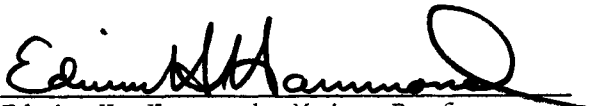
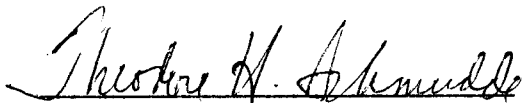


To the Graduate Council:

I am submitting herewith a thesis written by Michael Wells Mayfield entitled "An Examination of the Anomalous Runoff Regime of the Obed-Emory Basin of the Cumberland Plateau, Tennessee." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geography.

  
Edwin H. Hammond, Major Professor

We have read this thesis  
and recommend its acceptance:





Accepted for the Council:

  
Vice Chancellor  
Graduate Studies and Research

Thesis  
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AN EXAMINATION OF THE ANOMALOUS RUNOFF REGIME  
OF THE OBED-EMORY BASIN OF THE  
CUMBERLAND PLATEAU, TENNESSEE

A Thesis  
Presented for the  
Master of Science  
Degree  
The University of Tennessee, Knoxville

Michael Wells Mayfield

March 1980

1116270

## ACKNOWLEDGEMENTS

The author is greatly indebted to Professor Edwin H. Hammond for his help in the development of this research project, his guidance and ideas during the research period, and his comments throughout the completion of this work; to Professor Theodore H. Schmudde for his ideas and encouragement; to Kerry Hake for his help with the field work; and to his wife Susan for her patience and help in the typing of this manuscript.

## ABSTRACT

Despite a number of basin characteristics which are generally believed to produce stable streamflow regimes, floods on the Emory River and its tributaries are extremely high and baseflow is minimal. The streamflow regime of the Obed-Emory system is described in detail and Thornthwaite's water budget is used to show input, depletion, and outflow of water from the basin. Streamflow characteristics and basin characteristics of the study area are compared to those of two other basins to emphasize the peculiarity of the study basin. It is concluded that the highly permeable soils and impervious bedrock of the Obed-Emory basin force surplus water to move laterally through the soil and into stream channels, while precluding large amounts of subsurface storage which would stabilize streamflow.

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## CHAPTER 1

### THE OBED-EMORY BASIN

#### Introduction

The tabular Cumberland Plateau of Tennessee is noted for its water supply problems and the irregularity of flow of its streams.<sup>1</sup> The Obed-Emory river basin was chosen for study because of the peculiar nature of flow in its streams. Peak flows at the basin outlet are extremely high and base flow is minimal despite the presence of several basin characteristics that are generally considered to favor relatively stable stream discharges. Figure 1 gives an indication of the peculiarity of that flow as compared to other streams in Tennessee. This flow duration chart shows that low flows are more poorly sustained and peak flows are higher than for all the other representative streams except for Wartrace Creek of the Nashville Basin. Streams of the basin exhibit peaked flows similar to those of the Cumberland Plateau streams. The extremely small drainage area of Wartrace Creek magnifies this extremity of flow. This thesis describes the runoff regime of the basin and offers an explanation for the observed streamflow regime. Although other basins on the tabular Cumberland Plateau may exhibit similar characteristics, the Obed-Emory was chosen for the study

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<sup>1</sup>Ann Zurawski, Summary Appraisals of the Nation's Groundwater Resources-Tennessee Division. U.S. Geological Survey Professional Paper 813-L (Washington: U.S. Government Printing Office, 1978), p. L28.

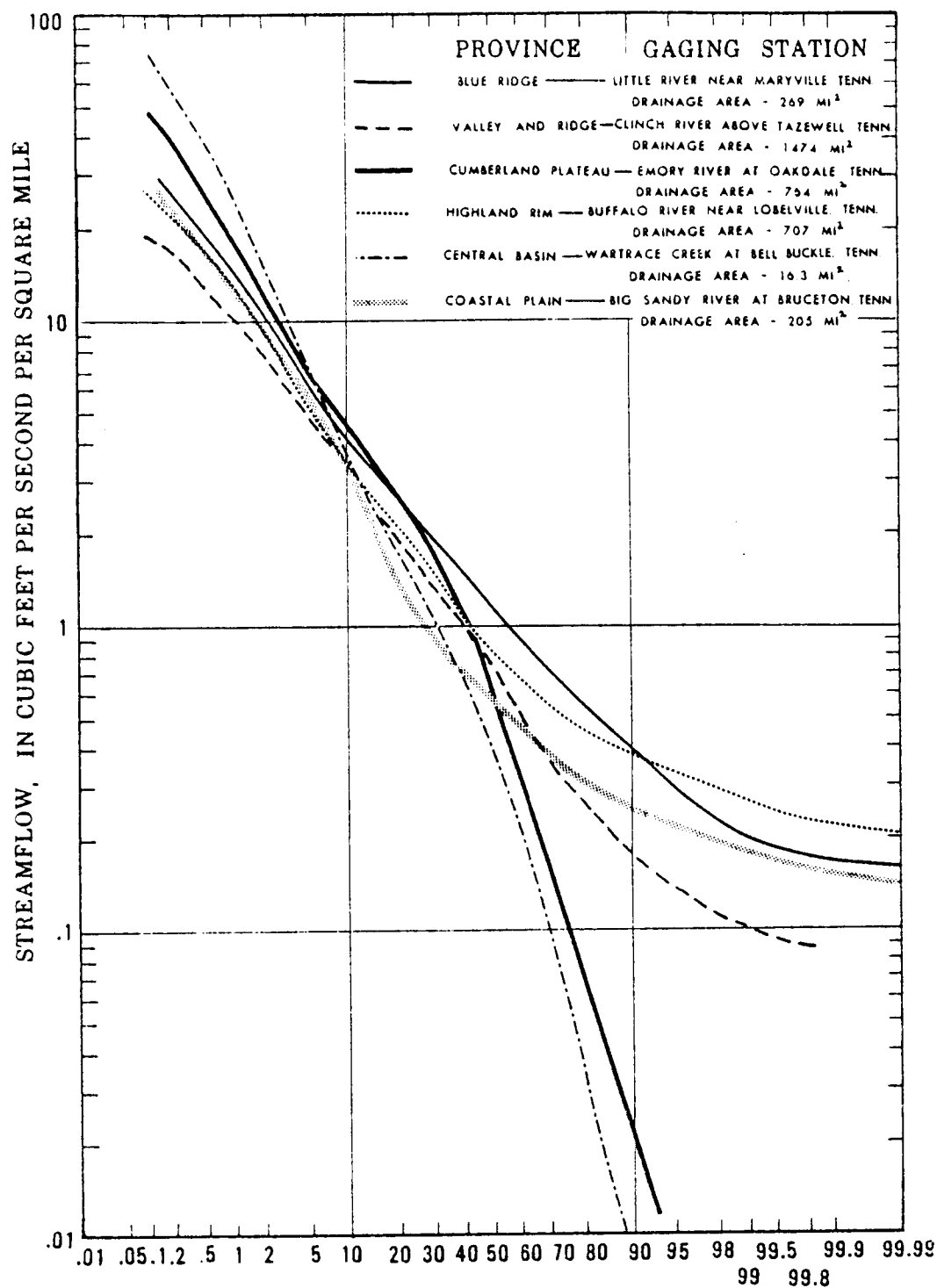


Figure 1. Streamflow duration curves for representative Tennessee streams.

because it is a large basin with no major structural controls on runoff (dams and reservoirs), yet it affords reliable stream gage data for over 50 years, and the basin is generally accessible by car, boat, or foot.

The study area consists of that part of of the Obed-Emory basin lying above the gaging station at Oakdale, an area of 764 square miles. The basin lies generally west of Knoxville and Oak Ridge, Tennessee (see Figure 2). It includes the Obed and Emory Rivers, Daddy's Creek, Clear Creek, White Creek, Crab Orchard Creek, Crooked Fork, and a number of smaller tributary streams. In order to show how the Obed-Emory system differs from other streams in the area, streamflow and basin characteristics of the Nolichucky River of western North Carolina and the Collins River of middle Tennessee are examined herein, and a thorough comparison of the three streams is made.

Streamflow information used in this study was gathered entirely from published records of gaging stations within the basin.<sup>2</sup> Meteorological data were obtained from reports of the National Oceanic and Atmospheric Administration and the Tennessee Valley Authority.<sup>3,4</sup> General information about soils was obtained from the Cumberland County, Tennessee soil survey, while more specific information about soil properties, such as infiltration capacity, was obtained from

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<sup>2</sup>U.S. Geological Survey, Water Resources Data for Tennessee, 1977 (Washington: U.S. Government Printing Office, 1978).

<sup>3</sup>National Oceanic and Atmospheric Administration, Environmental Data Service, Climatological Data-Tennessee (Asheville, North Carolina: 1976).

<sup>4</sup>Tennessee Valley Authority, Division of Water Control Planning, Hydraulic Data Branch, Precipitation in Tennessee River Basin (Knoxville, Tennessee: Tennessee Valley Authority, 1977).

