	2.60	1.47	0.99	29.99
Webster	0.41	0.63	1.67	2.28	3.71	2.66	2.92	2.81	2.14	1.64	0.97	0.59	22.44
Winona	0.34	0.37	1.12	1.41	3.31	2.86	2.74	2.40	1.51	1.37	0.63	0.45	18.52
Average yearly total													23.29

Table 2. Average monthly air temperature records in degrees Fahrenheit for the 25-year period (1964–1988) for all 19 stations in and around the Solomon watershed shown in Figure 1.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Colby	25	29	36	48	58	69	75	72	62	50	36	27
Concordia	24	30	40	52	62	72	78	75	66	54	40	29
Ellsworth	26	32	42	54	64	74	79	77	68	56	41	31
Glen Elder	22	28	39	51	60	71	78	75	65	53	39	28
Goodland	27	31	37	48	58	68	75	72	63	50	37	29
Hays	25	30	40	52	61	72	78	75	66	53	40	29
Hoxie	28	33	41	53	61	72	78	75	66	54	39	30
Kirwin	23	28	38	51	59	70	77	74	64	51	38	26
Lincoln	26	32	43	54	63	74	80	78	69	56	41	31
Mankato	21	27	37	49	60	69	75	73	63	52	36	26
Norton	21	27	35	49	58	68	74	69	60	48	35	26
Oakley	28	33	40	51	59	70	77	73	64	53	38	31
Oberlin	26	32	40	51	61	70	77	75	65	52	38	29
Quinter	26	31	37	49	60	70	77	74	65	52	39	29
Russell FAA	26	32	41	52	62	73	79	76	66	55	40	30
Russell Springs	27	31	38	49	59	69	77	73	63	52	38	29
Salina	26	32	42	54	63	73	80	77	68	56	42	31
Webster	24	29	39	51	61	72	77	74	65	52	39	28
Winona	27	31	38	48	57	69	76	72	64	52	38	29

Table 3. Thornthwaite potential evapotranspiration calculation (inches per month)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total
1964	0.00	0.00	0.14	1.76	4.08	5.07	7.26	5.34	3.59	1.74	0.47	0.00	29.46
1965	0.00	0.00	0.00	2.10	4.16	4.96	6.20	5.30	2.72	2.04	0.67	0.08	28.23
1966	0.00	0.00	0.69	1.39	3.48	5.37	7.35	5.11	3.49	1.72	0.29	0.99	28.88
1967	0.00	0.00	0.82	2.17	2.98	4.64	5.63	4.96	3.22	1.88	0.47	0.00	26.76
1968	0.00	0.00	0.87	1.79	2.76	5.48	6.30	5.55	3.31	1.87	0.34	0.00	28.26
1969	0.00	0.00	0.00	2.08	3.65	4.40	6.40	5.49	3.69	1.27	0.58	0.00	27.56
1970	0.00	0.00	0.00	1.28	4.11	5.06	6.49	6.16	3.14	1.36	0.23	0.00	27.83
1971	0.00	0.00	0.28	1.88	2.87	5.76	5.67	5.40	3.21	2.13	0.53	0.00	27.73
1972	0.00	0.00	0.92	1.79	3.36	5.26	5.87	5.25	3.44	1.45	0.18	0.00	27.50
1973	0.00	0.00	0.90	1.47	2.96	5.24	6.04	5.74	3.08	1.91	0.40	0.00	27.72
1974	0.00	0.03	0.73	1.86	3.68	4.76	6.31	4.77	2.78	2.05	0.48	0.00	27.45
1975	0.00	0.00	0.07	1.66	3.48	4.70	6.15	5.59	3.01	1.80	0.32	0.00	26.78
1976	0.00	0.48	0.50	2.11	2.98	5.00	6.22	5.58	3.30	1.19	0.12	0.00	27.49
1977	0.00	0.16	0.77	2.23	4.22	5.60	6.76	4.89	3.42	1.65	0.39	0.00	30.07
1978	0.00	0.00	0.30	2.16	3.20	5.30	6.39	5.30	3.80	1.65	0.22	0.00	28.31
1979	0.00	0.00	0.52	1.82	3.17	4.98	6.03	5.23	3.68	2.12	0.17	0.11	27.83
1980	0.00	0.00	0.10	1.49	3.15	5.27	7.05	5.71	3.69	1.88	0.52	0.00	28.86
1981	0.00	0.00	0.81	2.75	2.83	5.48	6.20	5.21	3.51	0.00	0.62	0.00	28.40
1982	0.00	0.00	0.54	1.68	3.82	3.39	6.33	5.60	3.23	1.77	0.17	0.00	26.52
1983	0.00	0.01	0.39	1.16	2.70	4.54	6.76	6.69	3.60	1.71	0.38	0.00	27.93
1984	0.00	0.25	0.09	1.23	3.24	5.19	6.14	6.00	3.06	1.47	0.35	0.00	27.02
1985	0.00	0.00	0.78	2.25	3.75	4.49	5.98	4.73	3.24	1.31	0.00	0.00	26.54
1986	0.04	0.00	0.96	1.84	3.21	5.81	6.66	5.18	3.82	1.64	0.08	0.00	29.24
1987	0.00	0.19	0.52	1.90	0.79	5.62	6.50	5.19	3.67	1.54	0.62	0.00	26.53
1988	0.00	0.00	0.45	1.52	3.82	5.18	5.76	5.24	2.98	0.11	0.44	0.00	25.51
Average yearly total													27.78

Streamflow and baseflow

The runoff from the Solomon watershed is measured at several stream gaging stations (fig. 1). The streamflow records for the Glade station have been analyzed for 1955–1976 (Phillips, 1980; U.S. Geological Survey, various years). The average streamflow over this period was 23,454 ac-ft/yr. Figure 2 shows the total annual streamflow and baseflow (the groundwater contribution to streamflow) data for that period of record, together with the mean precipitation over the area. Baseflow data were obtained from streamflow data following the separation procedures outlined by Busby and Armentrout (1965). To distinguish the data trend more clearly, we applied a seven-year moving-average time-trend analysis (Davis, 1973) to the data, also as shown in fig. 2. The moving-average analysis indicates how the major or long-term features of the record are emphasized at the expense of shorter variations. A streamflow decline is evident from the data, although average areal precipitation over the same period of record does not decrease (fig. 2). This indicates that a growing increase in groundwater use is probably one major cause of this streamflow decline.

To estimate the average yearly declines in streamflow and baseflow, we performed a linear regression on the log-transformed data, with the resulting straight lines on the semilog paper plotted in fig. 3. Projection to the future is possible by extrapolation. Correlation coefficients of 93.5% for the streamflow and 82.3% for baseflow are calculated, indicating that the straight line on the semi-log plot adequately approximates the flow data. From figs. 2 and 3 it can be seen that, during the 1950's and 1960's, the long-term average streamflow was 40,000 ac-ft/yr and the baseflow was 10,000 ac-ft/yr, whereas during the 1970's and 1980's they were approximately 10,000 ac-ft/yr and 4,000 ac-ft/yr, respectively.

