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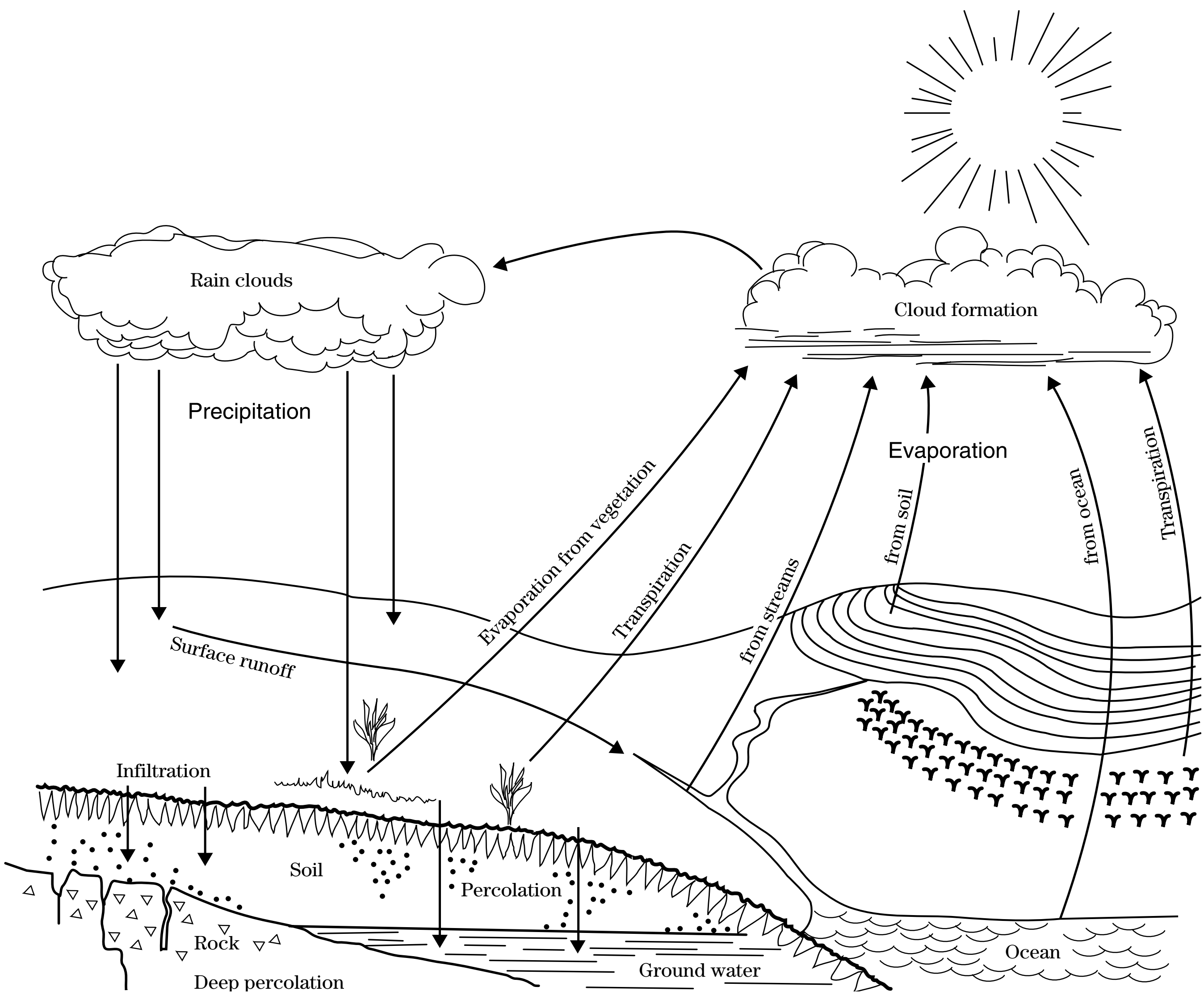
National Engineering Handbook

Chapter 20 Watershed Yield



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630.2000 Introduction

Watershed yield, or water yield, is useful in some planning and design activities. The term, however, is somewhat loosely used in the literature and can refer either to a long-term average (e.g., 1971–2000 average annual streamflow) or can be synonymous with runoff volume for a specific period (e.g., flow for May 1999). The period referred to is most often either a year or a month, but one could also consider a day or any other period in between. For the purposes of this chapter, consider water yield to be long-term average flow, although the concepts described are not limited to this. The term yields is used to convey the idea that only a volume of water is being referred to, as opposed to a hydrograph; i.e., no information is given about the time distribution of flow within the period.

Long-term averages provide sufficient information to determine representative conditions without any knowledge of the expected variation in the record. Without estimates of variability, these average values are of fairly restricted usage. For some planning and design purposes, the flows for certain exceeding probabilities, such as 10 percent or 90 percent, may be more important to know. For this, distribution functions are necessary, requiring the application of statistical methods. See NEH630.18, Statistics, for a description of statistical methods.

NEH630.20 reviews basic water balance concepts as well as some general calculation methods and suggested data sources.

630.2001 Water balance

Considering hydrologic processes taking place continuously in the watershed, the water yield, i.e., the net amount of water flowing past a given point on a stream during a given period, can be described by a basic water balance equation:

$$Q = P + I - ET - G - \Delta S - D \qquad \text{(eq. 20–1)}$$

where:

Q = streamflow
P = precipitation
I = import of water into the watershed
ET = evapotranspiration
G = net export of ground water
ΔS = change in moisture storage
D = diversions out of the watershed

The unit used in this equation is arbitrary as long as it is applied consistently to all parameters.

Several of the terms in the equation are themselves an integration of many subprocesses and can be difficult to evaluate. The shorter the time period considered, the more important the short-term dynamics become, and therefore, quantifying some of these terms, particularly ΔS and G, is more complex. Over long periods, such as a year or more, these two terms generally become small because of time averaging and are often considered to be negligible. The net export of ground water, however, can be important, particularly in areas of unique geology, such as the lava fields in the Snake River Plain of Idaho or in karst areas. The I and D terms are important in irrigated areas, or where large water supply works divert water into or out of the watershed. A more detailed consideration of each term in the water balance equation is given later.

630.2002 Methods of computing water yield

Estimating water yield can be done in several ways. The method chosen depends on the data availability, the time period desired, and whether long-term averages or estimates for a given period are to be made. Methods used to estimate water yield include:

- runoff map
- regression equations
- water balance

(a) Runoff map

The simplest method is to read a value from a map, if one exists. In some States and regions, maps with contours of equal average annual or monthly runoff (in terms of depth) have been produced. There is no comprehensive set of such maps, nor is there a uniform method for their production, so those that exist vary widely in content and quality. To find out if a particular one exists, one should consult local technical experts. A basic reference is U.S. Geological Survey (USGS) Hydrologic Atlas 71, Average Annual Runoff in the United States 1951–1980.

(b) Regression equations

In some areas, special studies have been conducted to develop multiple regression equations to predict water yield from precipitation and watershed characteristics. For example, Hawley and McCuen (1982) developed an equation to predict average annual water yield for each of five regions in the Western United States. The equations from these studies, however, are location specific and should not be used in any other areas. Local experts should be consulted for information on the existence and applicability of regional equations.

The most important variable in the regression equations is precipitation; therefore, the key to using this method is to have a good estimate of watershed average precipitation for the time period of interest. The best current source for annual and monthly averages are the maps and geographic information system (GIS) data layers developed in the PRISM project, sponsored by the NRCS National Water and Climate Center in Portland, Oregon. See 630.2003, Data sources, for details.

Other watershed characteristics, such as mean elevation or watershed area, can be obtained by analyzing topographic maps, or better yet, by using digital elevation models within a GIS.

The National Water and Climate Center provides seasonal water yield estimates of 700 locations in the Western States and have information about past events which can be helpful to determine monthly and annual water yields.

(c) Water balance

The most comprehensive method to estimate water yield is to quantify each term in the water balance equation. The simplest and most feasible case is for average annual water yield, in which some simplifying assumptions can be made to make the problem more manageable. If, however, all terms of the water balance can be reliably estimated, a water balance for monthly averages or for annual, monthly, or even daily time series can be computed. A hydrologic model is required, however, for time series computation, when determining monthly or shorter duration water balances.