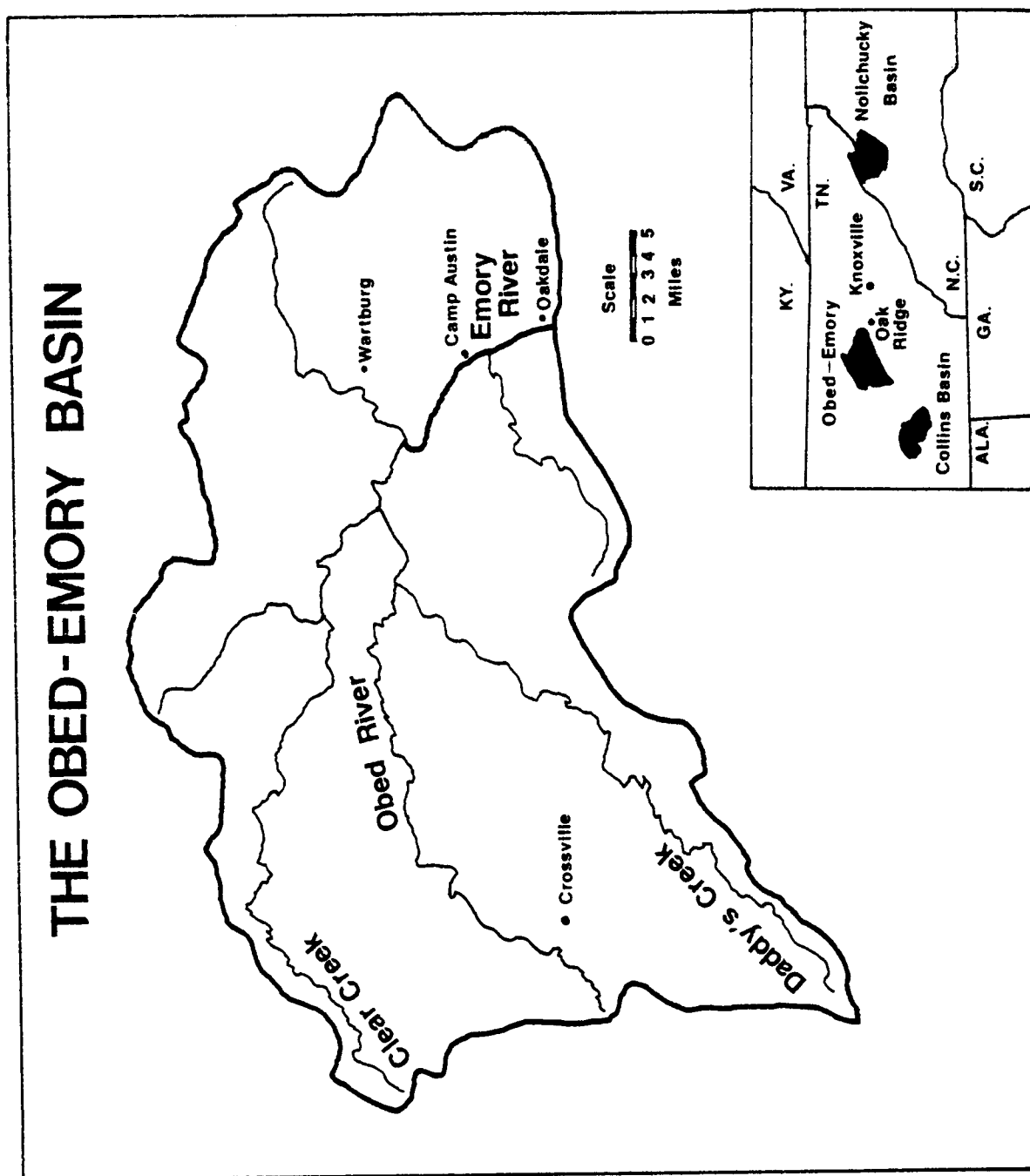


Figure 2. The Obed-Emory basin.

University of Tennessee Agricultural Experiment Station reports and from personal interviews with agricultural extension agents.<sup>5,6</sup>

Extensive field investigation enabled determination of the routes by which storm water moves through the system and the processes involved in the stormwater delivery system. Several excursions made during times of precipitation afforded observation of the processes in action.

The Obed-Emory basin lies mostly within Fenneman's Cumberland Plateau, as distinct from his Cumberland Mountain section, which is much more heavily dissected. Fenneman described the Plateau as having "an undulating surface submaturely dissected by young valleys whose steepness and depth increase towards the edges."<sup>7</sup> He interpreted the flat plateau surface as an erosional peneplain produced before subsequent uplift raised the entire Appalachian Plateau.<sup>8</sup> An alternate, and currently more acceptable explanation, is that this surface has developed by stripping of the overlying layers until the resistant sandstone strata were encountered at a level well above base level.

Some of the basin characteristics which influence streamflow are topography, basin lithology and groundwater system, the drainage

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<sup>5</sup>E. H. Hubbard, B. L. Matzak, and M. E. Austin, Soil Survey of Cumberland County, Tennessee. U.S. Department of Agricultural Soil Conservation, Series 1938, No. 25 (Washington: U.S. Government Printing Office, 1950).

<sup>6</sup>T. J. Longwell, W.L. Parks, and M. E. Springer, "Moisture Characteristics of Tennessee Soils," University of Tennessee Agricultural Experiment Station Bulletin 367, 1963.

<sup>7</sup>Nevin M. Fenneman, Physiography of the Eastern United States (New York: McGraw-Hill Book Company, 1938), p. 337.

<sup>8</sup>Ibid.

net, climate, soils, and land use. Summaries of these characteristics are presented as a basis for understanding the hydrology of the study area.

### Landforms

The majority of the land surface in the Obed-Emory basin is gently rolling, with most slopes in the upper reaches of the basin having an inclination of 8% or less. Upland slopes of 8% to 15% are more common closer to the outlet end of the basin(see Figure 3). A gentle regional slope exists such that elevations on the uplands decrease from nearly 2,000 feet near Crossville to 1,300 feet at Wartburg.

Several large ridges, most notably the Crab Orchard Mountains, break up the smooth upland areas. The Crab Orchard group is developed on the more northerly of an extensive pair of anticlines that extend some 215 miles from Blount County, Alabama, to the Emory River near Camp Austin.<sup>9</sup> The more southerly of these two anticlines has been broken through by surface erosion and collapse of cavernous limestone, forming the Sequatchie Valley.<sup>10</sup> The northern (Crab Orchard Mountains) anticline has no significant erosional breaks and forms the drainage divide for the southeastern part of the basin. A number of smaller, though prominent, ridges in the basin are the result of differential

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<sup>9</sup>Richard G. Stearns, The Cumberland Plateau Overthrust and Geology of the Crab Orchard Mountains Area, Tennessee. State of Tennessee Department of Conservation, Division of Geology Bulletin 60 (Nashville, Tennessee: 1954), p. 33.

<sup>10</sup>Ibid., p. 35.



Figure 3. A view of the upland surface of the Cumberland Plateau near Crossville.

erosion on localized thrust faults.<sup>11</sup> These ridges include Hatfield Mountain, Little Peavine Mountain, Big Peavine Mountain, Lavender Knob, Pilot Knob, and others.

The northeast section of the basin, which is drained by the upper Emory River, is a highly dissected mountainous region developed on more easily eroded shales and siltstones that overlie the sandstones. This mountainous section accounts for about 10% of the area of the Emory basin. Coal seams within the shale units have been heavily exploited, resulting in significant local modifications of the landscape. Access roads and strip mine scars along the horizontal outcrops, highwalls, tailings, and other relics of mining are common. These mining activities may have affected the runoff hydrology of the sub-basin.

Peak elevations<sup>3</sup> in this northeastern part of the basin are much higher than those in the plateau section; at least 20 peaks exceed 3,000 feet, and Frozen Head Mountain reaches an elevation of 3,324 feet, the highest point in the basin. The lowest elevation in the basin is 761 feet, at the drainage outlet at Oakdale; thus the total relief is 2,563 feet.

#### The Drainage Net

The drainage network pattern in the Obed-Emory basin is dendritic, with no evident structural control except for the linearity of certain sections of the main streams along faults. One such section is the Emory River from Nemo to Camp Austin.

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<sup>11</sup> Ibid.

The major streams flow across the sandstone caprock of the plateau in their upper reaches but become progressively entrenched downstream. These gorges are as much as 500 feet deep, and the bluffs are often vertical or even overhung. House-sized boulders have separated from the rimrock and fallen to the bottom in many areas (see Figure 4). The steepest gradients are not in the upper reaches of the streams, as is common, but in the lower entrenched sections (Figure 5). The streams do not have consistent gradients, but alternate between pools and rapids.

In her study of streams in the Appalachian Plateau, Morisawa found that streams have gentle gradients where they flow across resistant strata, but have steep gradients where they cut through the resistant rock.<sup>12</sup> This relationship is generally valid in the Emory basin. Where streams are cutting through these same strata, gradients are much steeper. The steepest segment of any of the major streams is the section of Daddy's Creek from the junction of Yellow Creek to Devil's Breakfast Table, yet the stream is embedded in shale along this section. It appears that bedrock lithology is not the only factor controlling the gradient of streams in the basin. Another possible explanation for the inverted stream profiles in this area is recent uplift of the Cumberland Plateau, causing rejuvenation of

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<sup>12</sup>Marie E. Morisawa, "Quantitative Geomorphology of Some Watersheds in the Appalachian Plateau," Geological Society of America Bulletin, v. 73, 1962, pp. 1025-1046.

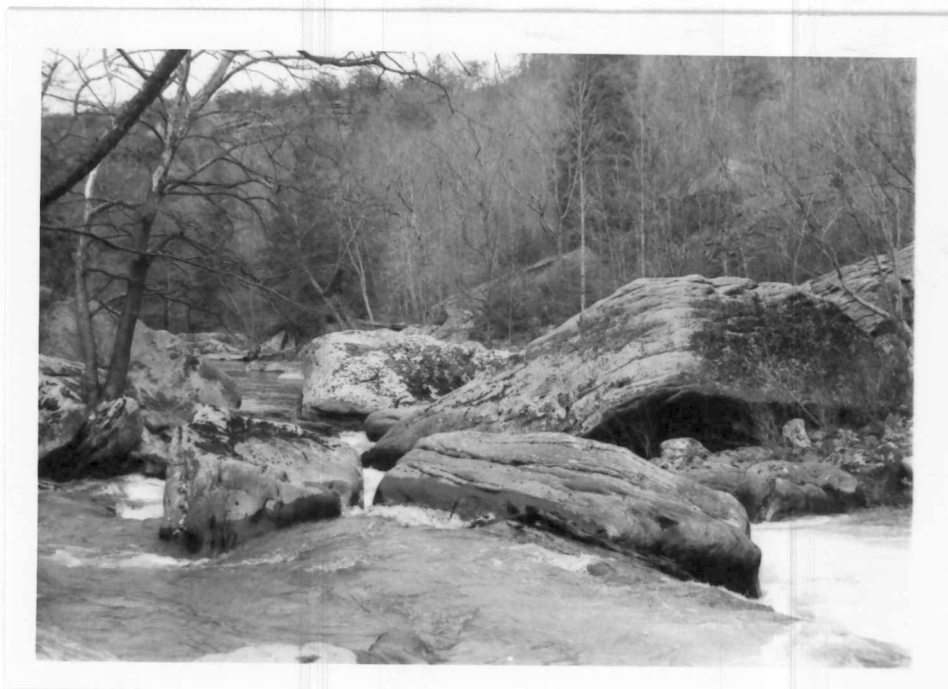


Figure 4. The gorge of the Obed River.