Solomon watershed soils

The soils of the Solomon watershed formed mainly from deposits of loess, outwash material, and alluvium. Figure 4 is a generalized soil associations map of the Solomon watershed. Construction of this map involved some grouping of various soil associations presented in the

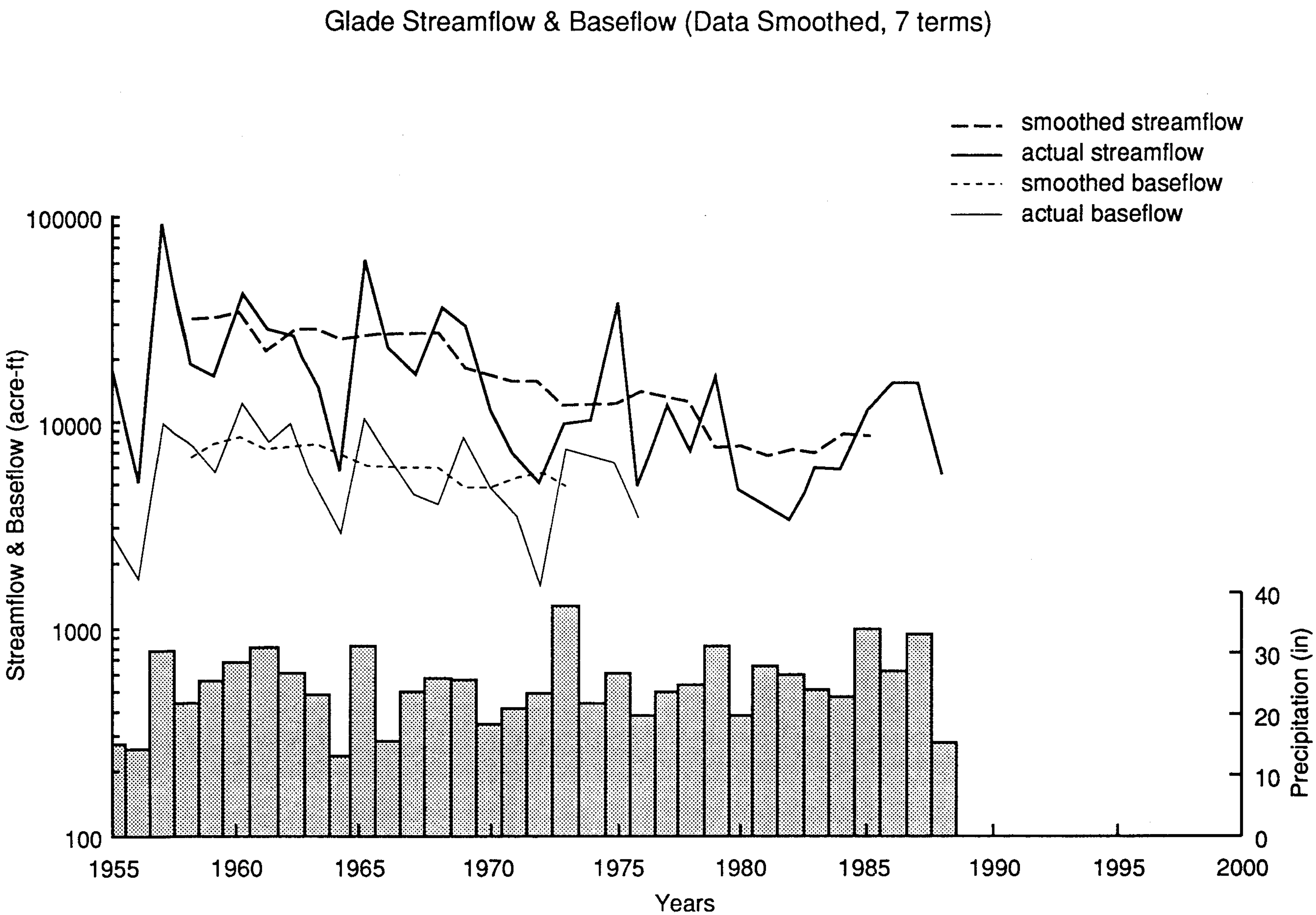


Figure 2: Annual streamflow, baseflow, and precipitation data for the Glade station. Dash lines indicate seven-year moving-average trend for streamflow and baseflow.

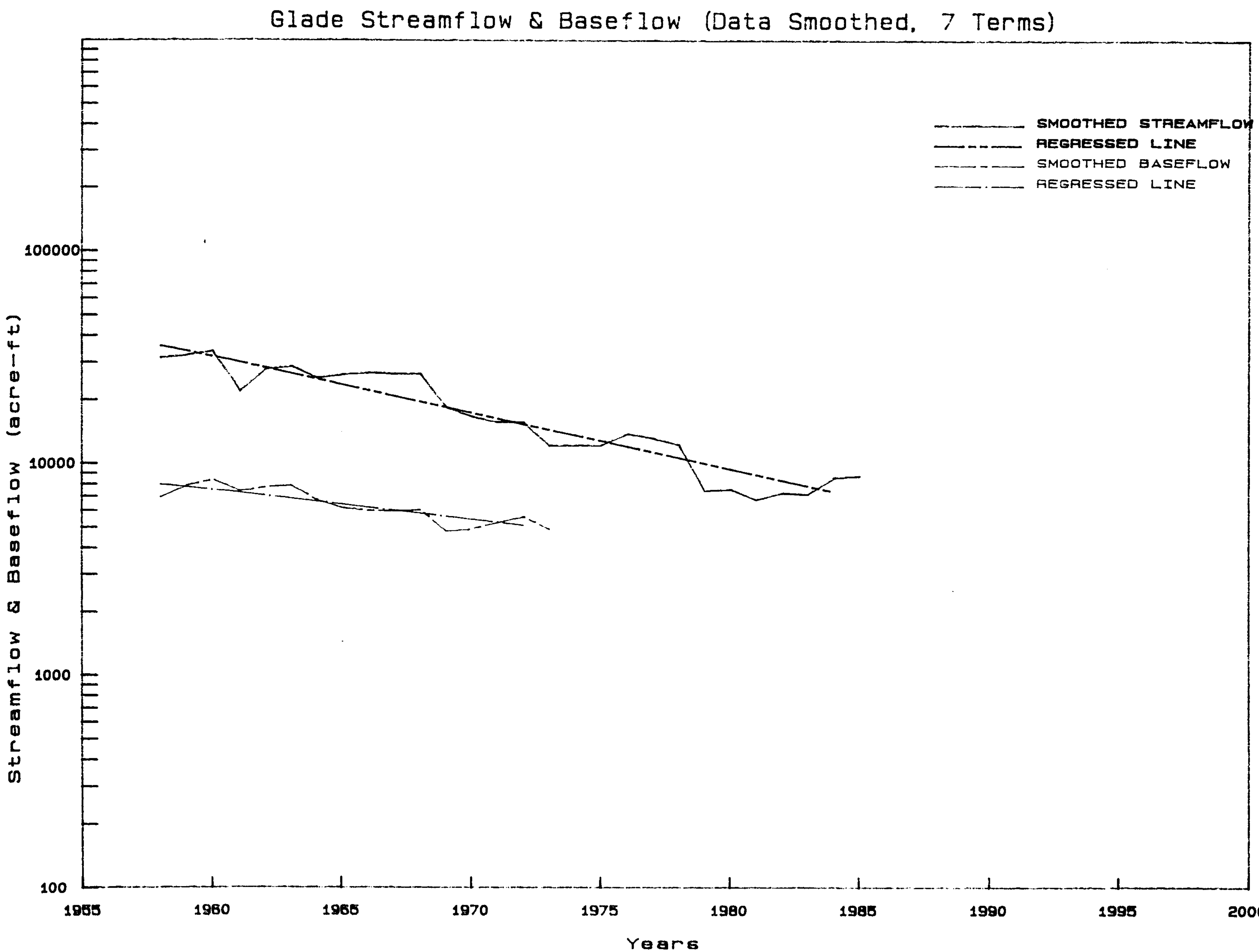


Figure 3: Linear repression lines superimposed on the seven-year moving average streamflow and baseflow data plotted on semilogarithmic paper.