Thornthwaite and Mather (1955) first developed the concept of a climatological water balance and a standard method for calculating it. Their method was originally applied at a monthly time step to obtain long-term averages of each term in the water balance equation (although it did not explicitly consider the I, D, or G terms). It has also been applied at a daily time step and has been used to simulate monthly time series. The Thornthwaite and Mather model, and other similar models, represented an important step in estimating water yield. More recent hydrologic simulation models predict daily or subdaily time series, hence requiring a great deal of input data and giving detailed output, which is beyond the scope of what is usually referred to as annual water yield. These models have the potential to provide more detailed estimates of water yield if there is enough data to calibrate the model.

Evaluating the water balance terms for a given time period is not simple because the variances are the integration of many complex processes operating at different spatial and temporal scales. This is why a monthly water balance model needs to be used with care. These models can compute the water balance to a certain approximation, of course, but some variability will be masked because the time scale of the processes is much smaller than the time scale of the model.

The easiest situation is to make the assumption that ΔS and G are near zero, in which case the most important loss becomes ET, and water yield is simply what is left of water input (precipitation plus water import minus export) after subtracting evapotranspiration losses. As with the regression equation method, the most important input is to have an accurate estimate of watershed average precipitation. In irrigated areas and where water diversion projects exist, good data are required to estimate the I and D terms in the water balance equation so that all watershed inputs are known.

A few comments about each of the water balance terms follow.

Precipitation (P)—A fundamental issue in computing a water balance is to estimate accurately the total precipitation input to the watershed. This can be done in a variety of ways depending on the available data and the spatial variability of precipitation in the watershed of interest.

In areas of relatively uniform terrain and little spatial variability of precipitation, classical textbook procedures, such as Thiessen polygons or the isohyetal method, can be used and are generally adequate. These procedures are simple methods of developing spatial averages from point measurements, but are inadequate to describe orographic or other spatially variable behavior of any appreciable complexity. In these cases, such as in mountainous areas, more comprehensive algorithms are needed to develop spatial averages from point measurements that describe the elevational (vertical) and horizontal variability. For time series at the watershed scale, the algorithm based on detrended kriging developed by Garen, Johnson, and Hanson (1994) is an example. (Further information on this procedure is available from the NRCS National Water and Climate Center in Portland, Oregon.) For annual or monthly averages or monthly time series at somewhat larger spatial scales (watershed to regional), the best method is to use the PRISM maps and GIS layers, as mentioned previously. This would be the recommended procedure in most watershed yield analyses.

Evapotranspiration—Evapotranspiration (ET) is difficult to estimate because it is a complex process. It is determined by the atmospheric demand for water vapor (potential ET) and the availability of water to be evaporated. ET is a sum of pure evaporation from free water surfaces, such as wet vegetation, puddles, and lakes, and the transfer of soil moisture through plants and out their leaves (transpiration). The former process depends only on the atmospheric conditions (temperature, humidity, wind), whereas the latter also depends on plant characteristics (stomatal resistance) and on soil moisture availability.

Many models are available for estimating potential evapotranspiration from meteorological data (Jensen, Burman, and Allen 1990; ASCE 1996). They vary in their assumptions, the processes described, the input data required, and the temporal scale for which they are appropriate. Potential ET can also be estimated from pan evaporation data if a suitable pan coefficients are available.

Even if potential ET is adequately estimated, the actual ET is less than or equal to this amount and depends primarily on soil moisture availability. Because of this interplay between the atmospheric demand and the soil moisture, determining actual ET is problematic without a detailed hydrologic model operated at a short time step (i.e., a day or less). If adequate assumptions can be made, however, reasonable estimates of actual ET as a fraction of potential ET are possible.

Net ground water export (G)—Knowing whether an appreciable net export (or import) of ground water even exists requires a good knowledge of the geology of the watershed. Even in areas where significant ground water phenomena are known to exist, estimates of the amount of these losses are difficult to make and to differentiate from other losses to the watershed.

Channel transmission losses are also included in this term. These losses are particularly important in arid areas where a significant amount of streamflow is absorbed by the porous streambank and streambed material. They represent a net loss from the channel system.

Storage change (ΔS)—Storage change encompasses any place where water can be temporarily stored in the watershed and can include plant surfaces, snowpack, puddles, and the soil depressions, lakes and reservoirs, ponds, wetlands, soil moisture, and aquifers. The capacity of some of these is relatively small and can be safely ignored as long as the time considered is sufficiently large. For example, if a period that begins and ends with dry plant surfaces were considered, then this would contribute nothing to a change in storage. Similarly, no snowpack change in storage occurs if the period began and ended with no snow on the ground. For an annual water balance, the change in soil moisture and aquifer storage is often assumed to be small because the period begins and ends at the same point in the annual cycle. This is appropriate for the average annual water balance, but may not be true for specific sequential years. It is certainly not true for periods of less than a year. If a watershed contains a large storage reservoir (or perhaps even a natural lake whose level can fluctuate significantly), the change in storage must be accounted for, requiring data on the volume of water stored at the beginning and end of the period.

Imports and diversions (I, D)—Imports of water from other watersheds or diversions out of the watershed occur typically in dry areas where irrigated agriculture is important or where large facilities for urban water supply have been developed. Since these are human works, rather than natural processes, they can only be evaluated using measured flow data from the operating agencies.

Various State and Federal agencies have produced reports describing the development of water budgets for selected areas. USGS Circular 1308 has a good description of water budget development and includes many examples. The Thornthwaite-Mather procedure for calculating recharge from the soil moisture balance can be used to develop monthly and annual water budgets. Soil-Plant-Atmosphere-Water (SPAW) is a daily hydrologic budget model for agricultural field and ponds (wetland, lagoons, ponds, and reservoirs). This model was developed by Agricultural Research Service (ARS) and has the capabilities to estimate both monthly and annual watershed yield. It also has an option to evaluate wetlands and make a reservoir operation study.

Example

A water budget is needed for a proposed site in southern New Jersey. It can be assumed that the coefficient to convert pan evaporation to ET is 0.7, and that National Oceanic and Atmospheric Administration (NOAA) Technical Report NWS 34 will be used as the source of evaporation data. It can be assumed is that the storage at the beginning of the calendar year is full and the deficient moisture will be taken from the storage. The annual yield is about 19 inches. Develop a monthly budget for the site.

- Determine the average monthly precipitation from the nearest rain gage.
- Determine the monthly pan evaporation from the NOAA Technical Report NWS 34.
- Determine the monthly ET using a 0.7 coefficient.
- Develop the monthly runoff assuming the storage is full in January and there will be no change in storage during the months when precipitation exceed ET and the change in storage for the year will be zero.

Month	Precipitation (in)	Pan evaporation (in)	ET (in)	Change in storage (in)	Runoff (in)
January	3.43	1.58	1.11	0.00	2.32
February	3.66	1.78	1.25	0.00	2.41
March	4.28	2.99	2.09	0.00	2.17
April	3.46	3.52	2.46	0.00	1
May	3.53	5	3.50	–0.97	1
June	3.88	5.47	3.83	–1.15	1.2
July	4.83	5.32	3.72	–0.39	1.5
August	5.12	4	2.80	0.32	2
September	4.88	4.56	3.19	–0.81	2.5
October	3.35	3.22	2.25	0.97	0.13
November	3.67	2.21	1.55	1.57	0.55
December	3.66	1.56	1.09	0.47	2.1
Totals	**47.75**	**47.77**	**28.85**	**0.00**	18.88

630.2003 Reservoir storage planning

(a) Determination of storage requirements to meet supply-demand relations

Purpose and scope

The purpose is to demonstrate techniques and procedures for determining the storage of water for use at a later date. The increasing demands for surface-water supplies for irrigation, recreation, municipal, industrial, and urban developments have emphasized the need for more information and study on the storage of water.

The storage provided depends upon the interrelationship between supply, losses, demand, and their respective distributions throughout the year, as well as the economics based upon the cost of storage against the benefits from use. This section provides examples using varying intensities of analyses to solve storage problems and consider some of the important factors.

Nomenclature and description of terms used are:

- supply—inflow at proposed site of reservoir
- losses—reservoir seepage and net lake evaporation (lake evaporation minus precipitation)
- water use—the amount of water available at the reservoir site. Losses between the reservoir outlet and the point of actual beneficial use should be included as part of the water use.

The solution of the storage problem requires the consideration of the following factors.

Legal aspects of water storage

The State and local laws governing the storage and use of water transcends all other considerations and complicate the study of water storage. Therefore, it is essential to first determine specifically the conditions under which water can be stored and used. This will answer the questions of by whom, when, and to a degree, how much water can be stored for future use.