OLD COUNCIL TREE  
BOND  
100% COTTON FIBER

## Longitudinal Stream Profiles

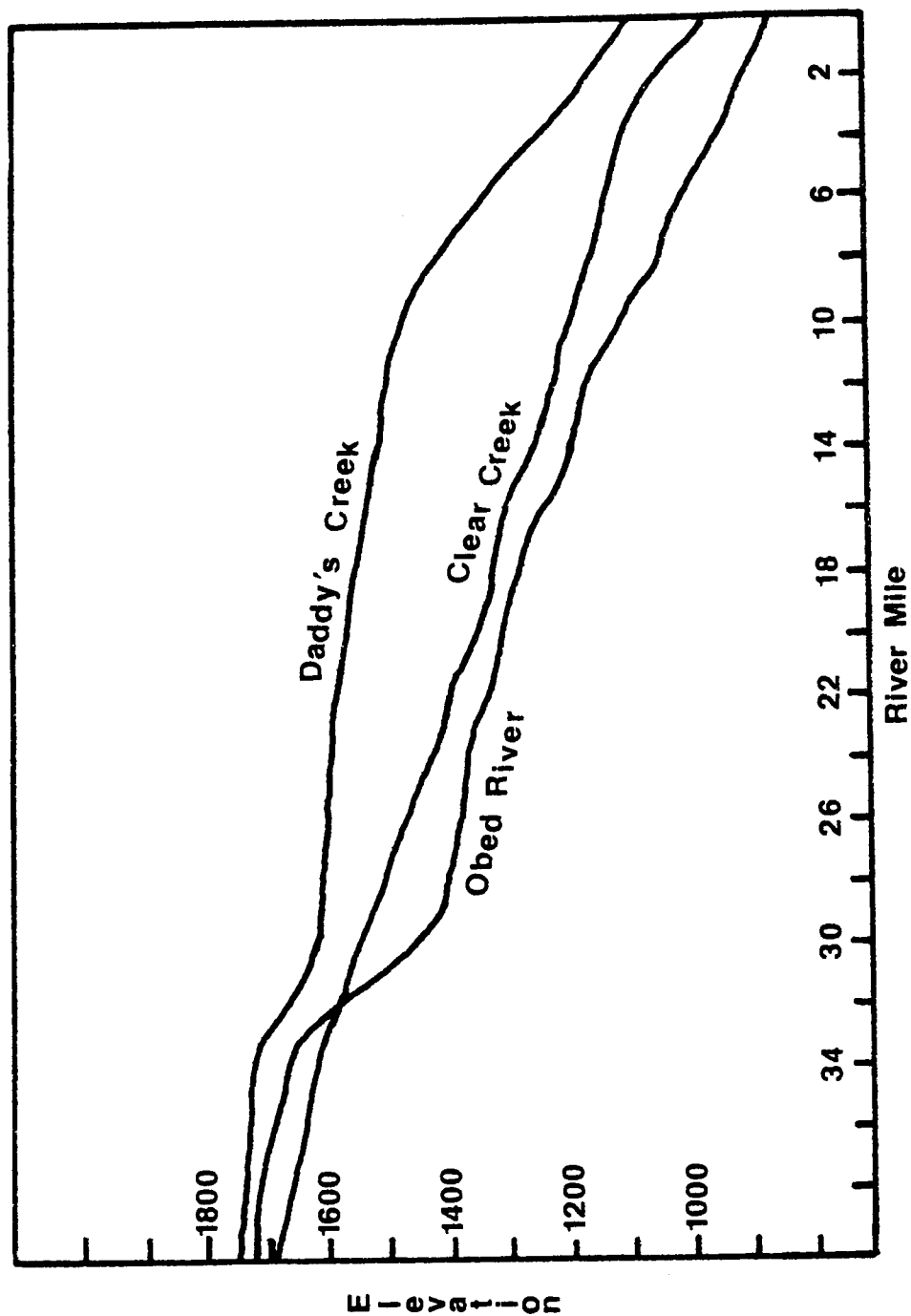


Figure 5. Longitudinal stream profiles.

the streams. In such a case, gradients would first be rejuvenated in the lower reaches of the stream and progress headward, so that upper reaches are rejuvenated last.<sup>13</sup> The present elevation above sea level of the southern Cumberland Plateau is direct evidence of fairly recent uplift, so the present longitudinal profile of streams in the Obed-Emory basin is probably a result of a combination of lithologic control and rejuvenation by uplift.

#### Lithology and Groundwater in the Emory Basin

The lithology of the Emory basin consists mostly of near-horizontal sedimentary strata of Pennsylvanian age. Alternate layers of sandstone, siltstone, and shale compose the bedrock. The complete series of rock units consists of alternating layers of sandstone and softer siltstones and shale layers.

Over most of the Emory basin, the two upper rock members have been removed, so that the Rockcastle Sandstone-Conglomerate is the most commonly exposed rock unit at the surface. Most of the broad, flat uplands are developed on the Rockcastle formation. Younger shales and sandstones are exposed in the remnant hills and knobs, while the older shales and sandstones are exposed in the deeply incised stream gorges. Figure 6 represents a portion of the Jones Knob quadrangle and illustrates the general geology of this section of the Cumberland Plateau.

The Rockcastle Sandstone-Conglomerate has a very low intergranular permeability but some secondary permeability is provided by

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<sup>13</sup>Ibid.

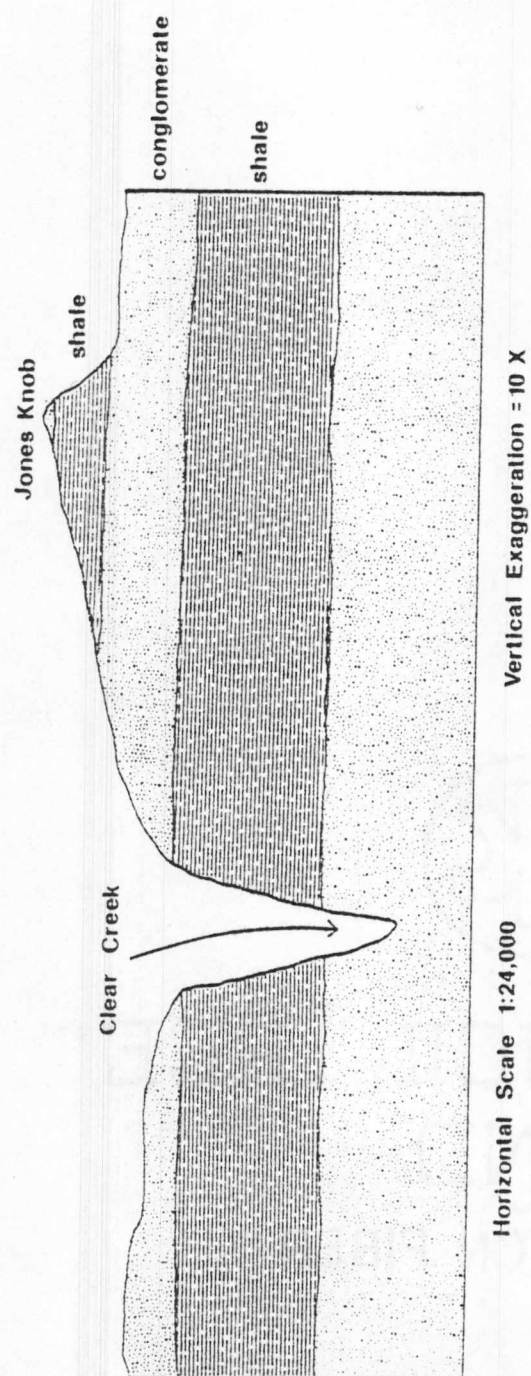


Figure 6. Representative lithology and topography in the Obed-Emory basin.

fractures in the unit.<sup>14</sup> As can be seen in Figure 6, the Rockcastle formation is underlain by a massive shale unit (the Vandever formation), which is impermeable to the downward movement of water. Because of the confining shale unit underlying the Rockcastle formation and thin beds of shale within the Rockcastle itself, water within the lower parts of the unit is under considerable artesian pressure. Water in wells rises as much as 200 feet when the water-bearing unit is penetrated.<sup>15</sup> Rises of 40 to 80 feet are more common.

Newcombe and Smith have noted that "Rain, falling on the outcrop areas, recharges the sandstone beds. . . water, flowing downdip in the fractured sandstones, is confined by overlying and underlying shale beds."<sup>16</sup> In their later discussion of groundwater discharge, Newcombe and Smith state that "Groundwater is discharged through springs, which are common in the walls of the many, deep, narrow stream valleys. . . . The springs in the Plateau generally issue from sandstones near their contact with shale beds. . . ."<sup>17</sup>

Water-storage capacity of the rock units underlying the Emory basin is poor, as evidenced by the poorly-sustained base flows of even larger streams in the basin. Examination of well records in the

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<sup>14</sup>Roy Newcombe, Jr., and Ollie Smith, Jr., Groundwater Resources of the Cumberland Plateau in Tennessee, State of Tennessee Department of Conservation, Division of Water Resources, (Nashville: 1958), p. 8.

area reinforces this point; of approximately 700 wells in the basin, over 50% yield less than 10 gallons of water per minute and only 6% produce more than 25 gallons per minute.<sup>18</sup> Many of these wells are only seasonally operative, producing adequate yields during the winter and spring but going dry during the summer and early fall.

### Climate

The higher elevations on the Cumberland Plateau result in lower temperatures and greater amounts of precipitation than are found in the adjacent lower lands of the Highland Rim to the west or the Ridge and Valley to the east. This combination of higher precipitation and lower temperatures yields a greater water surplus for the Plateau; Crossville has an average annual surplus of 25.0 inches of water while Knoxville's annual surplus is only 17.7 inches (see Figure 7).

The Obed-Emory basin is within the broad region that Trewartha has identified as having a Cfa, or humid mesothermal climate, yet the Crossville climatic data indicate that this specific area actually falls within the cooler Do, or temperate oceanic climate.<sup>19</sup> The year-to-year variations of weather in the basin are great enough that the climate classification could fall in either of the two categories during a given year. According to Koppen's definitions, this area

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<sup>18</sup> Tennessee Department of Conservation, Division of Water Resources, Summary of Groundwater Data for Tennessee through May, 1972 (Nashville: 1972), p. 86.

<sup>19</sup> Glenn T. Trewartha, An Introduction to Climate, 4th Ed. (New York: McGraw-Hill Book Company, 1968), p. 250.