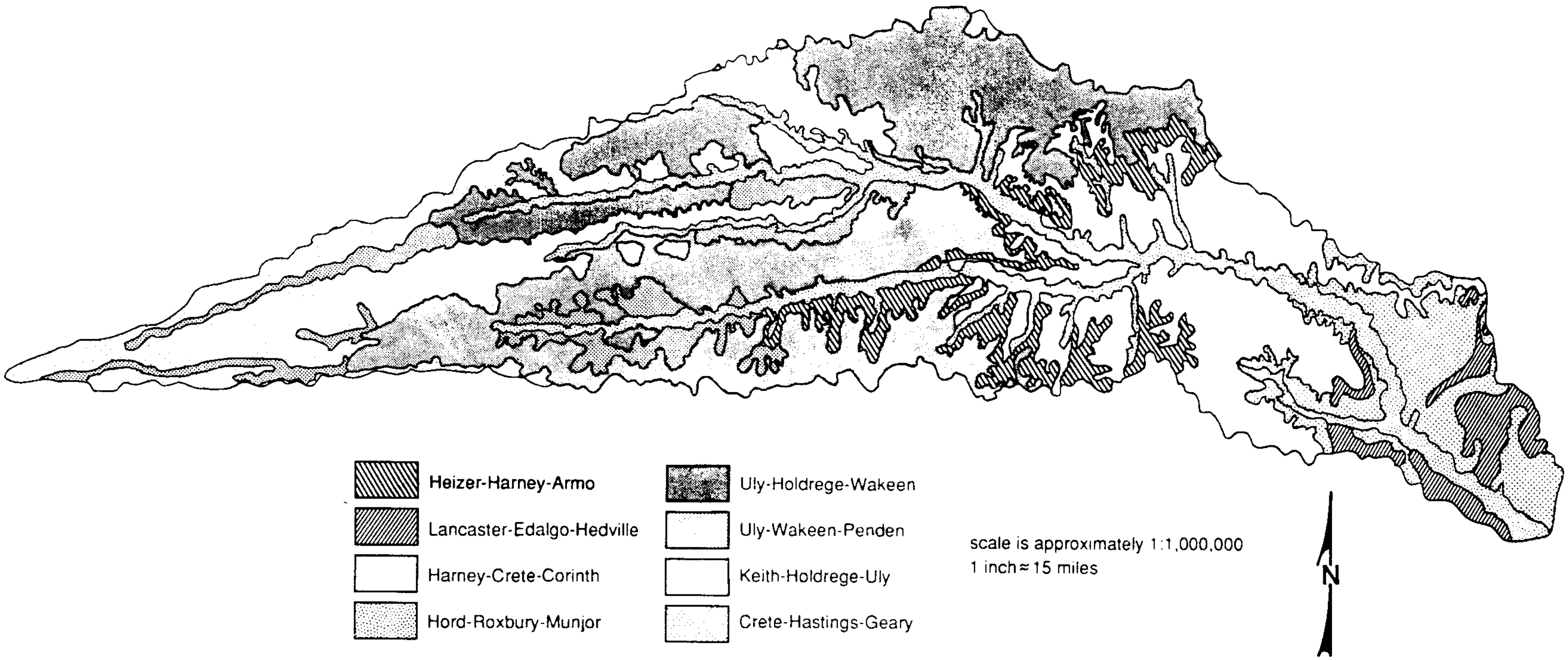


Figure 4: Generalized soil associations of the Solomon basin

county soil maps (Angell et al., 1973, 1984; Atkinson, 1976; Atkinson and Grimwood, 1980; Barker et al., 1980; Barker and Hamilton, 1985; Cline et al., 1959; Fleming, 1977; Hamilton, 1978, 1980, 1984; Hamilton et al., 1989; Jantz and Saffry, 1980; Jantz et al., 1982; Palmer, 1982; Palmer and Hamilton, 1987; Watts et al., 1986) and some regrouping of soil associations used in those reports to better reflect the pattern of soils in the natural landscapes for the multi-county area. Table 4 indicates the major soil associations, their areal extent, the percentage of watershed covered by the associations, and their water-holding properties.

Soil-moisture budget

To estimate actual evapotranspiration, we followed the soil-moisture budget approach. The measured precipitation and the calculated potential evapotranspiration values have been used together with the Holmes and Robertson (1959) moisture budget technique to determine the monthly and annual actual evapotranspiration and the moisture surplus available for runoff and groundwater recharge. This method takes into account soil texture, expansion of plant roots during the growing season, and the decreasing withdrawal of moisture from the root zone with increasing moisture stress. With the aid of the computer program POTEV (Freeze, 1967), the analysis was carried out for four different soil-moisture capacities varying from 9 to 12 in. These soil-moisture capacity values cover the range of values observed in the watershed area (table 4). A brief discussion on the basic concepts of soil-moisture budget analysis are presented in what follows.

A soil is saturated with water if all its interstices are filled. When the soil is permitted to drain freely, some water will be removed. This amount, expressed as a volume ratio, is called the specific yield of the soil. After gravitational water has drained out, the soil is said to be at field capacity. The moisture tension at field capacity is normally between 0.1 and 0.3 atmospheres (atm). Field capacity is the upper limit of moisture available to plant life; the lower limit is reached at the wilting point, which corresponds to a moisture tension of about 15 atm. The actual amount

Table 4. Soil association coverage of the Solomon watershed

Item	Soil association	Area of soils in basin (mi^2)	% of assoc. in basin	% Breakdown of units in generalized soil associations	Weighted ave. soil-moisture capacity (in.) in upper 5 ft of soil
1	Keith–Holdredge–Ulysses	1174.4	17.6	46–43–10	12.0
2	Uly–Holdrege–Wakeen	2219.9	33.2	39–26–15	12.0
3	Uly–Wakeen–Pender	471.0	7.0	38–20–16	12.0
4	Hord–Roxbury–Munjor	697.0	10.4	31–28–17	11.4
5	Harney–Crete–Corinth	1124.5	16.8	52–8–12	10.8
6	Crete–Hastings–Geary	378.9	5.7	40–30–27	10.8
7	Lancaster–Edalgo–Hedville	228.4	3.4	38–26–22	9.0
8	Heizer–Harney–Armo	390.4	5.8	28–27–24	9.0
	Total	6685.4			

Soil association item	Soil-moisture capacity (in.)	% Area covered
1 + 2 + 3	12.0	57.8
4	11.4	10.4
5 + 6	10.8	22.5
7 + 8	9.0	9.3

of moisture stored in the root zone between moisture tensions of 0.1 and 15 atm depends mainly on the soil texture and is called the available storage capacity or soil-moisture capacity.

Soil-moisture deficit is the amount of moisture that has to be added to the root zone (here considered 5 ft deep) to bring it to field capacity. A soil-moisture surplus exists when more moisture has been added to the root zone than the amount required to satisfy the transpiration demands of the vegetation and to bring the soil to field capacity. Thus rain infiltrating the ground first meets the vegetation demands; only excess water can pass below the root zone and eventually to the water table if the soil in the root zone is at field capacity. It is therefore possible to determine whether percolation will take place or whether it has taken place by knowing the relationship among precipitation, actual and potential evapotranspiration, and antecedent soil-moisture conditions. This relation, which is generally presented in the form of a soil-moisture budget, can be calculated from meteorologic records.

There are several techniques for calculating soil-moisture budgets. The technique used here is the Thornthwaite method for calculating potential evapotranspiration in conjunction with the modulated soil-moisture technique devised by Holmes and Robertson (1959) to obtain the actual evapotranspiration and moisture surplus or deficit. If more detailed climatic data are available, the Penman method (Penman, 1948), which is generally considered superior to the Thornthwaite method, can be employed. Figure 5 shows the flow diagram for the computer program POTEV for calculating potential evapotranspiration and the Holmes and Robertson moisture budget. The data processing steps for running this program are outlined in fig. 6.

An accurate visual representation of wet and dry seasons of an area is usually represented by a water-balance diagram. A complete water-balance diagram consists of comparing potential and actual evapotranspiration with the amount of precipitation, usually on a monthly basis. This comparison then gives information on the amount of deficit or surplus water available during different seasons. When the evapotranspiration rate is higher than the precipitation rate, the soil moisture is used until depleted and a moisture deficiency occurs. When the precipitation rate exceeds the evapotranspiration rate, soil moisture recharge occurs. In addition to variations in location, the appearance of the water balance can vary considerably in one location from year to year.