Supply

Monthly and annual runoff amounts—The monthly and annual runoff values must be determined for a period of time long enough to reflect the “long-time” variability of runoff. Mean monthly values should be computed and used to determine the monthly percentages of the mean annual runoff. A frequency curve should be developed for the series of annual runoff (NEH630.18).

Distribution of monthly values for any given percent chance annual yield is made according to the monthly percentages of the mean annual flow. This is not exactly true, but furnishes reasonable estimates for short-cut procedures.

Mass-flow diagram—The mass-flow diagram is extremely valuable in the study of storage requirements or the determination of the flow which could be assured with a given amount of storage. The mass-flow curve is the integral of the hydrograph; the abscissa being in units of time and the ordinate at any point being the total volume of flow that passed that point since zero time. The time unit is days, which may be accumulated by months and plotted versus the volume unit second-foot-day. The slope for the curve at any point indicates the rate of change of volume with respect to time and is thus a rate of flow. Since the units are second-foot days and days, the rate of flow becomes cubic feet per second. Many kinds of data can be studied by the mass-diagram technique, but proper conversion units are essential.

Watershed condition—The drainage area above the reservoir site should be examined to determine important hydrologic characteristics such as soils, land use, and climatic variability. Possible future changes in land use that may affect runoff should be considered. Other upstream changes that would influence future runoff, such as additional storage, irrigation, municipal, domestic, and industrial uses should also be considered.

Frequency of supply criteria—A frequency of total annual supply should be selected based on the intended use and the adverse results of supply shortages during some years. For irrigation, it is common NRCS practice to use the 80 percent probability as a minimum criteria. This criteria provides, on the average, a complete annual supply 4 in 5 years and would permit a shortage during 1 in 5 years. There are some irrigated crops that may indicate the probability should be raised to 90 or 95 percent and others where a design probability of 70 percent or less will be adequate to provide an economical design. The hydrologist should be certain the water user has a complete understanding of the probability of supply criteria used.

Storage

Storage, as used here, is net storage and does not include the amount required to provide for future sediment accumulation. Net storage does include use, reservoir evaporation, and seepage. Estimates of sediment storage requirements will be furnished by the geologist.

Survey of reservoir site—A survey of the reservoir site is made to determine elevation, surface area, and capacity relationships. The required capacity must provide storage for sediment, use, losses, and flood water. Specific site conditions, such as spillway location, may place limitations on the available storage.

Demand

Potential annual demand—An estimate of the potential annual demand consisting of use, reservoir evaporation, and seepage will have to be made. The use value should reflect all losses associated with the transit of water from the reservoir to the point of use and the actual efficiency of use to show the demand at the reservoir. This information is normally provided by the irrigation engineer or other engineers concerned with the water use requirement. The potential annual supply value is then compared with the annual runoff values. The average annual runoff is the average maximum amount that could be supplied through "carry-over" storage. Reservoir evaporation and seepage losses would reduce this maximum amount. The average potential demand may be larger than the average annual runoff. In this case, it is known that demand cannot be satisfied and lower amounts will have to be considered. The potential demand may be less than the minimum year of record. In this case, the annual supply is adequate, but the seasonal distribution of supply and demand are important items.

Distribution of demand during year—This distribution will normally be furnished to the hydrologist by other engineers concerned with the intended use of the water supply. The monthly demand should be determined in units of percent of total annual demand. The actual monthly demand may be determined by the product of the monthly percent and the selected total annual demand. Determining the monthly demand in percent will facilitate the computations of actual monthly demand when several values of total annual demand are being considered. The demand distribution should be compared with the average monthly runoff distribution. If the runoff distribution is predominantly during one period of the year, the comparison will be of assistance in estimating storage required to provide a given supply. For example, in many areas, a high percent of the annual runoff occurs during the winter and spring seasons. If the water use is for irrigation during July, August, and September, it will be necessary to store an amount nearly equal to total demand plus reservoir losses due to evaporation and seepage.

Reservoir losses—All possible reservoir losses must be considered. The principal losses are generally evaporation and seepage. A geologist should be requested to furnish estimated rates of permeability and/or transmissibility. The hydrologist will determine seepage losses using monthly values of surface area and the associated permeability and/or transmissibility rates. Evaporation losses may be estimated on a monthly basis if past evaporation and precipitation records are available. Evaporation, like many climatic elements, is a variable. The past record should be long enough to reflect the long-time variability of net evaporation.

Adequate evaporation data will not be available for many reservoir locations. Where this is the case, it is suggested that evaporation estimates should be made on an annual, seasonal, or monthly basis using the NOAA publication, Technical Report NWS 34, Mean Monthly, Seasonal, and Annual Pan Evaporation for the United States.

If average annual evaporation, precipitation, and water surface area are used in estimating annual evaporation losses, these estimates will be too low during the years of above normal net evaporation. The standard deviation of evaporation is available in NOAA Technical Report NWS 34. This value may be added to the average value to obtain an evaporation that represents conditions during the years of higher losses.

The average surface area may be determined from the storage-surface area relationship and the mean storage. If there is a definite change in storage during the seasons, the evaporation and seepage losses may be computed separately for the May through October period and the November through April period. Evaporation data on the two periods are obtained from NOAA Technical Report NWS 34. In this case, a different average surface area is used for each period.

Example

The construction of a storage reservoir on Council Creek near Stillwater, Oklahoma, has been proposed. The purpose of the storage is to provide irrigation water during the summer months. The area to be irrigated is located downstream from the reservoir site.

Legal aspects of water storage—In this example, water appropriation rights authorize the storage of the total runoff that occurs from October 1 through May 31 of any year. An amount equivalent to the runoff that occurs from June 1 through September 30 must be released from the reservoir as it occurs.

Supply—The drainage area at the reservoir site is 31 square miles (19,840 acres). A recording stream gage is located immediately below the structure site. Records are available from April 1934 through 1958. Analysis of the double mass curves of surrounding stations indicates this period to be representative of the long-term average.

A nonrecording precipitation gage with records from 1931 to 1958 is located at Stillwater, Oklahoma. Pan evaporation and wind records are available from 1948 through 1957 at Stillwater. A first-order Weather Bureau Station record is available at Oklahoma City, Oklahoma, where all the climatalogical factors are recorded that are necessary in the determination of evaporation from reservoir.

Monthly and annual runoff amounts—The monthly and annual runoff amounts for October through May for water years 1935 through 1958 were determined from the records. This period of time reflects the long-time variability of runoff.

Watershed condition—For this example, land use and climate are not considered. Additional demands for use are not foreseen during life expectancy of the project.

Frequency of supply criteria—A frequency curve was developed for runoff from October through May for water years 1935 through 1958. The 80 percent probability from this curve was used as the minimum supply (fig. 20–1).

The distribution of the 80 percent supply was made according to the percentage distribution of the mean monthly values of October through May for the period of record, 1935 through 1958.

Storage—A survey of the reservoir site provided information for the preparation of the elevation-surface area and elevation-storage curves (fig. 20–2). The geologist estimated the sedimentation rate to be 0.2 acre-foot per square mile per year. With a life expectancy of 50 years and a drainage area of 31 square miles, the required storage for the sediment pool is 310 acre-feet. The invert of the intake is set at the elevation of the top of the sediment pool. The principal spillway crest is set at the indicated maximum required storage and the emergency spillway crest at the elevation dictated by design criteria. Flood water is detained between the crest of the principal spillway and the emergency spillway crest.

Demand—The estimate of the potential annual demand consisted of making estimates of the net lake evaporation and reservoir seepage losses plus the intended use by months. Net lake evaporation was computed by subtracting mean monthly precipitation at Stillwater from the mean monthly lake evaporation. The mean monthly use requirements for the proposed project are shown in line 8 of table 20–1.

A water budget equation can be written as follows: watershed yield at point of storage plus precipitation on reservoir minus dead storage, required releases, evaporation, transpiration, and seepage equal the amount available for use. When any of these items are small, they may be omitted for simplicity.