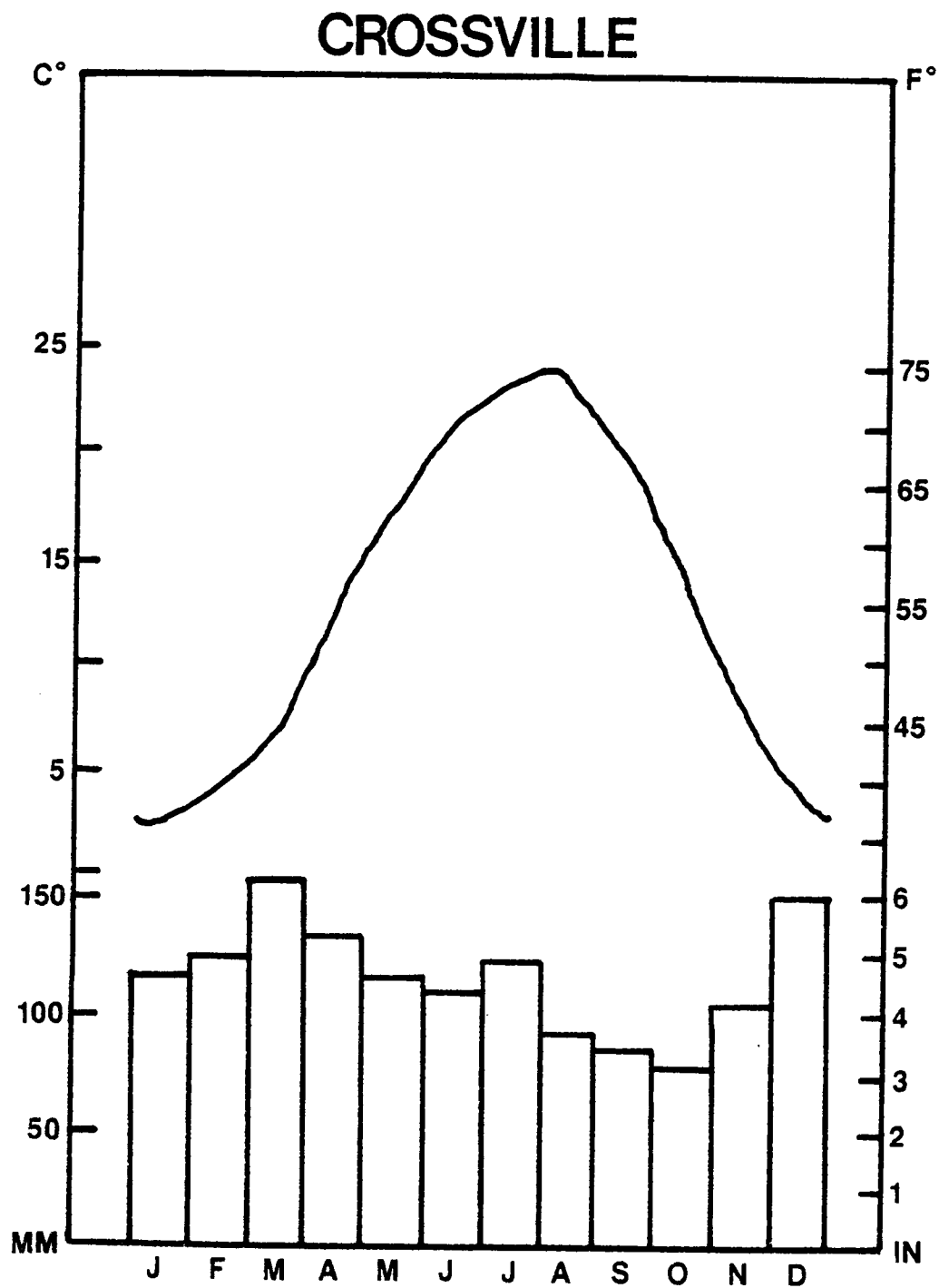


Figure 7. Climograph for Crossville, Tennessee.

falls well within the Cfa (humid subtropical) climate during even the coldest of years.<sup>20</sup>

Daily precipitation amounts are measured at six locations within the Obed-Emory basin. The oldest of these stations has been recording precipitations for 43 years. Consistent temperature monitoring is done only at the National Weather Service station at the Crossville Airport. Table 1 lists the six stations in the basin along with average precipitation amounts by month and year.

Precipitation in the basin is abundant year-round, with a winter and spring maximum and a summer-early fall minimum (see Figure 8). The month of greatest precipitation is March, while October receives the least. At 5.7 and 2.9 inches respectively, the wettest month averages almost twice as much precipitation as the driest.

Precipitation averages vary from 45.53 inches per year at Frankfort to 60.61 at Isoline. Most of this difference is due to orographic responses; Frankfort has the lowest elevation of the six stations and Isoline the highest.

A Thornthwaite water balance account for the basin is discussed in Chapter III.

### Soils

The only published detailed investigation of soils in the Obed-Emory basin is the 1950 Soil Survey of Cumberland County.<sup>21</sup>

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<sup>20</sup>Ibid., p. 245.

<sup>21</sup>E.H. Hubbard, B.L. Matzek, and M.E. Austin, Soil Survey of Cumberland County, Tennessee, United States Department of Agriculture Soil Conservation Service, Series 1938, No. 25 (Washington : U.S Government Printing Office, 1950).

TABLE 1

PRECIPITATION GAGING STATIONS  
IN THE OBED-EMORY BASIN

| Station      | Station Number | Elevation in Feet |
|--------------|----------------|-------------------|
| Isoline      | 800            | 1880              |
| Clarkrange   | 164            | 1770              |
| Hebbertsburg | 159            | 1770              |
| Big Lick     | 699            | 1770              |
| Frankfort    | 418            | 1460              |
| Crossville   | 417            | 1862              |

| Station | Average Precipitation in Inches |      |      |      |     |      |      |      |      |      |      |      |      |
|---------|---------------------------------|------|------|------|-----|------|------|------|------|------|------|------|------|
|         | Jan.                            | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
| 800     | 5.2                             | 4.5  | 5.7  | 6.0  | 6.0 | 4.9  | 6.0  | 3.6  | 3.6  | 3.4  | 4.4  | 7.1  | 60.6 |
| 164     | 5.3                             | 4.8  | 5.3  | 4.3  | 3.9 | 3.9  | 4.8  | 3.9  | 3.3  | 2.5  | 3.9  | 4.6  | 50.5 |
| 159     | 5.3                             | 5.3  | 5.5  | 4.4  | 3.9 | 3.9  | 5.4  | 3.8  | 3.4  | 2.7  | 4.2  | 5.0  | 52.6 |
| 699     | 5.4                             | 5.4  | 6.2  | 4.8  | 4.5 | 4.5  | 5.5  | 3.7  | 4.2  | 2.9  | 4.4  | 6.1  | 57.6 |
| 418     | 3.8                             | 4.3  | 4.9  | 4.3  | 3.4 | 3.9  | 4.4  | 3.3  | 2.8  | 2.6  | 3.5  | 4.4  | 45.5 |
| 417     | 4.6                             | 5.0  | 6.3  | 5.4  | 4.7 | 4.4  | 4.9  | 3.7  | 3.4  | 3.1  | 4.2  | 6.0  | 55.6 |
|         | 4.9                             | 4.9  | 5.7  | 4.9  | 4.4 | 4.3  | 5.2  | 3.7  | 3.5  | 2.9  | 4.1  | 5.5  | 53.8 |

Average

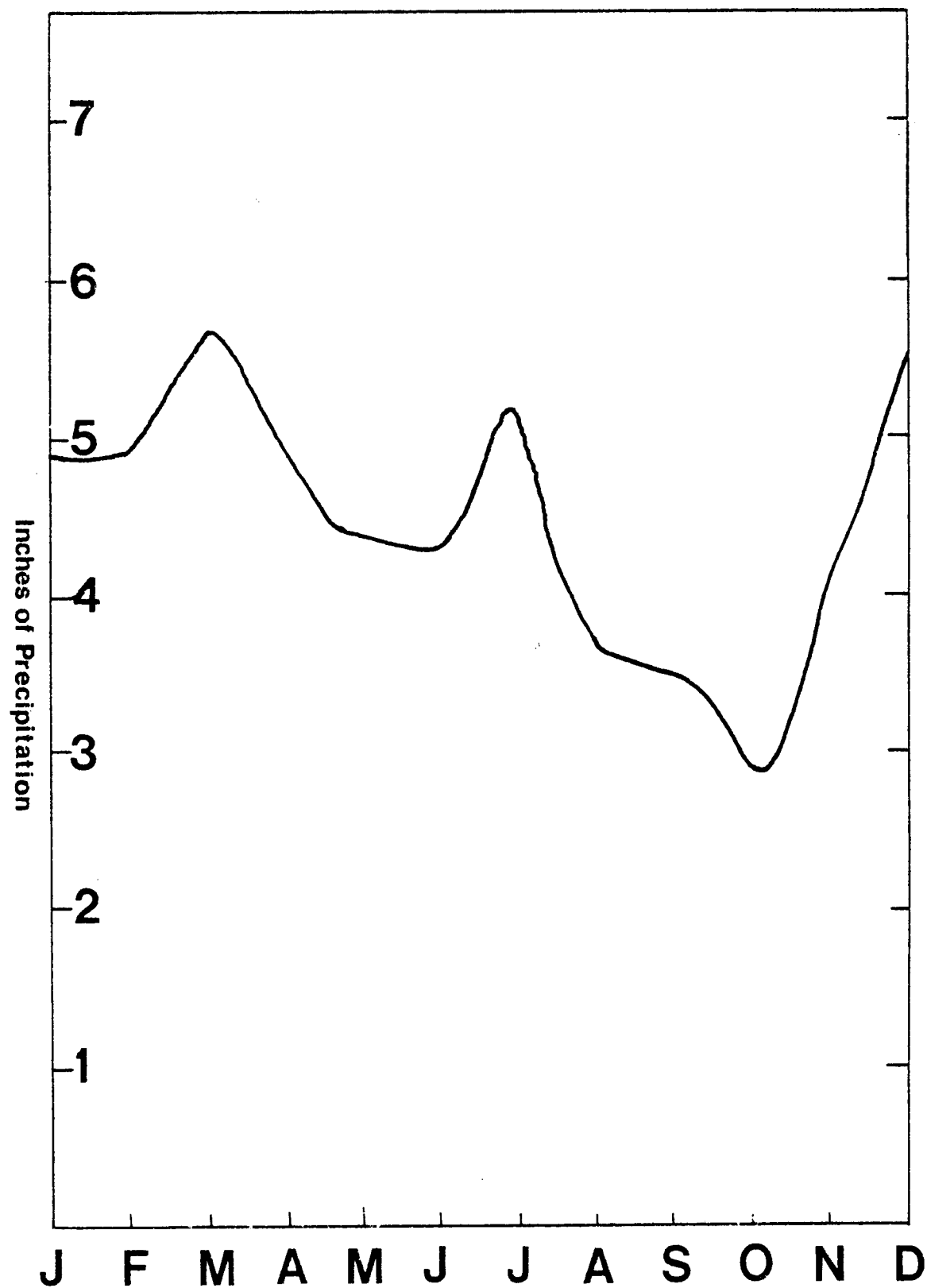


Figure 8. Average precipitation in the Obed-Emory basin.

This survey covers slightly less than one-half of the basin, but since the geology, climate, and topography of the basin as a whole are effectively represented by Cumberland County, it can be assumed that the soils are similar in the area not covered by the survey.

Two soil series, the Hartsells fine sandy loam and the Muskingum fine sandy loam, account for about 95% of the soils in the basin. Both series are derived principally from sandstone interbedded with thin shale layers and average only about 30 inches to bedrock.<sup>22</sup> Muskingum soils tend to be somewhat stonier, lie on steeper slopes, and have faster internal drainage than the Hartsells series.<sup>23</sup> Hartsells soils are rated as second-or-third class, which means that they are poor to good for cropland and fair to very good pastureland.<sup>24</sup> The Muskingum soils are mostly in the fifth-class soil category because of their dominant stoniness and steeper slopes. Fifth-class soils are defined as soils that are very poor for cropland because of steep slopes, stoniness, or susceptibility to accelerated erosion.<sup>25</sup>

The Hartsells soils are generally underlain by "a relatively thin layer of yellowish-gray sand."<sup>26</sup> The Muskingum series is similarly underlain by "decomposed rock mixed with many small fragments of sandstone."<sup>27</sup> This interface between soil and bedrock may be the site of important hydrologic activity.

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<sup>22</sup>Ibid., pp. 26-27.

<sup>23</sup>Ibid., p. 27.

<sup>24</sup>Ibid., p. 66.

<sup>25</sup>Ibid., p. 68.

<sup>26</sup>Ibid., p. 26.

<sup>27</sup>Ibid., p. 28.