Water-balance diagrams resulting from the moisture budget analysis based on 25-year means (1964–1988) for the Hoxie, Webster, Kirwin, Glen Elder, and Salina stations (fig. 1) are shown in figs. 7 through 11. These diagrams are based on the most prominent soil-moisture capacity of the Solomon watershed soils. In all these figures, part (a) displays the entire 25-year water balance of the station on an annual basis, part (b) displays the 25-year average water balance on a monthly basis, and parts (c) and (d) display the monthly water balance of a particularly wet and dry year, respectively. As can be seen from these diagrams, precipitation increases during the warm months, as do potential and actual evapotranspiration. A mild bimodal precipitation distribution occurs, with peaks in May and August–September. A bimodal characteristic is prevalent in a large portion of the central United States (Eagleman, 1975). This reflects the influence of frontal systems in the spring and fall with slightly less precipitation from air-mass thunderstorms in midsummer. Agricultural practices and crop distributions can be related directly

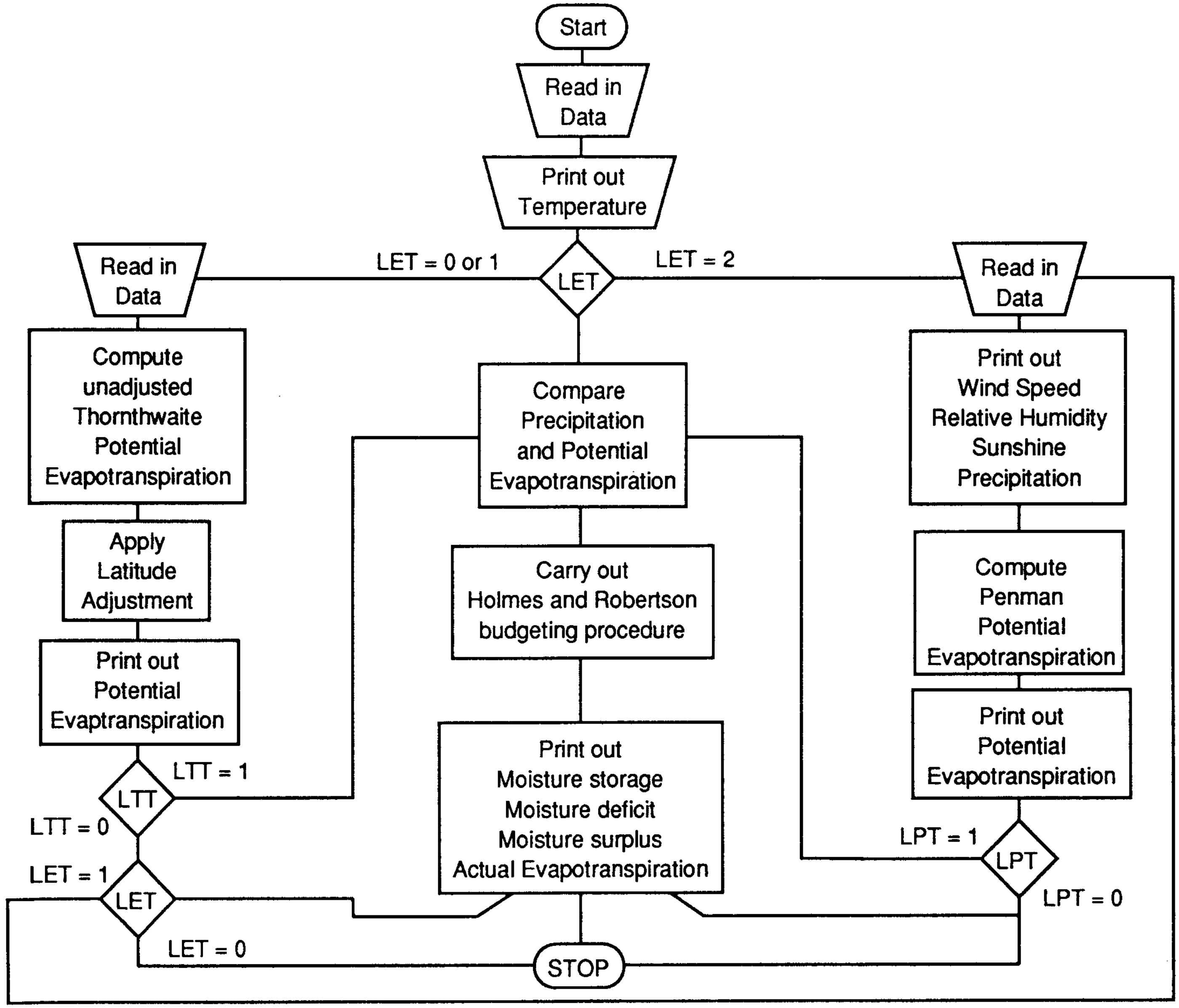
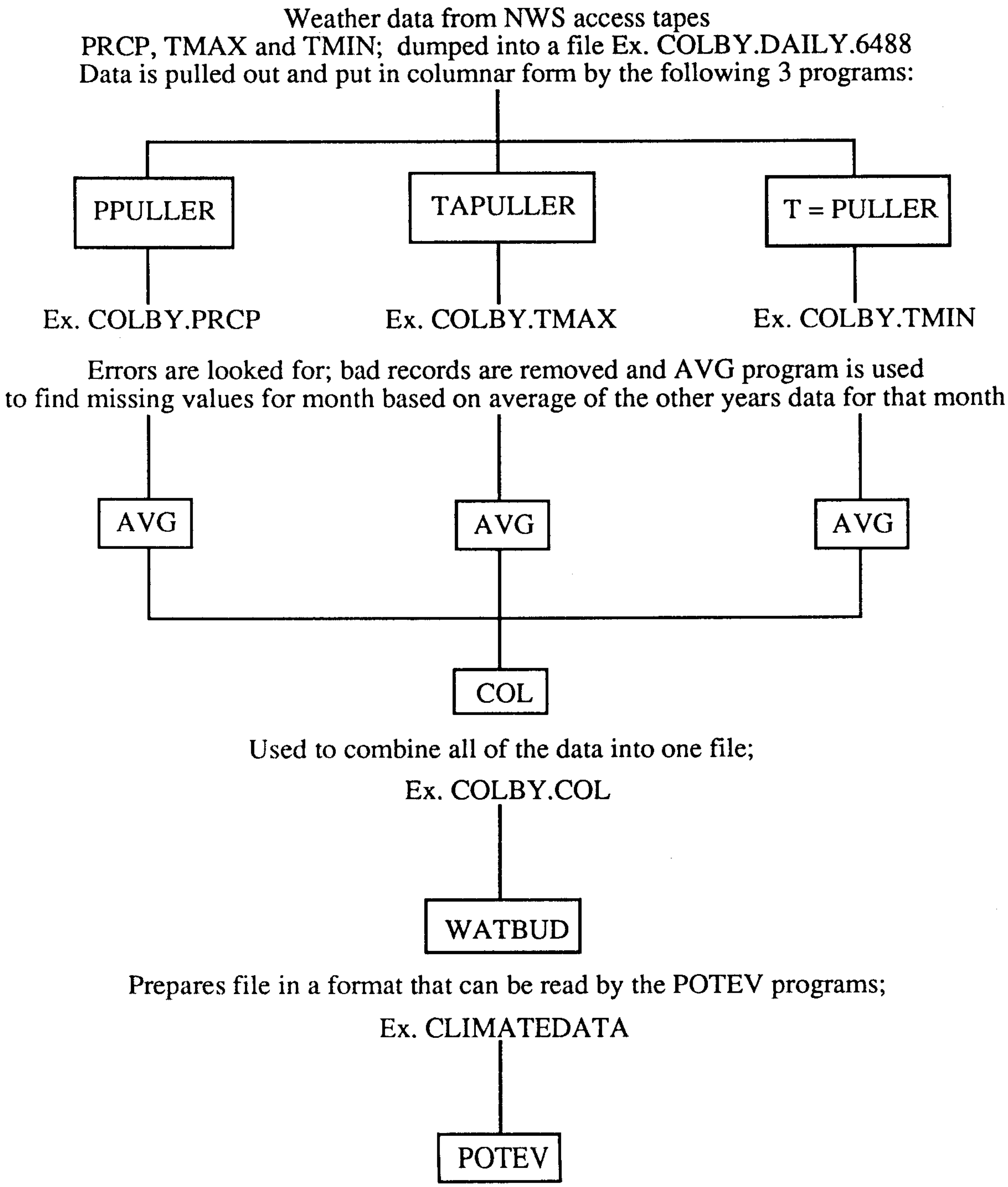


Figure 5: Flow diagram for the potential evapotranspiration and soil-moisture budget calculations using the program POTEV.