Approximation using annual values—For approximations, it is possible to use annual values developed from regionalizations of specific data. This involves the use of isolines of annual runoff and evaporation. USGS presents the distribution of average pan annual runoff in the United States. NOAA Technical Report NWS 34 shows the distribution of average annual evaporation in the United States. With a map study of the proposed site and estimates of annual losses based

Figure 20–1 Water yield October through May 1935 to 1958, 80 percent chance 810 acre-feet near Stillwater, OK

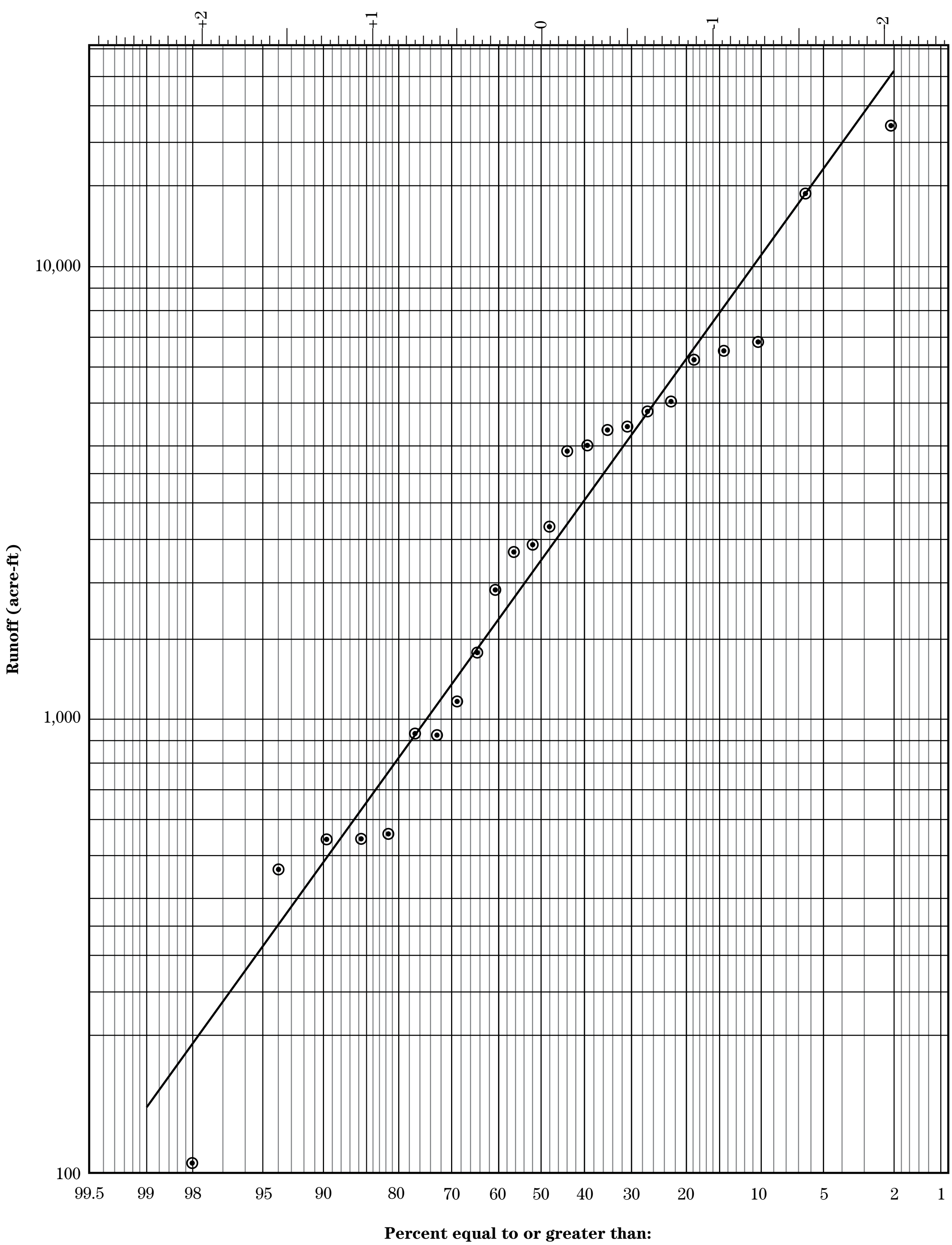


Figure 20–2 Reservoir site on Council Creek, near Stillwater, OK

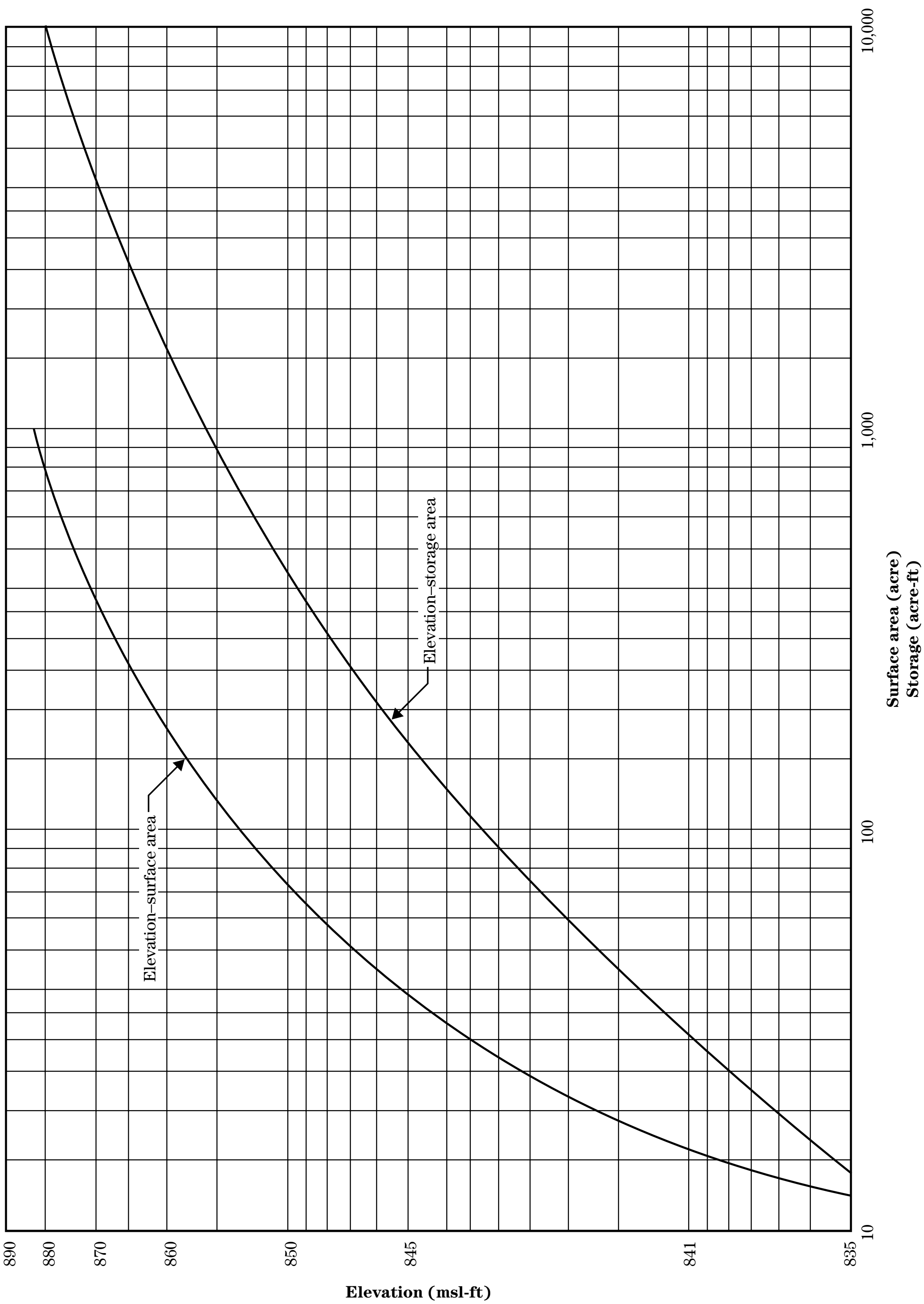


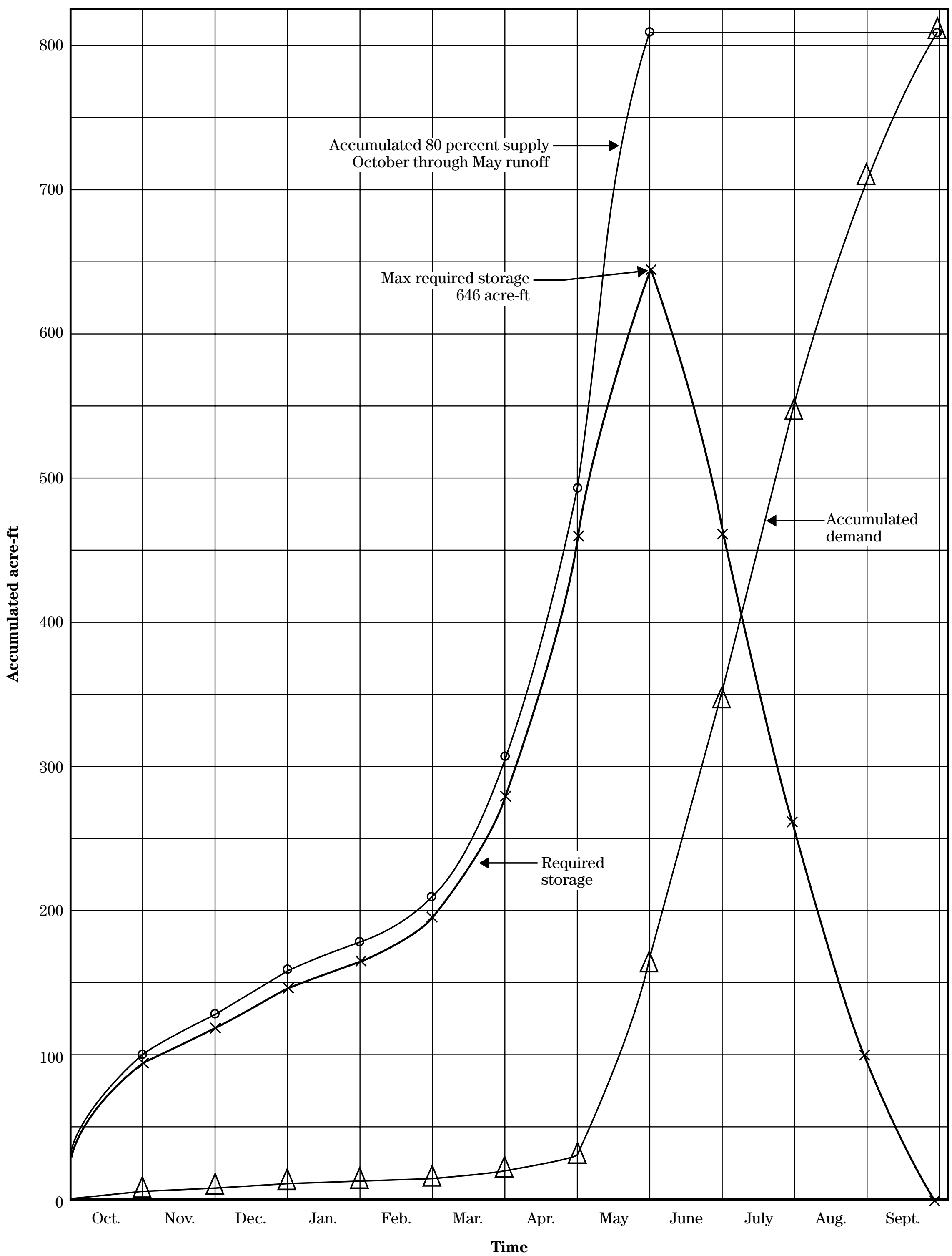
Table 20–1 Council Creek near Stillwater, OK, storage required to meet supply-demand relationship

Line	Item	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Year
1	Mean monthly supply acre-ft	493	179	134	107	144	494	926	1571	1248	620	508	439	
2	Accumulated mean monthly acre-ft	493	672	806	913	1057	1551	2477	4048	No storage allowed				
3	Accumulated mean monthly %	12.2	16.6	19.9	22.6	26.1	38.3	61.2	100					
4	Accumulated 80% probability acre-ft	99	134	161	183	211	310	496	810	810	810	810	810	66
5	Lake evaporation (ES–1016) in	6.3	3.5	2	1.5	1.9	3.1	4.7	5.5	7.8	10.2	10.7	8.8	
6	Precipitation (Stillwater, OK) in	2.85	2.01	1.35	1.14	1.27	2.16	3.53	4.83	4.08	2.98	3.05	3.62	32.87
7	Net lake evaporation ft	0.287	0.124	0.054	0.030	0.052	0.078	0.098	0.056	0.310	0.602	0.638	0.432	2.761
8	Mean monthly use acre-ft								288	362	362	294	192	1498
9	Accumulated mean monthly use acre-ft								288	650	1012	1306	1498	
10	Accumulated mean monthly use %								19.23	43.39	67.56	87.18	100.0	
11	Average mean monthly 80% prob. supply acre-ft	50	116	148	172	197	260	403	653	810	810	810	810	
Trial No. 1														
12	Use acre-ft								125	157	157	128	83	650
13	Accumulated use acre-ft								125	282	439	567	650	
14	Mean monthly use acre-ft								62	204	360	503	608	
15	Accumulated mean monthly storage (line 11–14)	50	116	148	172	197	260	403	591	606	450	307	202	
16	Elevation assoc. with 15 ft	841.7	843.7	844.6	845.2	845.8	847.3	849.5	852	852.2	850.3	848	845.9	

Table 20–1 Council Creek near Stillwater, OK, storage required to meet supply-demand relationship—Continued

Line	Item	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Year
17	Surface area assoc. with 16 acres	18	30	35	38	42	50	67	86	88	73	56	42	
18	Seepage acre-ft	1	1	1	1	1	2	3	4	4	3	2	1	
19	Evaporation (line 7×17) acre-ft	5	4	1	1	2	4	7	5	27	44	36	18	
20	Use acre-ft	—	—	—	—	—	—	—	125	157	157	128	83	
21	Demand acre-ft	6	5	2	2	3	6	10	134	188	204	166	102	
22	Accumulated Demand acre-ft	6	11	13	15	18	24	34	168	356	560	726	828	
Trial No. 2														
12	Use acre-ft								121	152	152	124	81	630