## Land Use

The majority of land in the Obed-Emory basin is covered by forest. Census of Agriculture data indicate that about 18% of the land is in farms, but a large part of this is classified as farm woodland. In 1974 less than 4% of the land was classified as harvested land and 4% as pasture. When cropland and pasture lands are subtracted from the total area, 92% remains as forested land.

The Catoosa Wildlife Management area covers 80,000 acres (about 16%) of the basin and is almost totally forested. Development within the Catoosa is minimal; a few access roads and open hunting fields are the only openings in the forest vegetation.

Several strip mines operate in the basin today, and a great many more have been mined in the past. Most of the mining is in the upper Emory drainage area in the mountainous subsection of the basin. Because the areal extent of these mines is not great, their effect on quantity and time concentration of runoff is probably minor, although water quality has certainly suffered.

Urban development in the basin is quite small; Crossville and Wartburg are the only towns of note, having a combined 1970 population of 5,922. With such a small areal extent of urbanization, the amount of land in the basin that is paved or roofed is insignificant. Interstate 40 crosses through the southeastern corner of the basin between Crab Orchard and Mayland Lake. Other paved roads include Highways 70, 127, 68, 27, 62, Genesis Road, and city streets in Crossville and Wartburg. The total length of these paved roads is

about 250 miles. At an average of 30 feet in width, this represents an area of only about 1.5 square miles, or two-tenths of 1% of the basin area.

Resort and retirement communities have proliferated (but have not necessarily prospered) in the Crossville area of the basin in recent years. Lake Tansi, Fairfield Glade, and Holiday Hills are the largest of these developments. Approximately 24,000 acres of land in the Obed-Emory basin fall within these developments.<sup>28</sup> Because of the required scenic amenities, development and alteration of the natural terrain in these areas is not intensive. Probably the most important influences that the resorts have on the hydrology of the basin is through the numerous ponds and reservoirs that have been constructed for water supply, recreation, and scenic purposes.

Congress passed legislation in 1976 to include parts of the Obed River in the National Wild and Scenic Rivers Act. Between 46 and 100 river miles on the Obed, Daddy's Creek, Clear Creek, and the Emory will eventually be included in this protected area. The purpose of such legislation is to preserve the stream in its natural, free-flowing state and to protect the quality of the stream by maintaining an essentially primitive watershed and shoreline.<sup>29</sup> As such, the current flow regime of the Obed River is likely to be retained in future years without significant alteration by man.

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<sup>28</sup>Hubert B. Stroud, "Amenity Land Development as an Element of Geographic Change: A Case Study, Cumberland County, Tennessee," Unpublished Ph.D. Dissertation, University of Tennessee, Department of Geography (Knoxville: 1974), p. 18.

<sup>29</sup>U.S. Department of the Interior, Bureau of Outdoor Recreation, Obed River, Tennessee Wild and Scenic River Study (Washington: 1976), p. 3.

## CHAPTER 2

### A DESCRIPTION OF THE RUNOFF REGIME IN THE OBED-EMORY BASIN

#### Seasonal Runoff Regime

The seasonal runoff regime of the Emory River is much like that of other free-flowing streams in the southeastern United States; peak flows occur during the late winter and early spring months, while discharge is least during the late summer and early fall.

Such a pattern of runoff is to be expected because of the climate of the region. During the months of June, July, August and September, potential evapotranspiration exceeds precipitation. During this time, soil moisture is depleted as plants take water from the root zone of the soil in order to maintain themselves. It is generally held that any available precipitation must first be used to replenish the soil moisture.<sup>1</sup> Until the soil reaches field capacity, no runoff can be generated. Exceptions to this rule are: 1) precipitation that falls directly into stream channels and 2) precipitation of sufficient intensity to exceed the rate at which water can enter the soil (the infiltration capacity). Recent research has indicated that saturation of the soil or precipitation more intense than the infiltration capacity of the soil may not be necessary to produce significant amounts of storm runoff. Beasley has found that significant amounts of subsurface flow can occur when the

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<sup>1</sup>C. W. Thornthwaite and J. R. Mather, The Water Balance, Drexel Institute of Technology Publications in Climatology, Vol. VII, no. 1 (Centerton, N.J.: 1955) pg. 10.

the soil is not saturated because of the existence of interconnected macropores made by burrowing animals and decaying plant roots.<sup>2</sup>

Although the general trend of seasonal stream flow in the Obed-Emory basin is not unusual, the magnitude of the flood peaks and low flows during those seasonal fluctuations seems to be anomalous. Despite several factors which are generally considered to contribute to relatively stable stream discharges and substantial baseflow, the Emory River and its tributaries exhibit remarkably peaked flows. Winter and spring discharges are unusually high and late summer to early fall flows are especially low. The mean discharge for March is over 20 times as great as the mean discharge for October.

Mean monthly flows are given in Table 2, but these averages are misleading because of the extreme variability of the summer and fall flows. For each month from June through November, the standard deviation of monthly flow actually exceeds the mean flow for the month. The median flow values are much lower than the mean flow values and are more representative of the monthly flow characteristics, because the mean is greatly influenced by unusually high flows of a few wet years. "Whenever there are considerably more extreme cases in one direction than the other, the median will generally be more appropriate than the

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<sup>2</sup>There is a great deal of disagreement about this subject at present. Some, including Beasley, argue that saturation is not a prerequisite to runoff because of the influence of macrochannels in the soil, while others argue in favor of Horton's classical approach to the processes involved in the production of runoff. See R.S. Beasley's "Contribution of Subsurface Flows From the Upper Slopes of Forested Watersheds to Streamflow," in Soil Science Society of America Journal, Vol. 40, 1976.

TABLE 2

MEDIAN AND MEAN MONTHLY FLOWS IN CUBIC FEET PER SECOND,  
EMORY RIVER AT OAKDALE

|           | Median | Mean | Standard Deviation |
|-----------|--------|------|--------------------|
| January   | 2428   | 2720 | 1833               |
| February  | 3337   | 3280 | 1845               |
| March     | 3253   | 3280 | 1454               |
| April     | 2177   | 2120 | 1000               |
| May       | 1091   | 1160 | 760                |
| June      | 333    | 539  | 946                |
| July      | 190    | 448  | 714                |
| August    | 150    | 267  | 376                |
| September | 63     | 210  | 390                |
| October   | 93     | 153  | 246                |
| November  | 416    | 844  | 1270               |
| December  | 2340   | 1940 | 1562               |

Source: V. Jeff May, George H. Wood, and Donald R. Rima, A Proposed Streamflow-Data Program for Tennessee. U.S. Geological Survey Open-File Report (Nashville, 1970)

the mean."<sup>3</sup> The median flow values show a more "typical" situation for summer and fall flow of the Emory River. Table 2 shows the median and mean monthly flow values for the gage at Oakdale. The significantly lower median values for the months of May through November are indicative of the severity of the low flows during the warm months.

### Floods on the Emory River

One of the most important aspects of the runoff regime in the Obed-Emory basin is the frequent occurrence and great magnitude of flood peaks. Flood flows are significant not only because of the damage that is often incurred on developed floodplains, but from a geomorphic viewpoint as well. It is generally believed that flood flows are responsible for most of the geomorphic work done in a drainage basin, both in the stream channel and on the hillslopes.

Extremely high flood peaks have been recorded on the Emory River in the past one hundred years. The single highest flood event since at least 1857 occurred on March 23, 1929. This flood had a maximum discharge of approximately 195,000 cubic feet per second (c.f.s.), which resulted in a gage height of 61.1 feet at Harriman. At least five other floods with peak discharges exceeding 100,000 cubic feet per second have occurred since 1900 (Table 3).

Perhaps more significant than these extremely high, infrequently occurring floods are the floods of relatively short recurrence intervals. The two-year recurrence peak flow for the Emory River is approximately

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<sup>3</sup>Hurbert M. Blalock, Jr., Social Statistics (New York: McGraw-Hill Book Co., 1972) pg. 69.

TABLE 3  
LARGE FLOODS ON THE EMORY RIVER

| Date              | Peak Discharge, Cubic Feet Per Second |
|-------------------|---------------------------------------|
| January 2, 1929   | 70,600                                |
| March 23, 1929    | 195,000                               |
| February 3, 1937  | 103,000                               |
| February 13, 1948 | 101,000                               |
| February 1, 1951  | 77,500                                |
| March 22, 1955    | 79,700                                |
| November 19, 1959 | 76,700                                |
| May 28, 1973      | 170,100                               |
| March 13, 1975    | 87,200                                |
| April 4, 1977     | 107,000                               |

Sources: Flood Peak Runoff and Associated Precipitation in Selected Drainage Basins in the United States. Geological Survey Water Supply Paper 1813(Washington: Government Printing Office, 1965) pg. 319 and U.S. Geological Survey, Water Resources for Tennessee, 1977 (Washington: Government Printing Office, 1977)

45,900 c.f.s., and the 10-year flood exceeds twice that rate. The frequent occurrence of floods of such magnitude is unusual for a stream of this size, as will be shown in the succeeding chapter.

The Emory River rises rapidly during large floods. During the flood of March 23, 1929, the river rose at a rate of about 8 feet per hour, increasing from bankfull stage to the crest in only 3 1/2 hours. Similar rapid rises can be seen in the hydrographs of other large floods on the river (Figure 9). These rapid increases of runoff rate indicate that an extremely efficient storm water delivery system has developed in the Obed-Emory basin.

Gamble and Randolph studied floods in 281 drainage basins in Tennessee and produced formulae for the estimation of flood flow volumes of various recurrence intervals.<sup>4</sup> The state was divided into four "hydrologic regions" on the basis of the results of a regression analysis of the floods on those 281 basins. Table 4 summarizes the regression equations, for the region in which the Emory River is located, for floods of 2- to 100-year recurrence intervals as presented by Gamble and Lewis and the values of those same recurrence interval floods on the Emory River as observed or extended beyond the gaging record on log probability graph paper. The large discrepancy between the observed and predicted floods is another indication of the unusual flow characteristics in the Obed-Emory basin.

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<sup>4</sup>W. J. Randolph and Charles R. Gamble, Technique for Estimating Magnitude and Frequency of Floods in Tennessee (Nashville: U.S. Geological Survey, 1976) pg. 2.