Figure 6. Data processing steps



*Boxed titles are FORTRAN77 programs.

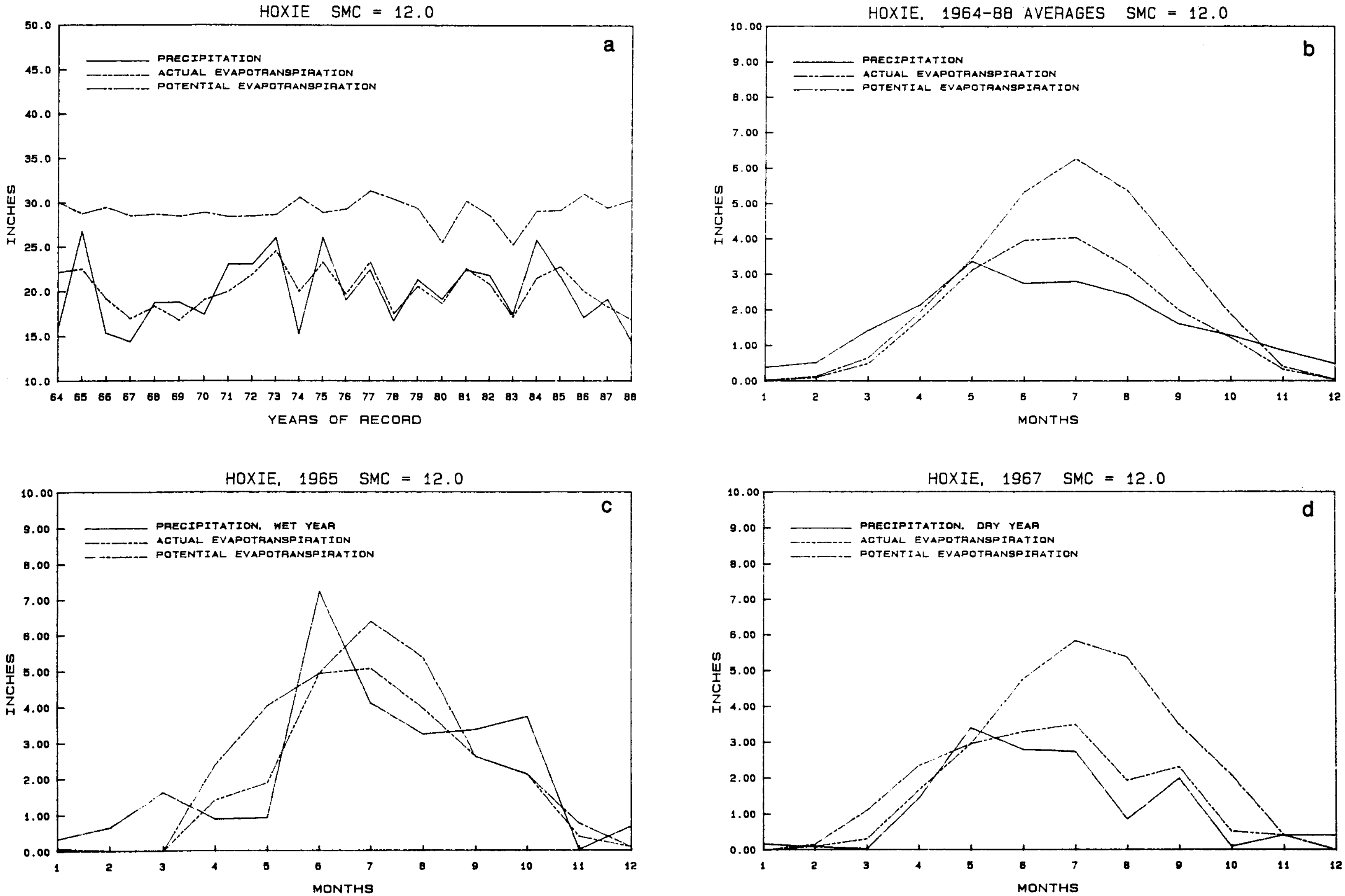


Figure 7: Water balance diagrams for the Hoxie station: (a) yearly water balance for the 1964–1988 period of record; (b) 1964–1988 average monthly water balance; (c) wet year water balance; (d) dry year water balance.

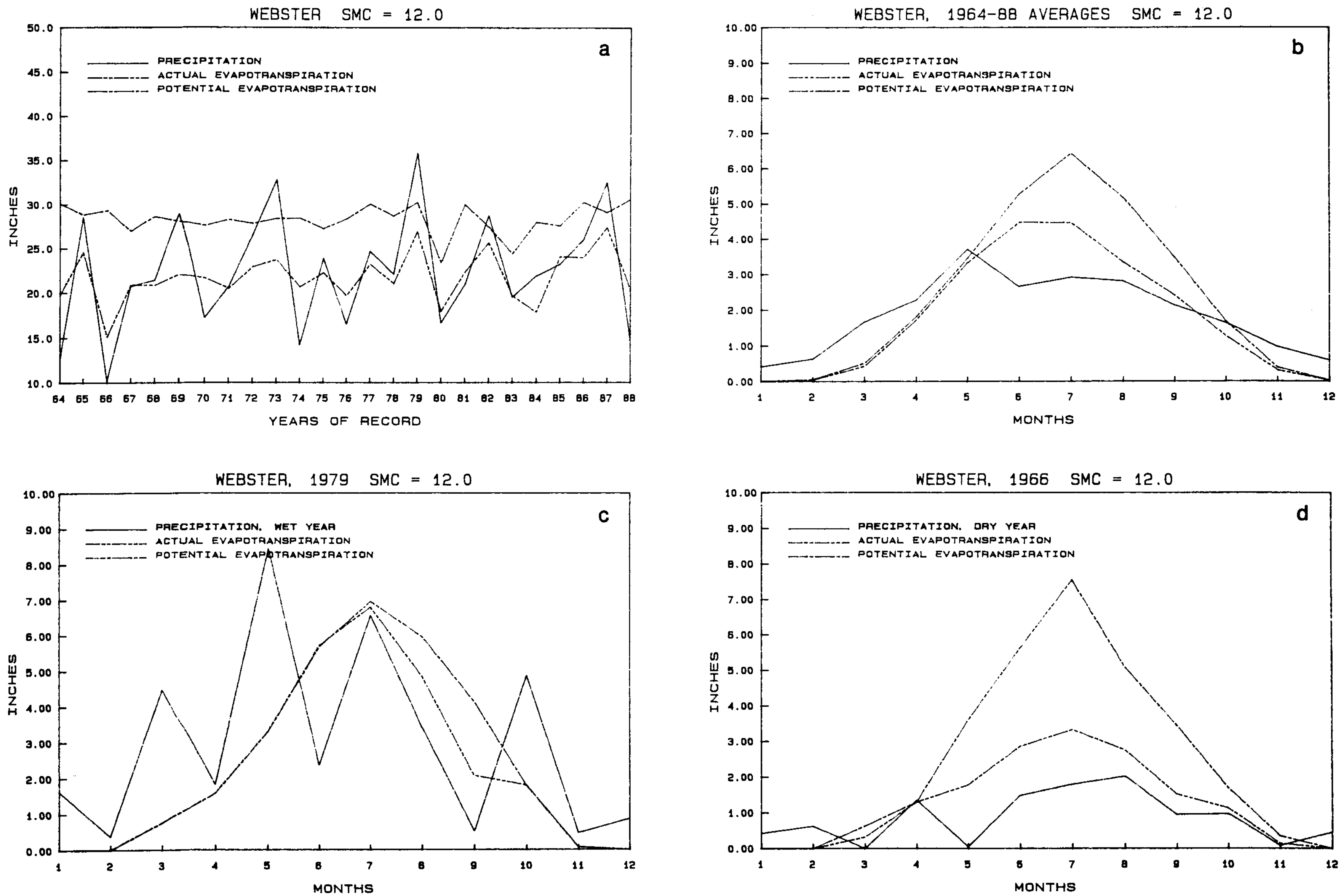


Figure 8: Water balance diagrams for the Webster station: (a) yearly water balance for the 1964–1988 period of record; (b) 1964–1988 average monthly water balance; (c) wet year water balance; (d) dry year water balance.