13	Accumulated use acre-ft								121	273	425	549	630	
14	Mean monthly use acre-ft								60	197	349	487	590	
15	Line 11–14 (Est. storage) acre-ft	50	116	148	172	197	260	403	593	613	461	323	202	
16	Elevation assoc. with line 15 ft	841.7	843.7	844.6	845.2	845.8	847.3	849.5	852	852.3	850.4	848.1	846.3	
17	Surface area assoc. with line 16 acres	18	30	35	38	42	50	67	86	89	74	57	45	
18	Seepage acre-ft	1	1	1	1	1	2	3	4	4	3	2	1	
19	Evaporation (line 7×17) acre-ft	5	4	1	1	2	4	7	5	28	45	36	19	
20	Use acre-ft	—	—	—	—	—	—	—	121	152	152	124	81	630
21	Demand (line 18+19+20) acre-ft	6	5	2	2	3	6	10	130	184	200	162	101	
22	Accumulated Demand acre-ft	6	11	13	15	18	24	34	164	348	548	710	811	
23	Required storage (Line 4–22) acre-ft	93	123	148	168	193	286	462	646	462	262	100	–1	

Figure 20–3 Accumulated 80 percent supply for October through May for proposed reservoir near Council Creek, OK



upon the best knowledge available, a reasonable water budget can be determined by applying the water budget formula. This will be an approximate answer to the question of whether, on the average, the annual storage available for use will meet the estimated needs. In most cases, however, we are concerned with adequacy of the seasonal distribution. The use of average annual values will not adequately answer this question, but it will indicate feasibility and whether there is justification in making a more detailed study.

Approximation using probability of annual supply and estimated losses—The 80 percent probability of supply (810 acre-ft) was taken from the frequency curve in and distributed by months according to the accumulated mean monthly values in table 20–1. The accumulated 80 percent supply for October through May is shown in figure 20–3.

An estimate of the accumulated mean monthly storage was made by subtracting the accumulated mean monthly use from the accumulated mean monthly 80 percent probability of supply (line 15, table 20–1). With this estimated storage and its associated elevation, surface area, and figures 20–2 and 20–4, the reservoir evaporation and seepage were computed. The accumulated demand should be equal to or less than the supply, or a new trial must be made after decreasing the use. The example shown in table 20–1 and figure 20–3 illustrates how the use had to be reduced so the demand would not exceed the supply. The original proposal of use (1,498 acres) exceeded the supply (810 acre-ft) without considering losses, therefore, the use had to be reduced.

The results of using the 80 percent probability of annual supply and estimated losses were checked by the water budget analysis using observed data. During water-short years of 1950 and 1951, the required storage estimate of 646 acre-feet was sufficient to satisfy the indicated use, but this was far below the proposed use of 1,498 acre-feet.