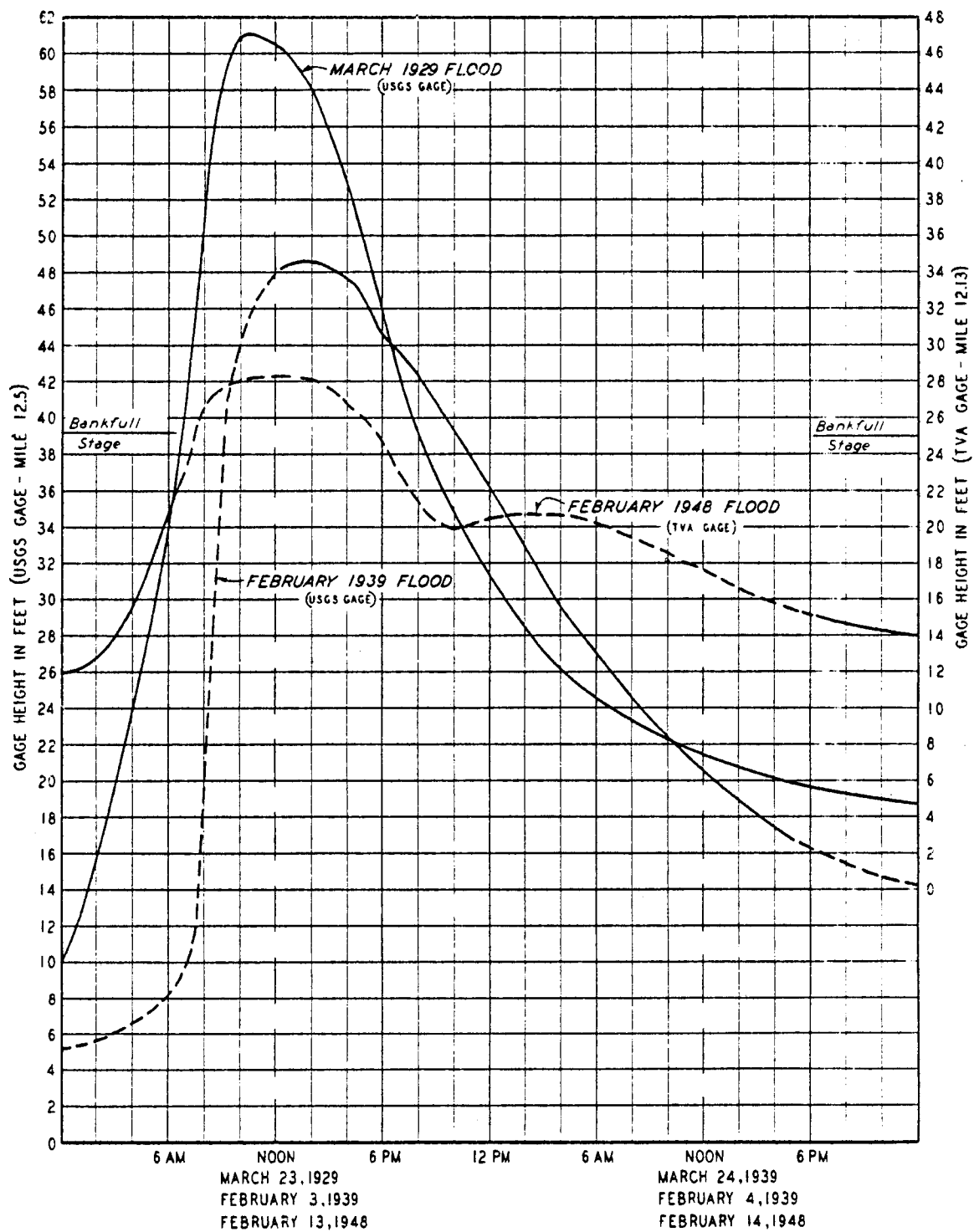


Figure 9. Stage hydrographs of floods on the Emory River.

TABLE 4  
FLOODS ON THE EMORY RIVER AS PROJECTED  
BY A REGIONAL REGRESSION ANALYSIS

| Recurrence Interval,<br>Years | Regression<br>Equation  | Resulting Projected<br>Flood, c.f.s. | Measured Flood,<br>c.f.s. |
|-------------------------------|-------------------------|--------------------------------------|---------------------------|
| 2                             | $Q_2 = 127A^{.752}$     | 18,702                               | 45,900                    |
| 5                             | $Q_5 = 211A^{.735}$     | 27,756                               | 72,800                    |
| 10                            | $Q_{10} = 276A^{.727}$  | 34,428                               | 92,500                    |
| 25                            | $Q_{25} = 366A^{.719}$  | 43,298                               | 119,000                   |
| 50                            | $Q_{50} = 442A^{.714}$  | 50,577                               | 140,000                   |
| 100                           | $Q_{100} = 524A^{.709}$ | 58,002                               | 162,000                   |

Source: W.J. Randolph and Charles R. Gamble, Technique for Estimating Frequency of Floods in Tennessee. U.S. Geological Survey (Washington: U.S. Government Printing Office, 1976)

## Low Flows

During the summer and fall months, potential evapotranspiration exceeds precipitation in the basin, so that the generation of runoff during the months of June through October is rare. The water that is in the streams during these months is the result of groundwater discharge, delayed vadose water discharge, and rainfall that has fallen directly into stream channels. The contribution of each of these processes is apparently small in the Obed-Emory basin, because the flows during September and October are quite low in most years.

Streamflow is usually at its yearly minimum in October, but extremely dry conditions sometimes persist into November. Occasional wet summers tend to raise the mean flow values for the summer and early fall months unduly. From June through October, the standard deviation of monthly flows actually exceeds the mean flow values (Table 2, p. 25). Hence median flow values are more representative of stream flow during the summer months.

On the average of every two years, the Emory River reaches a week-long average flow of only 5.0 c.f.s., which is unusually low for a drainage basin of more than 750 square miles. Since 1927, there have been two periods of no flow at all.

These frequently-occurring low summer flows preclude the use of the Obed-Emory river system's surface waters for water supply systems under natural conditions. Most water users in the basin acquire their water either from groundwater supplies or from reservoirs. The consistently poor groundwater supplies in the basin are responsible for the profusion of small reservoirs on this part of the Cumberland Plateau in recent years.

## CHAPTER 3

### A WATER BUDGET FOR THE OBED-EMORY BASIN

C.W. Thornthwaite developed a method by which water income via precipitation and water use from evapotranspiration can be evaluated. From these two factors, the water surplus, water deficit, soil moisture storage, and water runoff may be calculated. This moisture accounting system is referred to as "the water balance" or "water budget." In order to compute the water budget for a specific location, the following information is required: 1) mean monthly or daily air temperatures, 2) mean monthly or daily precipitation, 3) information on the water holding capacity of the soil at that location, and 4) tables for converting temperature readings and daylight period into potential evapotranspiration values. These tables have been compiled by Thornthwaite and are readily available.<sup>1</sup>

By analyzing the inputs and consumptive uses of water in the Emory basin using Thornthwaite's method, a better understanding of the movement of water in the basin can be achieved.

Other methods for determining potential evapotranspiration have been developed since Thornthwaite's original work, but most of them require considerably more climatic data. Safley compared the Penman,

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<sup>1</sup>C. W. Thornthwaite and J. R. Mather, The Water Balance. Drexel Institute of Technology Laboratory of Climatology Publications in Climatology Series, Vol. 8, no. 1, 3rd. ed. Centerton, New Jersey, 1955.

Blaney-Criddle, and Thornthwaite methods for estimating drought intensity and its relationship to crop yields in Tennessee. He found that not only was the Thornthwaite model the easiest to compile, but that "crop yield variation proved to be most sensitive to drought calculated using Thornthwaite-derived evapotranspiration values."<sup>2</sup> While crop yield variation is not necessarily the best measure of soil moisture conditions in relation to runoff, Safley's study does indicate that the Thornthwaite model does an adequate job of predicting soil moisture withdrawal rates and amounts in this area.

In order to understand better the precipitation-runoff relationships in the Emory River basin, Thornthwaite's water balance was computed for the basin for three time periods: 1) a mean monthly water budget, 2) a monthly water budget for calendar year 1976, and 3) a daily water budget for 1976.<sup>3</sup>

Values for potential evapotranspiration were obtained from Thornthwaite's 1957 tables, which allow for reduced actual evapotranspiration with reduced soil moisture. Temperature data are available for only one station in the basin. This station, the Crossville airport, at 1862 feet in elevation, is somewhat higher than the mean elevation of the basin. Additional temperature recording stations would permit more accurate prediction of potential evapotranspiration.

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<sup>2</sup>John Marcus Safley, "Comparison of Methods For Estimation of Drought Intensity and the Relationship of Drought to Yields of Agronomic Crops in Tennessee." Master's Thesis, University of Tennessee, Knoxville, 1974.

<sup>3</sup>C. W. Thornthwaite and J. R. Mather, Instructions and Tables for Computing Potential Evapotranspiration and the Water Balance. Drexel Institute of Technology Laboratory of Climatology Publications in Climatology Series, Vol. 10, no. 3. Centerton, New Jersey, 1957.

Six precipitation reporting stations are operative within the basin. All precipitation figures used in calculating the water balance represent the arithmetic mean of the six stations. This is well within the gage network density recommended for hydrometeorological studies by the World Meteorological Organization.<sup>4</sup>

The mean monthly water budget is shown in Table 5. A soil moisture storage capacity of three inches was assumed rather than the standard four or six inches because of the dominant sandiness of the soils in the basin. This figure seems to work better than any other, and the Agricultural Extension Leader for Morgan County agreed that this figure is most representative of soils in the Emory basin.<sup>5</sup>

The mean monthly water budget does a good job of accounting for water occurrences and losses within the basin. The predicted annual water yield for the basin is 25.0 inches, while the observed 20-year average is 24.97 inches. Monthly runoff volumes predicted by the water balance computation are reasonably close to the actual runoff values as measured by the gage at Oakdale and averaged over a 20-year period. Perhaps the most noticeable errors in prediction are those for the months of September and October, when the predicted flows are less than one-half the values of the mean observed runoff volumes. One possible explanation for this deviation is that the high flow rates during a few years are great enough to influence the mean values to an excessive degree.

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<sup>4</sup>World Meteorological Organization, "Guide to Hydro-Meteorological Practices." W.M.O., No. 168, Technical Paper 82. Geneva, 1970.

<sup>5</sup>Personal interview with Morgan County Agricultural Extension agent, C. Jansck.