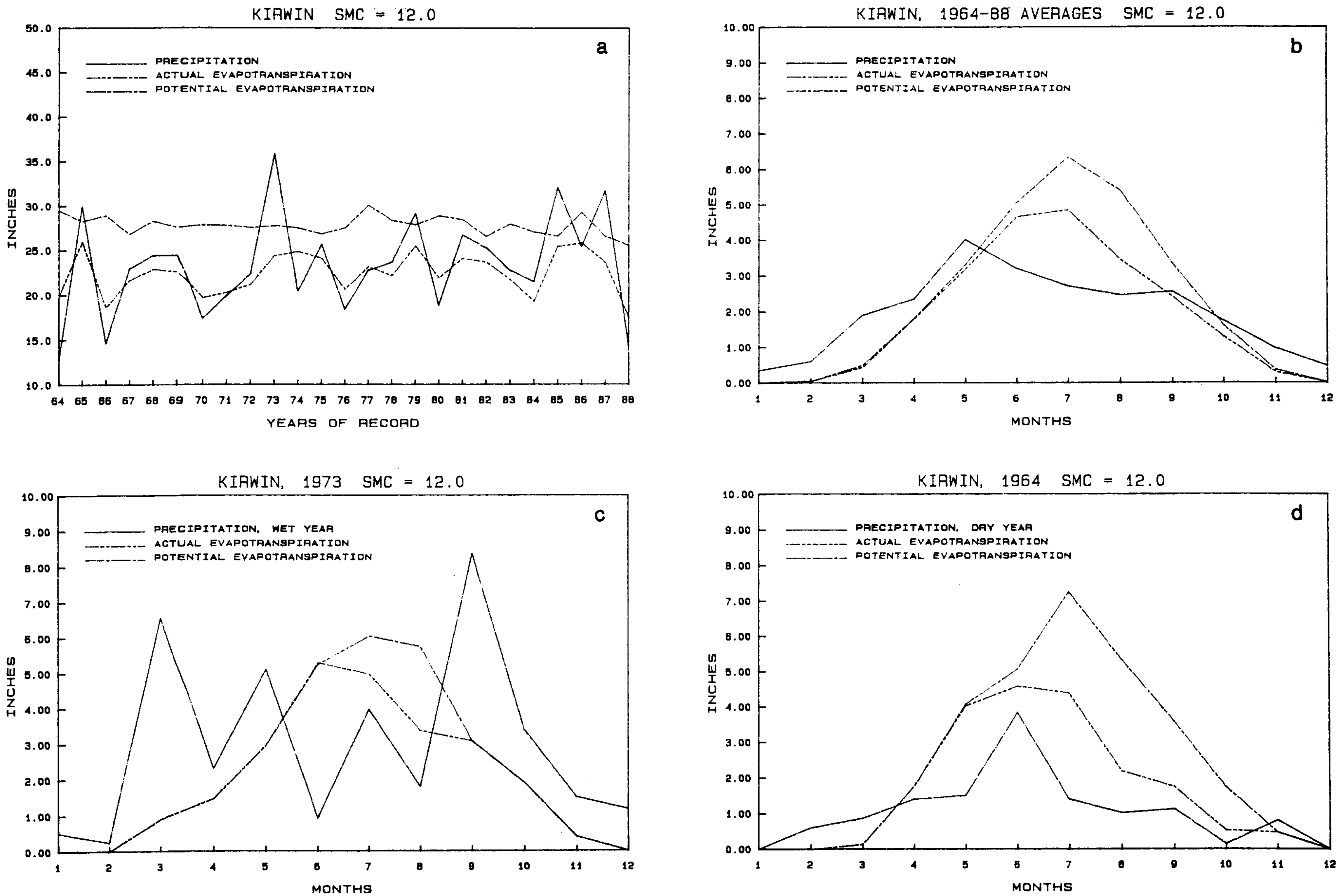


Figure 9: Water balance diagrams for the Kirwin station: (a) yearly water balance for the 1964–1988 period of record; (b) 1964–1988 average monthly water balance; (c) wet year water balance; (d) dry year water balance.