Approximation using storage—The original proposal was to provide 1,498 acre-feet of use distributed by months as shown in line 8, table 20–1. It has been shown the 80 percent probability of supply would not supply the proposed use, but with carry-over storage, it might. A procedure for the estimation of required storage follows with the results shown in figure 20–5.

- Plot the accumulated runoff for a critical low flow period (1949–1952).
- Superimpose the accumulated use curve on the mass runoff diagram with time ordinates coinciding and the use line tangent to the mass curve at starting time. The use curve must intersect the mass runoff curve. The maximum ordinate value (1800) between the accumulated runoff and the accumulated use represents the maximum needed storage without consideration of storage needed to satisfy reservoir evaporation and seepage losses. This storage value is used as the mean storage value to determine mean surface elevation from which estimates can be made of the reservoir evaporation and seepage losses.
- An accumulated demand curve is developed by summing the values of use, reservoir evaporation and seepage losses.
- The accumulated demand curve is superimposed on the accumulated mass curve in a similar manner to the use curve. The maximum ordinate between the accumulated runoff curve and the accumulated demand curve is the required storage.

The results of this analysis were checked by the water budget approach and found to more than adequately provide the needed storage for water-short years 1949 through 1951.

Water budget analysis—The water budget computation is a trial-and-error procedure. One must estimate the average monthly water budget from which the average monthly elevation can be obtained. This is then compared with the computed average monthly water surface elevation. This should be in agreement; if not, a new estimate of elevation should be made and the computed elevation recalculated.

Figure 20–4 Council Creek near Still Water, OK reservoir seepage

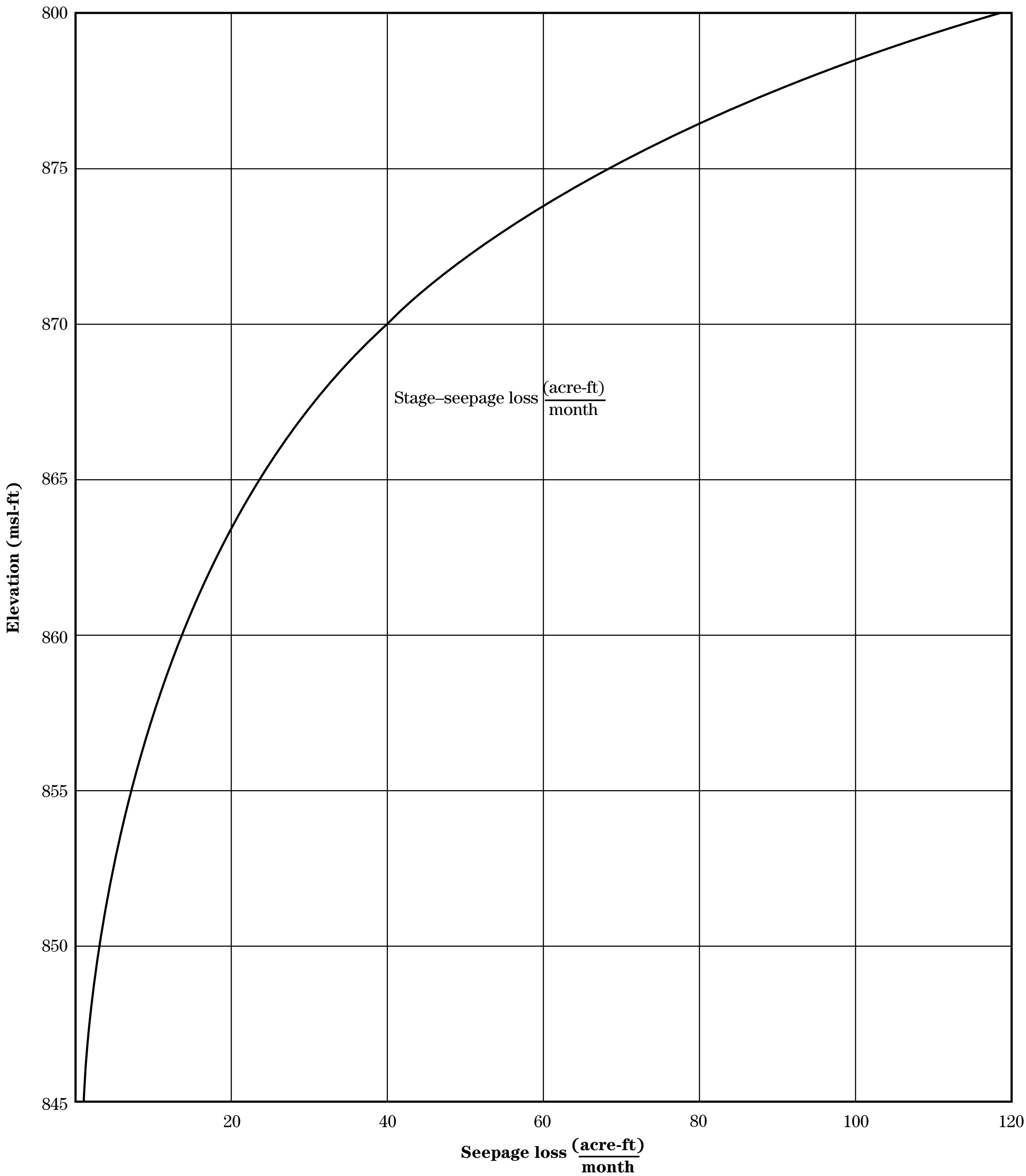
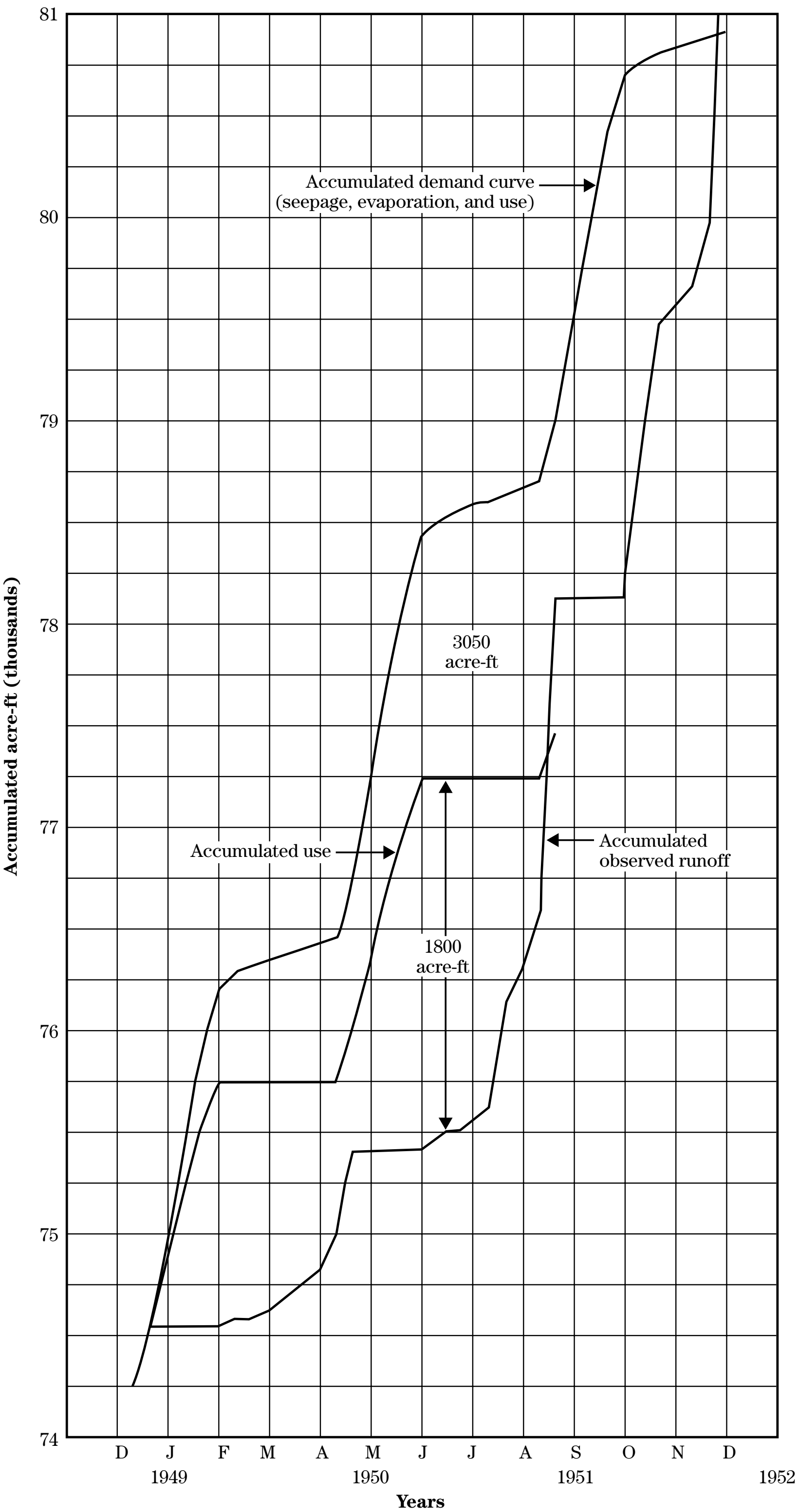