TABLE 5  
AVERAGE MONTHLY WATER BUDGET

|                                   | All figures in inches |      |      |      |     |      |      |      |      |      |      |      |      |
|-----------------------------------|-----------------------|------|------|------|-----|------|------|------|------|------|------|------|------|
|                                   | Jan.                  | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
| Precipitation                     | 4.9                   | 4.9  | 5.7  | 4.9  | 4.4 | 4.3  | 5.2  | 3.7  | 3.5  | 2.9  | 4.1  | 5.5  | 54.0 |
| Potential evapo-<br>transpiration | 0.3                   | 0.5  | 0.9  | 2.0  | 3.6 | 4.8  | 5.6  | 5.2  | 3.7  | 2.0  | 0.8  | 0.3  | 29.7 |
| Actual evapotrans-<br>piration    | 0.3                   | 0.5  | 0.9  | 2.0  | 3.6 | 4.8  | 5.5  | 4.6  | 3.6  | 2.0  | 0.8  | 0.3  | 28.9 |
| Change in storage                 | -                     | -    | -    | -    | -   | -0.5 | -0.3 | -0.9 | -0.1 | +0.9 | +0.9 | -    |      |
| Storage                           | 3.0                   | 3.0  | 3.0  | 3.0  | 3.0 | 2.5  | 2.2  | 1.3  | 1.2  | 2.1  | 3.0  | 3.0  |      |
| Deficit                           | -                     | -    | -    | -    | -   | -    | -    | -    | -    | -    | -    | -    | 0.0  |
| Surplus                           | 4.6                   | 4.4  | 4.8  | 2.9  | 0.8 | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 2.4  | 5.2  | 25.1 |
| Carryover                         | 3.2                   | 3.9  | 4.1  | 4.4  | 3.6 | 2.2  | 1.1  | 0.5  | 0.2  | 0.1  | 0.0  | 1.2  |      |
| Total                             | 7.8                   | 8.3  | 8.9  | 7.3  | 4.4 | 2.2  | 1.1  | 0.5  | 0.2  | 0.1  | 2.4  | 6.4  |      |
| Calculated runoff                 | 3.9                   | 4.2  | 4.5  | 3.7  | 2.2 | 1.1  | 0.6  | 0.3  | 0.1  | 0.1  | 1.2  | 3.2  | 25.1 |
| Observed runoff                   | 4.1                   | 4.5  | 4.9  | 3.1  | 1.8 | 0.8  | 0.7  | 0.4  | 0.3  | 0.2  | 1.2  | 2.9  | 25.0 |

This explanation is corroborated by the fact that the median flow values for the months of September are significantly lower than the mean flow values (Table 2, p. 25). A second possible explanation is that unevenly distributed storm precipitation or variable soil conditions in the basin may produce local soil saturation and subsequent runoff even though the "average soil" of the basin is not at field capacity. Such an explanation is in line with the recent research results of Dunne, Black, and others, who have found that the major portion of storm runoff is produced on small portions of a watershed.<sup>6</sup> A third possibility is that runoff has occurred during these months without the soil being at field capacity, as Whipkey has suggested.<sup>7</sup>

The monthly water budget for 1976 shows considerable error in prediction of monthly water yield (See Table 6). Comparison of the daily water budget with the monthly budget for 1976 shows where some of the error arises (Tables 7-18). Potential evapotranspiration is underestimated for all but two months in the monthly analysis. The daily analysis shows only 25.4 inches. The largest errors occurred during the winter months, when periods of especially cold temperatures bring the monthly average below 36°F. even though significant evapotranspiration occurs during the warmer periods. This error accounts for two inches of excess predicted surplus, which is almost half of the total error.

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<sup>6</sup>Thomas Dunne and Richard D. Black, "Partial Area Contributions to Storm Runoff in a small New England Water shed." Water Resources Research, Vol. 6, no. 5, pg. 1296.

<sup>7</sup>Ronald Z. Whipkey, "Theory and Mechanics of Subsurface Stormflow," in International Symposium on Forest Hydrology, W.E. Sopper and H. W. Lull, eds. (Pergammon Press: Oxford, 1967).

TABLE 6

## MONTHLY WATER BUDGET, 1976

| All figures in inches             |      |      |      |      |      |      |      |      |      |      |      |           |
|-----------------------------------|------|------|------|------|------|------|------|------|------|------|------|-----------|
|                                   | Jan. | Feb. | Mar. | Apr. | May  | June | July | Aug. | Sep. | Oct. | Nov. | Dec. Year |
| Precipitation                     | 4.6  | 2.8  | 6.8  | 1.3  | 6.1  | 6.1  | 4.5  | 2.8  | 4.1  | 6.3  | 1.7  | 3.3 50.4  |
| Potential evapo-<br>transpiration | 0.0  | 0.8  | 1.5  | 2.0  | 2.5  | 4.4  | 4.8  | 4.5  | 3.1  | 1.5  | 0.3  | 0.0       |
| Actual evapotrans-<br>piration    | 0.0  | 0.8  | 1.5  | 2.0  | 2.5  | 4.4  | 4.8  | 4.5  | 3.1  | 1.5  | 0.3  | 0.0 25.4  |
| Change in storage                 | -    | -    | -    | -.7  | + .7 | -    | -.4  | -1.7 | +1.0 | +1.1 | -    | -         |
| Storage                           | 3.0  | 3.0  | 3.0  | 2.3  | 3.0  | 3.0  | 2.6  | 0.9  | 1.9  | 3.0  | 3.0  | 3.0       |
| Deficit                           | -    | -    | -    | -    | -    | -    | -    | -    | -    | -    | -    | -         |
| Surplus                           | 4.6  | 2.0  | 5.3  | 0.0  | 2.9  | 1.7  | 0.0  | 0.0  | 0.0  | 3.7  | 1.4  | 3.3 24.9  |
| Carryover                         | 2.9  | 3.7  | 2.8  | 4.0  | 2.0  | 2.4  | 2.0  | 1.0  | 0.5  | 0.2  | 1.9  | 1.6       |
| Total                             | 7.5  | 5.7  | 8.1  | 4.0  | 4.9  | 4.1  | 2.0  | 1.0  | 0.5  | 3.9  | 3.3  | 4.9       |
| Calculated runoff                 | 3.8  | 2.9  | 4.1  | 2.0  | 2.5  | 2.1  | 1.0  | 0.5  | 0.3  | 2.0  | 1.7  | 2.5 25.4  |
| Observed runoff                   | 4.7  | 2.3  | 3.9  | 1.7  | 1.8  | 1.7  | 1.4  | 0.1  | 0.04 | 0.8  | 0.8  | 2.2 21.4  |

TABLE 7  
DAILY WATER BUDGET, JANUARY 1976

| Date       | Mean<br>T, °F | Adj.<br>PE | Prec. | P-PE | Soil<br>Moist.<br>Change | Moist.<br>Def. | Moist.<br>Surp. | Observed<br>Runoff |
|------------|---------------|------------|-------|------|--------------------------|----------------|-----------------|--------------------|
| 1          | 37            | .01        | .49   | .48  | -                        | -              | .48             | .46                |
| 2          | 40            | .02        | .04   | .02  | -                        | -              | .02             | .26                |
| 3          | 36            | .00        | .52   | .52  | -                        | -              | .52             | .23                |
| 4          | 18            | .00        | -     | -    | -                        | -              | -               | .25                |
| 5          | 21            | .00        | -     | -    | -                        | -              | -               | .17                |
| 6          | 30            | .00        | -     | -    | -                        | -              | -               | .12                |
| 7          | 36            | .00        | .09   | .09  | -                        | -              | .09             | .10                |
| 8          | 17            | .00        | .45   | .45  | -                        | -              | .45             | .14                |
| 9          | 09            | .00        | -     | -    | -                        | -              | -               | .12                |
| 10         | 26            | .00        | -     | -    | -                        | -              | -               | .10                |
| 11         | 35            | .00        | .12   | .12  | -                        | -              | .12             | .09                |
| 12         | 36            | .00        | .29   | .29  | -                        | -              | .29             | .10                |
| 13         | 45            | .02        | .25   | .23  | -                        | -              | .23             | .10                |
| 14         | 30            | .00        | .55   | .55  | -                        | -              | .55             | .28                |
| 15         | 30            | .00        | -     | -    | -                        | -              | -               | .21                |
| 16         | 35            | .00        | -     | -    | -                        | -              | -               | .15                |
| 17         | 19            | .00        | .02   | .02  | -                        | -              | .02             | .12                |
| 18         | 16            | .00        | -     | -    | -                        | -              | -               | .09                |
| 19         | 25            | .00        | -     | -    | -                        | -              | -               | .07                |
| 20         | 31            | .00        | .04   | .04  | -                        | -              | .04             | .07                |
| 21         | 29            | .00        | .01   | .01  | -                        | -              | .01             | .06                |
| 22         | 30            | .00        | -     | -    | -                        | -              | -               | .05                |
| 23         | 42            | .02        | -     | -.02 | -.02                     | -              | -               | .05                |
| 24         | 50            | .04        | .10   | .06  | +.02                     | -              | .04             | .04                |
| 25         | 52            | .04        | .68   | .64  | -                        | -              | .64             | .06                |
| 26         | 42            | .02        | .66   | .64  | -                        | -              | .64             | .29                |
| 27         | 26            | .00        | .20   | .20  | -                        | -              | .20             | .36                |
| 28         | 27            | .00        | .02   | .02  | -                        | -              | .02             | .20                |
| 29         | 34            | .00        | .02   | .02  | -                        | -              | .02             | .14                |
| 30         | 35            | .00        | .02   | .02  | -                        | -              | .02             | .11                |
| 31         | 35            | .00        | .00   | -    | -                        | -              | -               | .09                |
| Monthly    |               |            |       |      |                          |                |                 |                    |
| Total or   |               |            |       |      |                          |                |                 |                    |
| Average 31 |               | .17        | 4.58  | 4.41 |                          |                | 4.41            | 4.69               |

TABLE 8  
DAILY WATER BUDGET, FEBRUARY 1976

| Date     | Mean<br>T, °F | Adj.<br>PE | Prec. | P-PE | Soil<br>Moist.<br>Change | Moist.<br>Def. | Moist.<br>Surp. | Observed<br>Runoff |
|----------|---------------|------------|-------|------|--------------------------|----------------|-----------------|--------------------|
| 1        | 32            | .00        | .17   | .17  | -                        | -              | .17             | .08                |
| 2        | 19            | .00        | .07   | .07  | -                        | -              | .07             | .07                |
| 3        | 36            | .00        | .10   | .10  | -                        | -              | .10             | .06                |
| 4        | 49            | .04        | -     | -.04 | -.04                     | -              | -               | .06                |
| 5        | 51            | .05        | .06   | .01  | +.01                     | -              | -               | .06                |
| 6        | 37            | .01        | .28   | .27  | +.03                     | -              | .24             | .06                |
| 7        | 23            | .00        | .02   | .02  | -                        | -              | .02             | .07                |
| 8        | 31            | .00        | -     | -    | -                        | -              | -               | .07                |
| 9        | 36            | .00        | -     | -    | -                        | -              | -               | .06                |
| 10       | 54            | .06        | -     | -.06 | -.06                     | -              | -               | .06                |
| 11       | 43            | .02        | .11   | .09  | +.06                     | -              | .03             | .05                |
| 12       | 43            | .02        | -     | -.02 | -.02                     | -              | -               | .05                |
| 13       | 60            | .08        | -     | -.08 | +.08                     | -              | -               | .04                |
| 14       | 57            | .07        | .01   | -.06 | -.06                     | -              | -               | .04                |
| 15       | 56            | .07        | -     | -.07 | -.07                     | -              | -               | .04                |
| 16       | 56            | .07        | -     | -.07 | -.07                     | -              | -               | .03                |
| 17       | 64            | .09        | .01   | -.08 | -.08                     | -              | -               | .03                |
| 18       | 52            | .05        | .84   | .79  | +.38                     | -              | .41             | .07                |
| 19       | 50            | .05        | .72   | .67  | -                        | -              | .67             | .33                |
| 20       | 49            | .04        | -     | -.04 | -.04                     | -              | -               | .20                |
| 21       | 59            | .07        | .05   | -.02 | -.02                     | -              | -               | .14                |
| 22       | 42            | .02        | .35   | .33  | +.06                     | -              | .27             | .14                |
| 23       | 37            | .01        | -     | -.01 | -.01                     | -              | -               | .12                |
| 24       | 48            | .04        | -     | -.04 | -.04                     | -              | -               | .09                |
| 25       | 53            | .06        | -     | -.06 | -.06                     | -              | -               | .08                |
| 26       | 58            | .07        | -     | -.07 | -.07                     | -              | -               | .07                |
| 27       | 50            | .05        | -     | -.05 | -.05                     | -              | -               | .06                |
| 28       | 54            | .06        | -     | -.06 | -.06                     | -              | -               | .05                |
| 29       | 60            | .08        | -     | -.08 | -.08                     | -              | -               | .05                |
| Monthly  |               |            |       |      |                          |                |                 |                    |
| Total or |               |            |       |      |                          |                |                 |                    |
| Average  | 46            | 1.18       | 2.79  |      |                          |                | 1.98            | 2.34               |