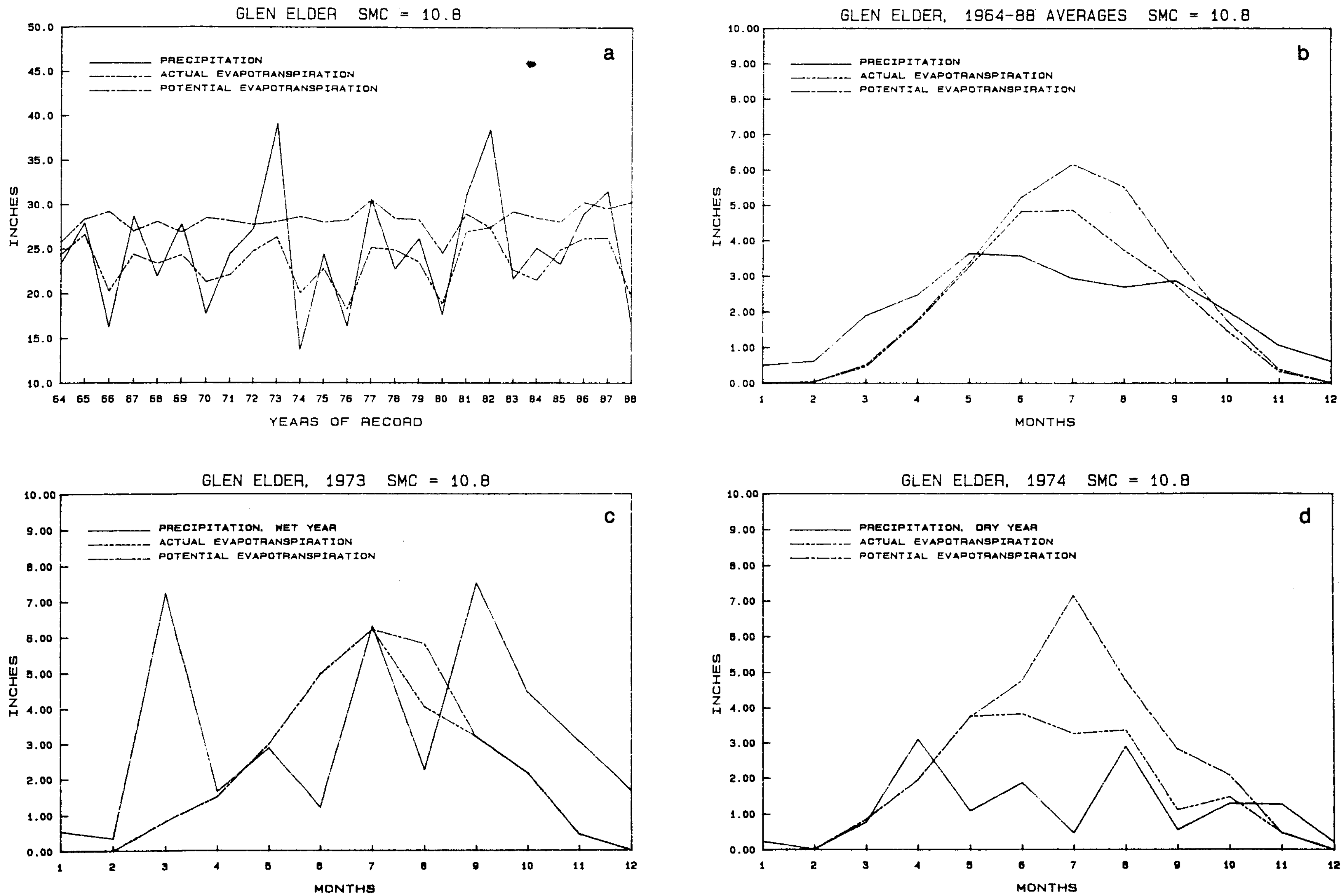


Figure 10: Water balance diagrams for the Glen Elder station: (a) yearly water balance for the 1964–1988 period of record; (b) 1964–1988 average monthly water balance; (c) wet year water balance; (d) dry year water balance.

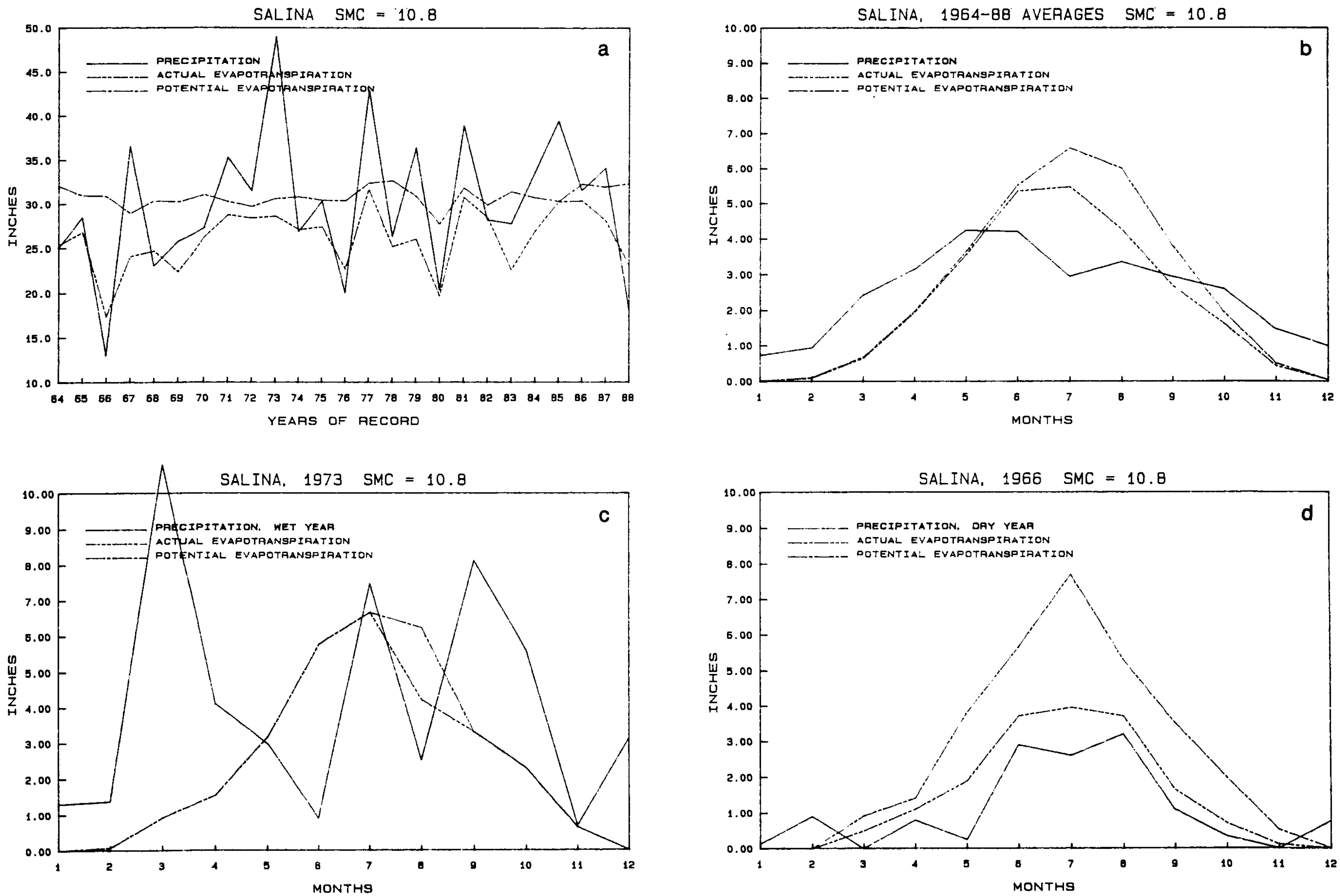


Figure 11: Water balance diagrams for the Salina station: (a) yearly water balance for the 1964–1988 period of record; (b) 1964–1988 average monthly water balance; (c) wet year water balance; (d) dry year water balance.

to the water balance. As can be seen from these diagrams, in the Solomon watershed adequate moisture occurs during November through April. This is the period when water is needed for growing wheat, the major crop of the area. At Hoxie potential evapotranspiration is always greater than precipitation. As one moves eastward, precipitation occasionally exceeds potential evapotranspiration, whereas at Salina it almost equals it (Figs. 7a, 8a, 9a, 10a, and 11a).

Information on many aspects of the water relations at any place can be obtained from the water-balance diagrams (Mather, 1974). The difference between the potential and the actual evapotranspiration provides a measure of the moisture deficit of a place (i.e., the amount by which the available moisture fails to satisfy the demand for water). Knowledge of the moisture deficit is basic to any understanding of the economic feasibility of irrigation, for it provides information on the total volume of water needed at any time and gives a definitive measure of drought. Information on the water surplus, the amount by which precipitation exceeds the water needs when the soil is at field capacity, is fundamental in hydrologic studies that deal with the recharge of groundwater or with the runoff of water in streams and rivers.

IV. Estimates of regional groundwater recharge

There are several methods by which estimates of regional groundwater recharge can be made (Meyboom, 1966; Freeze, 1967; Sophocleous, 1981; Sophocleous and McAllister, 1987), such as: (1) actual field measurements at the recharge end of the flow system, (2) interpretation of streamflow records at the discharge end of the flow system, (3) the use of soil-moisture budgets based on hydrometeorological data, and (4) calculation of quantitative regional flow by analytical or numerical model analysis. In this report, the second and third methods have been employed to estimate groundwater recharge.

The long-term average recharge to the alluvial aquifer was assumed to equal the long-term average groundwater outflow during the early times of the Solomon watershed irrigation development. Such an equilibrium condition existed in the watershed until the early 1960's (Weston, 1979). During 1960 and 1961, the average amount of groundwater appropriated in the

~395,674-acre area drained by the North Fork Solomon above Glade (fig. 1) was 13,860 ac-ft/yr, which amounts to 0.42 in./yr over that subwatershed area (water appropriation data from Division of Water Resources, Kansas State Board of Agriculture). The average annual baseflow during the period 1960–1961, as derived from the streamflow data at Glade, was ~10,200 ac-ft/yr, which amounts to 0.31 in. of water over the same subwatershed area. Thus the total groundwater outflow (baseflow plus pumpage) for 1960–1961 was 0.73 in./yr, which, under the assumption of equilibrium, represents the amount of groundwater recharge. Groundwater outflow through evapotranspiration was presumed negligible and therefore was not considered in the calculations.