Figure 20–5 Results of Council Creek near Stillwater, OK,. storage



The basic water budget equation can be written as follows:

$$U = S + I - E - E_s - Q_S - R \qquad \text{(eq. 20–2)}$$

where:
U = water available for use, acre-ft
S = water storage above the intake elevation, acre-ft
I = inflow watershed yield, acre-ft
E = evaporation, acre-ft
E_s = seepage out of reservoir, acre-ft
Q_s = spillway discharge, acre-ft
R = required reservoir release, acre-ft

The geologist provided a geologic cross section through the reservoir site with log-borings indicating the type of materials present and their permeability rates. These rates were associated with stratum elevations and appear in column 5 of table 20–2.

The assumptions for this example are as follows:

- Seepage into the ground occurs in this particular reservoir site.
- The laws of seepage apply.
- Hydraulic gradient developed is assumed to be 1:1 or 100 percent.
- Seepage loss equilibrium exists.
- The site consists of uniform material.

Table 20–2 for reservoir seepage losses was prepared as follows:

Col. 1 Elevation (ft) mean sea level (msl) datum.

Col. 2 Surface area (acre) (fig. 20–2)

Col. 3 Incremental surface area (acre): difference in surface area associated with the elevation in question and the previous elevation

Col. 4 Storage (acre-ft) total storage associated with elevation in question. (fig. 20–2)

Col. 5 Seepage loss (ft/mo) (furnished by geologists)

It is expected that laboratory tests of undisturbed samples for the reservoir site and the borrow area will be available for making the estimate of seepage loss.

Col. 6 Incremental seepage loss (acre-ft/mo) column 6 equals column 3 times column 5.

Example: Elevation 846

Col. 6 $6 = (43)(.03) = 1.29$ acre-ft/mo

Col. 7 Summation seepage loss (acre-ft) This is the accumulation of incremental seepage losses.

Example: Elevation 848

Col. 7 $7 = (13)(.03) + 1.29 + 1.68$ acre-ft/mo

Figure 20–4 is plotted from items 1 and 7 of table 20–2. Figure 20–5 is a plot of the resulting graphical solution to the water budget of Council Creek near Stillwater, OK.

Water budget computations were prepared as illustrated in table 20–3. An explanation of the column headings and the method of computing the data in each column are described:

Col. 1 Year

Col. 2 Month

Col. 3 Runoff (acre-ft) total watershed yield from recording stream gage record at site or from regional estimate

Col. 4 Estimated average water surface elevation for the month (ft). An estimate is made of the water budget as follows:

Summation for month in question (Σ) col. 12 (previous month+col. 3–col. 7 –col. 8–col. 9–col. 10–col. 11=col. 12 storage at end of current month (acre-ft) Determine stage associated with the average of col. 12 (previous month) and col. 12 current month storage. This estimated stage col. 4 is then used for computing actual values.

Col. 5 Water surface area in reservoir (acre) for stage in col. 4 (from stage-area curve for the reservoir)

Table 20–2 Reservoir seepage losses

Column 1 Elevation (ft msl)	Column 2 Surface area (acre)	Column 3 Δ surface area	Column 4 Storage (acre-ft)	Column 5 Seepage rate (ft/mo)	Column 6 Δ seepage (acre-ft/mo)	Column 7 Σ monthly seepage (acre-ft)
		43		0.03	1.29	
846	43		211			1.29
		13		.03	.39	
848	56		310			1.68
		14		.09	1.26	
850	70		436			2.94
		16		.09	1.44	
852	86		592			4.38
		18		.09	1.62	
854	104		782			6.00
		21		.09	1.89	
856	125		1011			7.89
		23		.09	2.07	
858	148		1284			9.96
		25		.12	3.00	
860	173		1605			12.96
		30		.12	3.60	
862	203		1981			16.56
		37		.12	4.44	
864	240		2424			21.00
		40		.12	4.80	
866	280		2944			25.80
		45		.12	5.40	
868	325		3549			31.20
		55		.15	8.25	
870	380		4254			39.45
		60		.15	9.00	
872	440		5074			48.45
		70		.15	10.50	
874	510		6024			58.95
		85		.21	17.85	
876	595		7129			76.80
		95		.21	19.95	
878	690		8414			96.75
		110		.21	23.10	
880	800		9904			119.85

Table 20–3 Water budget analysis for Council Creek Watershed near Stillwater, OK

1 Year	2 Month	3 Runoff (acre-ft)	4 Est. avg. monthly water surface elevation (ft)	5 Est. avg. water surface area (acre)	6 Evaporation (ft)	7 Evaporation (acre-ft)	8 Seepage (acre-ft)	9 Reservoir release (acre-ft)	10 Spillway discharge (acre-ft)	11 Demand (acre-ft)	12 Storage at end of month (acre-ft)	13 Water surface elev. at end of month (ft)	14 Computed avg. storage for month (acre-ft)	15 Elev. for avg. monthly storage (ft)
	Mar.								0		0			
1949	Apr.	85	841.3	15	0.459	7	0	0	0	0	78	842.9	39	841.3
	May	4470	859.9	173	0.51	88	13	0	1397	0	3050	866.5	1564	859.9
	June	121	865.6	270	0.68	184	24	121	0	274	2568	864.7	2809	865.6
	July	105	863.8	237	0.721	171	20	105	0	238	2139	862.9	2354	863.8
	Aug.	6	861.9	202	0.685	138	17	6	0	242	1742	860.9	1940	861.9
	Sept.	289	860.5	182	0.507	92	14	289	0	0	1636	860.2	1689	860.5
	Oct.	38	860.2	178	0.309	55	13	0	0	0	1606	860.1	1621	860.2
	Nov	13	860	175	0.202	35	13	0	0	0	1571	589.9	1588	860
	Dec	24	859.9	173	151	26	13	0	0	0	1556	859.8	1563	859.9
	Subtotal	5151				796	127	521	1397	754	1556	Check		
1950	Jan.	72	860	175	0.122	21	13	0	0	0	1596	860	1575	860
	Feb.	64	860.1	177	0.166	29	13	0	0	0	1616	860.2	1605	860.1
	Mar.	54	860.1	177	0.371	29	13	0	0	0	154	860.7	1604	860.1
	Apr.	157	860.1	177	0.606	107	13	0	0	0	1628	860.2	1610	860.1
	May	498	860.7	184	0.531	98	14	0	0	184	1830	861.3	1729	860.7
	June	382	859.7	168	0.641	108	13	382	0	413	1296	858.2	1513	859.7
	July	5020	858	148	0.415	61	10	5020	0	0	1225	857.7	1260	858
	Aug.	1170	857.1	137	0.497	68	9	1170	0	107	1041	856.4	1133	857.1
	Sept.	104	855.8	123	0.352	43	8	104	0	100	890	835.1	966	855.8
	Oct.	21	855	114	0.386	44	7	0	0	0	860	854.8	875	855
	Nov.	35	854.8	113	0.228	26	7	0	0	0	862	854.8	861	854.8
	Dec.	32	854.8	113	0.14	16	7	0	0	0	1	854.9	866	854.8
	Subtotal	7609				687	127	6676	0	804	1	Check		
1951	Jan.	75	855.1	117	0.17	20	7	0	0	0	919	855.3	895	855.1

Table 20–3 Water budget analysis for Council Creek Watershed near Stillwater, OK—Continued

1 Year	2 Month	3 Runoff (acre-ft)	4 Est. avg. monthly water surface elevation (ft)	5 Est. avg. water surface area (acre)	6 Evaporation (ft)	7 Evaporation (acre-ft)	8 Seepage (acre-ft)	9 Reservoir release (acre-ft)	10 Spillway discharge (acre-ft)	11 Demand (acre-ft)	12 Storage at end of month (acre-ft)	13 Water surface elev. at end of month (ft)	14 Computed avg. storage for month (acre-ft)	15 Elev. for avg. monthly storage (ft)
	Feb.	514	857.2	139	0.155	22	9	0	0	0	1402	858.9	1160	857.2
	Mar.	167	859.2	163	0.367	60	12	0	0	0	1497	859.5	1450	859.2
	Apr.	277	860	175	0.373	65	13	0	0	0	1696	860.6	1596	860
	May	1560	863.9	238	0.421	100	21	0	72	13	3050	866.5	2372	869.9
	June	762	866	280	0.512	143	26	762	0	100	2781	865.4	2916	866
	Subtotal	3355				410	88	762	72	113	2781	Check		

Col. 6 Evaporation on average water surface area in reservoir (ft).

Pan evaporation for station at Stillwater was fragmentary, record necessitating correlation with first-order station at Oklahoma City.

Steps used in arriving at lake evaporation at Stillwater: From climatological records at Oklahoma City. Monthly pan and lake evaporations for Oklahoma City were computed using climatological factors.

A correlation equation was written between the computed pan evaporation at Oklahoma City and the measured monthly pan evaporation at Stillwater.

$$Y = 0.4 + 1.17X \qquad \text{(eq. 20–3)}$$

where:
X = computed pan evaporation, using adjusted wind for Oklahoma City
Y = measured monthly pan evaporation at Stillwater, Oklahoma

The next assumption was that the pan-lake evaporation relationship at Oklahoma City would be a reasonable estimate of the pan-lake evaporation relationship at Stillwater.

Monthly lake evaporation at Stillwater was computed by multiplying the computed monthly lake evaporation at Oklahoma City by the ratio of the observed monthly pan evaporation at Stillwater to the computed monthly pan evaporation at Oklahoma City.

$$E_{\ell s} = \frac{P_{os}}{P_{oc}} \quad E_{\ell o} \qquad \text{(eq. 20–4)}$$

where:
$E_{\ell s}$ = computed monthly lake evaporation at Stillwater
P_{os} = observed monthly pan evaporation at Stillwater
P_{oc} = computed monthly pan evaporation at Oklahoma City
$E_{\ell o}$ = computed monthly lake evaporation at Oklahoma City

Col. 7 Evaporation from average water surface area (acre-ft). Evaporation (col) equals column 15 times column 16 in acre feet.

Example: April 1940

$$7 = 15 \times 0.459 \qquad \text{(eq. 20–4)}$$

Col. 8 Total seepage using average monthly water surface elevation.

Example: November 1949

Estimated average monthly water surface elevation 860.0 (msl). From stage–seepage loss curve (fig. 20–4) the total seepage equals 13.0 acre-ft.

Col. 9 Reservoir release (acre-ft) released to meet prior appropriations or maintain low flows. In this example, all runoff that occurs from June 1 through September 30 must be passed through the reservoir without depletion.

Col. 10 Spillway discharge computed for the month (acre-ft) computed from mean stage over crest of spillway and hydraulics of the spillway.

Col. 11 Gross water needed for month (acre-ft). This information will be provided by the user or the agents.

Col. 12 Storage at end of month (acre-ft). Current month (column 12) equals the summation of the previous month's storage at end of the month. Storage equals column 12 plus column 3 minus the sum of columns 7, 8, 9, 10, and 11.

Example: April 1940

$$0 + 85 - (7 - 10 + 0 + 0 + 0) = 78$$

Col. 13 Water elevation at end of month (ft). Mean sea level (msl) from stage-storage curve with storage at the end of month, (col. 12).

Col. 14 Computed average storage for the month (acre-ft). Computed as average of previous end of month storage and current end of month storage.

Col. 15 Elevation for the average monthly storage (ft). msl: stage (ft) msl associated with average monthly storage (acre-ft)

The water budget analysis for the period March 1949 through June 1951 indicated that carry-over storage of 3,050 acre-feet provided for all the necessary requirements. In July of 1954 and 1956, 3,050 acre-feet of storage were not sufficient to provide for the demand. The determination of whether the storage is adequate, inadequate, or excessive is a judgment decision based upon this kind of analysis and the nature of the intended use. In this example, if the use were water supply, fire protection, or recreation, the storage might not be considered adequate. The storage could be considered adequate for irrigation, livestock water, or orchard spray water where periods of low supply can be tolerated.

Water stored below the elevation of sediment pool cannot be used; however, if depletion has lowered the water level to the elevation of the sediment pool, evaporation and seepage will continue to deplete this storage, and the storage would have to be replaced before water would be available for beneficial use. The reservoir operations study program (RESOP) or other reservoir operation computer program can be used in lieu of manual computations.

630.2004 Data Sources

Some primary data source for the retrieval of stream flow, reservoir, diversion, and climate data used in watershed yield analysis are described in this section. Other specific sources may be required depending on the site situation.

(a) Stream flow data

The USGS is responsible for collecting and maintaining daily stream flow data and reservoir levels within the United States These data are available on a current and historic basis in their National Water Information System Web site (NWISWeb). Selected water-resources data for approximately 1.5 million sites across the United States from 1857 to the present. The USGS NWISWeb tutorial includes step-by-step guides for the first-time user of NWISWeb. The current Web address is *http://water.usgs.gov/data*. Some State and local government agencies maintain their stream gage networks which may or may not be incorporated into NWIS. Streamflow data collection by other Federal agencies is generally incorporated in the to NWIS Web site.

(b) Precipitation data

The National Weather Service is responsible for collecting climate data. The National Climate Data Center (NCDC) stores this data and their Web site is *http://www.ncdc.noaa.gov/oa/ncdc.html*. The NRCS has some precipitation data available which is a download from NCDC. The operators and owners of reservoirs and sewage treatment plants may have collected precipitation data that is not included in the NCDC databases. The state climatologist should have a good idea of what precipitation data is available.

(c) Evaporations data

The NOAA technical reports NWS 33 and NWS 34 contain the best evaporation data available. Various state universities and agricultural agencies may have collected evaporation data at selected locations. The state climatologist should have a good idea of what evaporation data is available.

630.2005 References

American Society of Civil Engineers. 1996. Hydrology handbook. ASCE Manuals and Reports on Engineering Practice No. 28 (2nd ed.).

Daly, C., R.P. Neilson, and D.L. Phillips. 1994. A statistical-topographic model for mapping climatological precipitation over mountainous terrain. J. Appl. Meteor. 33(2):140-158.

Garen, D.C., G.L. Johnson, and C.L. Hanson. 1994. Mean areal precipitation for daily hydrologic modeling in mountainous regions. Water Resourc. Bul. 30(3):481-491.

Gebert, W.A., D.J. Graczyk, and W.R. Krug. 1987. Average annual runoff in the United States 1951–80. U.S. Geological Survey Hydrologic Atlas 710. Washington, DC.

Hawley, M.E., and R.H. McCuen. 1982. Water yield estimation in western United States. Amer. Soc. Civ. Eng., J. Irrig. and Drain. Div. 108(IR1):25-34.

Healy, R.W., T.C. Winter, J.W. LaBaugh, and O.L. Franke. 2007. Water budgets: Foundations for effective water-resources and environmental management. U.S. Geological Survey Circular 1308. Washington, DC. 90 p.

Jensen, M.E., R.D. Burman, and R.G. Allen (eds.). 1990. Evapotranspiration and irrigation water requirements. Amer. Soc. Civ. Eng. Manuals and Reports on Engineering Practice No. 70.

National Oceanic and Atmospheric Administration. 1982. Mean monthly seasonal and annual pan evaporation for the United States. Technical report NWS 34. Washington, DC.

Saxton, K.E., and P.A.H. Willey. 2005. Soil-plant-air-water Users Manual. 37 pp.

Thornthwaite, C.W., and J.R. Mather. 1955. The water balance. *In* Climatology, Vol. VIII, No.1, Lab. of Climatol., Drexel Instit. Tech. Centerton, NJ.

U.S. Geological Survey. 2007. A monthly water-balance model driven by a graphical interface. Open-file report 2007, 1088. Washington, DC.

U.S. Geological Survey. 1987. Average annual runoff in the United States 1951–1980. Hydrologic atlas 710.