The second method for estimating regional groundwater recharge in the Solomon watershed is the moisture-budget technique. Table 5 presents the calculated average monthly moisture surpluses for all the climatic stations in and around the Solomon watershed, and the frequencies at which surpluses occurred during the 1959–1978 period. The table indicates that in the Solomon watershed and for the predominant soil-moisture capacity of 12 in., moisture surpluses occur 4% or less of the time from July to September; 20% or less of the time during June and from October to January, and <60% of the time from February to May. The column labeled "3" in Table 5 shows the total average moisture surplus, which constitutes potential groundwater replenishment. The column labeled "4" shows the same amount as a percentage of the average total annual precipitation from 1959 to 1978. In the summary table 6, the precipitation potential and actual evapotranspiration and the moisture surplus for various soil-moisture capacities representative of the Solomon watershed soils are listed for all the climatic stations shown in fig. 1. The soil map (fig. 4) has been interpreted in terms of the percentage of the effective drainage area covered by soils representing each of the soil-moisture capacities (table 4).

If the 25 years of records (1964–1988) for all these stations are at all representative of the average conditions in the Solomon watershed, moisture budgets indicate that the average potential annual groundwater replenishment in this watershed for the predominant 12-in. soil-moisture capacity varies from 0 in. to 3.8 in. Or, in other words, the potential annual recharge in this area

Table 5. Calculated average monthly moisture surpluses for all 19 stations in and around the Solomon watershed shown in fig. 1 during the 1964–1988 period[a]

SOIL MOISTURE CAPACITY= 12.00 in.

Station	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sept		Oct		Nov		Dec		Period	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	3	4
Colby	0.00	0	0.00	0	0.00	0	0.02	4	0.16	8	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.18	0.9
Concordia	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0.0
Ellsworth	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0.0
Glen Elder	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0.0
Goodland	0.00	0	0.00	0	0.00	0	0.00	0	0.22	4	0.01	4	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.23	1.3
Hays	0.00	0	0.00	0	0.17	12	0.13	12	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.30	1.4
Hoxie	0.00	0	0.00	0	0.00	0	0.14	8	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.14	0.7
Kirwin	0.01	4	0.01	8	0.43	20	0.15	24	0.38	24	0.05	4	0.00	0	0.00	0	0.00	0	0.04	4	0.05	8	0.05	8	1.16	5.0
Lincoln	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0.0
Mankato	0.16	20	0.22	28	0.93	40	0.60	60	0.95	52	0.21	12	0.00	0	0.00	0	0.08	4	0.17	8	0.19	12	0.27	16	3.78	13.7
Norton	0.06	12	0.09	12	0.22	20	0.43	32	0.30	20	0.12	8	0.00	0	0.00	0	0.00	0	0.09	4	0.02	8	0.06	8	1.39	5.9
Oakley	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0.0
Oberlin	0.02	4	0.02	4	0.05	8	0.12	8	0.16	12	0.18	4	0.00	4	0.00	0	0.02	4	0.04	4	0.00	0	0.00	0	0.60	2.7
Quinter	0.00	0	0.03	8	0.09	12	0.30	16	0.08	16	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.50	2.2
Russell FAA	0.01	4	0.00	0	0.62	32	0.49	44	0.32	20	0.04	8	0.00	0	0.24	4	0.12	4	0.00	0	0.00	0	0.08	4	1.92	7.3
Russell Springs	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0.0
Salina	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0.0
Webster	0.01	4	0.00	0	0.36	20	0.27	16	0.21	8	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.06	4	0.91	4.1
Winona	0.00	0	0.00	0	0.00	0	0.00	4	0.06	4	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.06	0.3

[a]Explanation of columns: 1, average monthly moisture surplus (in.) for the period 1964–1988; 2, percentage of years during the period 1964–1988 in which moisture surplus occurred during the month indicated; 3, total average moisture surplus from Jan to Dec (in.); 4, total average moisture surplus from Jan. to Dec. expressed as percentage of average total annual precipitation 1964–1988.

Table 6. Holmes and Robertson soil-moisture budget for all 19 stations in and around the Solomon watershed shown in Fig. 1 during the 1964–1988 period

Station	Precip. (in.)	Thornwt. Potent. ET (in.)	Actual ET (in.) for various soil-moisture capacities				Moisture surplus (in.) for various soil-moisture capacities			
			9.0	10.8	11.4	12.0	9.0	10.8	11.4	12.0
Colby	19.05	26.43	–	–	–	19.15	–	–	–	0.18
Concordia	29.01	29.23	25.34	25.60	25.69	–	3.95	3.70	3.63	–
Ellsworth	27.89	30.48	25.45	25.74	25.82	–	2.72	2.45	2.38	–
Glen Elder	24.92	28.29	23.18	23.47	23.55	–	2.01	1.73	1.66	–
Goodland	18.18	26.62	–	–	–	18.19	–	–	–	0.23
Hays	21.68	28.85	21.43	–	21.67	21.72	0.55	–	0.34	0.30
Hoxie	19.97	29.08	–	–	–	20.20	–	–	–	0.14
Kirwin	23.31	27.78	–	–	22.32	22.39	–	–	1.23	1.16
Lincoln	27.39	30.06	24.86	25.23	25.33	–	2.82	2.50	2.41	–
Mankato	27.56	27.04	23.65	23.91	23.99	24.07	4.17	3.92	3.85	3.78
Norton	23.71	25.67	–	–	22.38	22.45	–	–	1.46	1.39
Oakley	18.96	28.12	–	–	–	19.29	–	–	–	–
Oberlin	22.63	28.23	–	–	22.17	22.22	–	–	0.65	0.60
Quinter	22.73	27.78	–	–	–	22.52	–	–	–	0.50
Russell FAA	26.36	29.73	24.18	24.56	24.68	24.78	2.48	2.13	2.02	1.92
Russell Springs	18.23	27.55	–	–	–	18.62	–	–	–	–
Salina	29.99	30.82	25.75	26.10	26.20	–	4.52	4.19	4.09	–
Webster	22.44	28.30	21.51	–	21.77	21.82	1.20	–	0.96	0.91
Winona	18.52	27.12	–	–	–	18.74	–	–	–	0.06

lies between 0% and 13.7% of the average total annual precipitation (table 5). For the 1960–1961 period and from the climatic data from the Kirwin station and the predominant soil-moisture capacity of 12 in., precipitation totaled 27.84 in., Thornthwaite potential evapotranspiration and actual evapotranspiration totaled 27.79 in. and 25.98 in., respectively, and moisture surplus totalled 1.89 in. Table 6 shows that as the soil moisture capacity increases, the percentage of the available water that is actually evapotranspired increases at the expense of the moisture surplus. The actual evapotranspiration plus the moisture surplus should equal the precipitation amount; the small discrepancies in table 6 are the result of the averaging of the budgeting procedure.

During the 1960–1961 period, the average total streamflow at Glade was 34,720 ac-ft/yr and the average baseflow was 10,200 ac-ft/yr, resulting in a direct surface runoff (the difference between total streamflow and baseflow) of 24,520 ac-ft/yr (0.74 in/yr). The moisture surplus must, however, satisfy the surface runoff and the groundwater recharge. This surface runoff figure, when subtracted from the average 1960–1961 moisture surplus of 1.89 in. based on the Kirwin station, results in a value for regional groundwater recharge of 1.15 in. This value is of the same order of magnitude as the recharge value (0.73 in./yr) calculated from baseflow and groundwater pumpage data.

Thus, assuming that the more than 395,000-acre subwatershed above Glade is typical of the entire Solomon watershed based on the two previously mentioned recharge estimation methods, the average estimated regional groundwater recharge for the Solomon watershed is 0.94 in., which represents only 4% of the average annual precipitation (23.29 in./yr). During 1980–1981, the groundwater appropriations in the Glade subwatershed, which reached 146,182 ac-ft, compared to 13,860 ac-ft in 1960–1961, amounted to more than 4.7 times the amount of estimated natural groundwater replenishment for that subwatershed.

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