TABLE 9  
DAILY WATER BUDGET, MARCH 1976

| Date       | Mean<br>T, °F | Adj.<br>PE | Prec. | P-PE | Soil<br>Moist.<br>Change | Moist.<br>Def. | Moist.<br>Surp. | Observed<br>Runoff |
|------------|---------------|------------|-------|------|--------------------------|----------------|-----------------|--------------------|
| 1          | 58            | .07        | -     | -.07 | -.07                     | -              | -               | .04                |
| 2          | 67            | .11        | -     | -.11 | -.11                     | -              | -               | .04                |
| 3          | 64            | .10        | -     | -.10 | -.10                     | -              | -               | .04                |
| 4          | 67            | .11        | -     | -.11 | -.11                     | -              | -               | .03                |
| 5          | 57            | .07        | .14   | .07  | +.07                     | -              | -               | .03                |
| 6          | 42            | .02        | .42   | .40  | +.40                     | -              | -               | .05                |
| 7          | 43            | .02        | -     | -.02 | -.02                     | -              | -               | .05                |
| 8          | 38            | .01        | .16   | .15  | +.15                     | -              | -               | .05                |
| 9          | 39            | .01        | .61   | .60  | +.16                     | -              | .44             | .10                |
| 10         | 42            | .02        | .45   | .43  | -                        | -              | .43             | .21                |
| 11         | 48            | .04        | -     | -.04 | -.04                     | -              | -               | .15                |
| 12         | 53            | .06        | .08   | .02  | +.02                     | -              | -               | .11                |
| 13         | 42            | .02        | .11   | .09  | +.02                     | -              | .07             | .10                |
| 14         | 41            | .02        | -     | -.02 | -.02                     | -              | -               | .08                |
| 15         | 46            | .03        | .01   | -.02 | -.02                     | -              | -               | .07                |
| 16         | 40            | .02        | .11   | .09  | +.04                     | -              | .05             | .06                |
| 17         | 32            | .00        | .06   | .06  | -                        | -              | .06             | .06                |
| 18         | 46            | .03        | -     | -.03 | -.03                     | -              | -               | .05                |
| 19         | 53            | .06        | -     | -.06 | -.06                     | -              | -               | .05                |
| 20         | 59            | .08        | .18   | .10  | +.08                     | -              | -               | .04                |
| 21         | 49            | .04        | .96   | .92  | +.01                     | -              | .91             | .09                |
| 22         | 44            | .03        | -     | -.03 | -.03                     | -              | -               | .14                |
| 23         | 44            | .03        | -     | -.03 | -.03                     | -              | -               | .11                |
| 24         | 55            | .06        | .03   | -.03 | -.03                     | -              | -               | .09                |
| 25         | 55            | .06        | .17   | .11  | +.09                     | -              | .02             | .08                |
| 26         | 57            | .07        | .05   | -.02 | -.02                     | -              | -               | .07                |
| 27         | 49            | .04        | .17   | .13  | +.02                     | -              | .11             | .07                |
| 28         | 48            | .04        | -     | -.04 | -.04                     | -              | -               | .07                |
| 29         | 57            | .07        | .43   | .36  | +.04                     | -              | .32             | .13                |
| 30         | 60            | .08        | 2.20  | 2.12 | -                        | -              | 2.12            | 1.10               |
| 31         | 45            | .03        | .26   | .23  | -                        | -              | .23             | .56                |
| Monthly    |               |            |       |      |                          |                |                 |                    |
| Total or   |               |            |       |      |                          |                |                 |                    |
| Average 50 |               |            |       |      |                          |                |                 |                    |
|            |               | 1.45       | 6.81  |      |                          |                | 4.89            | 3.90               |

TABLE 10  
DAILY WATER BUDGET, APRIL 1976

| Date     | Mean<br>T, °F | Adj.<br>PE | Prec. | P-PE | Soil<br>Moist,<br>Change | Moist.<br>Def. | Moist.<br>Surp. | Observed<br>Runoff |
|----------|---------------|------------|-------|------|--------------------------|----------------|-----------------|--------------------|
| 1        | 41            | .02        | .19   | .17  | -                        | -              | .17             | .39                |
| 2        | 48            | .04        | .02   | -.02 | -.02                     | -              | -               | .24                |
| 3        | 55            | .06        | -     | -.06 | -.06                     | -              | -               | .16                |
| 4        | 50            | .05        | -     | -.05 | -.05                     | -              | -               | .12                |
| 5        | 48            | .04        | -     | -.04 | -.04                     | -              | -               | .09                |
| 6        | 51            | .05        | -     | -.05 | -.05                     | -              | -               | .08                |
| 7        | 52            | .05        | .02   | -.03 | -.03                     | -              | -               | .07                |
| 8        | 53            | .06        | -     | -.06 | -.06                     | -              | -               | .06                |
| 9        | 42            | .02        | -     | -.02 | -.02                     | -              | -               | .05                |
| 10       | 48            | .04        | -     | -.04 | -.04                     | -              | -               | .04                |
| 11       | 55            | .06        | .03   | -.03 | -.03                     | -              | -               | .04                |
| 12       | 46            | .03        | .19   | .16  | +.16                     | -              | -               | .04                |
| 13       | 51            | .05        | -     | -.05 | -.05                     | -              | -               | .03                |
| 14       | 58            | .08        | -     | -.08 | -.08                     | -              | -               | .03                |
| 15       | 63            | .11        | -     | -.11 | -.11                     | -              | -               | .03                |
| 16       | 65            | .12        | -     | -.12 | -.12                     | -              | -               | .03                |
| 17       | 63            | .11        | -     | -.11 | -.11                     | -              | -               | .02                |
| 18       | 65            | .12        | -     | -.12 | -.12                     | -              | -               | .02                |
| 19       | 65            | .12        | -     | -.12 | -.12                     | -              | -               | .02                |
| 20       | 64            | .12        | -     | -.12 | -.12                     | -              | -               | .02                |
| 21       | 65            | .12        | .20   | .08  | +.08                     | -              | -               | .02                |
| 22       | 56            | .08        | .10   | .02  | +.02                     | -              | -               | .02                |
| 23       | 60            | .09        | -     | -.09 | -.09                     | -              | -               | .02                |
| 24       | 62            | .10        | .05   | -.05 | -.05                     | -              | -               | .02                |
| 25       | 51            | .06        | .31   | .25  | +.25                     | -              | -               | .02                |
| 26       | 41            | .02        | .02   | 0    | -                        | -              | -               | .02                |
| 27       | 44            | .03        | -     | -.03 | -.03                     | -              | -               | .02                |
| 28       | 46            | .03        | -     | -.03 | -.03                     | -              | -               | .02                |
| 29       | 53            | .07        | -     | -.07 | -.07                     | -              | -               | .01                |
| 30       | 53            | .07        | -     | -.07 | -.07                     | -              | -               | .01                |
| Monthly  |               |            |       |      |                          |                |                 |                    |
| Total or |               |            |       |      |                          |                |                 |                    |
| Average  | 53            | 2.04       | 1.31  |      |                          |                |                 | 1.70               |

TABLE 11  
DAILY WATER BUDGET, MAY 1976

| Date                              | Mean<br>T, °F | Adj.<br>PE | Prec. | P-PE | Soil<br>Moist.<br>Change | Moist.<br>Def. | Moist.<br>Surp. | Observed<br>Runoff |
|-----------------------------------|---------------|------------|-------|------|--------------------------|----------------|-----------------|--------------------|
| 1                                 | 54            | .07        | .64   | .57  | +.57                     | -              | -               | .02                |
| 2                                 | 55            | .07        | .12   | .05  | +.05                     | -              | -               | .02                |
| 3                                 | 44            | .03        | -     | -.03 | -.03                     | -              | -               | .03                |
| 4                                 | 45            | .03        | -     | -.03 | -.03                     | -              | -               | .02                |
| 5                                 | 58            | .08        | -     | -.08 | -.08                     | -              | -               | .02                |
| 6                                 | 65            | .12        | .11   | -.01 | -.01                     | -              | -               | .02                |
| 7                                 | 52            | .06        | .46   | .40  | +.40                     | -              | -               | .02                |
| 8                                 | 52            | .06        | .01   | -.05 | -.05                     | -              | -               | .02                |
| 9                                 | 52            | .06        | -     | -.06 | -.06                     | -              | -               | .02                |
| 10                                | 54            | .07        | -     | -.07 | -.07                     | -              | -               | .02                |
| 11                                | 65            | .13        | .20   | .07  | +.07                     | -              | -               | .02                |
| 12                                | 63            | .12        | .02   | -.10 | -.10                     | -              | -               | .02                |
| 13                                | 65            | .13        | .06   | -.06 | -.06                     | -              | -               | .02                |
| 14                                | 63            | .12        | .35   | .23  | +.23                     | -              | -               | .02                |
| 15                                | 66            | .13        | 1.25  | 1.12 | +.23                     | -              | .89             | .19                |
| 16                                | 59            | .09        | .33   | .24  | -                        | -              | .24             | .23                |
| 17                                | 59            | .09        | .09   | 0.0  | -                        | -              | -               | .14                |
| 18                                | 49            | .05        | .30   | .25  | -                        | -              | .25             | .10                |
| 19                                | 49            | .05        | .08   | .03  | -                        | -              | .03             | .09                |
| 20                                | 55            | .07        | .01   | -.06 | -.06                     | -              | -               | .07                |
| 21                                | 60            | .09        | -     | -.09 | -.09                     | -              | -               | .06                |
| 22                                | 64            | .12        | -     | -.12 | -.12                     | -              | -               | .04                |
| 23                                | 63            | .12        | .43   | .31  | +.27                     | -              | .04             | .04                |
| 24                                | 59            | .10        | .03   | -.07 | -.07                     | -              | -               | .04                |
| 25                                | 56            | .07        | -     | -.07 | -.07                     | -              | -               | .04                |
| 26                                | 55            | .07        | -     | -.07 | -.07                     | -              | -               | .03                |
| 27                                | 57            | .08        | .02   | -.06 | -.06                     | -              | -               | .02                |
| 28                                | 58            | .09        | .39   | .30  | +.27                     | -              | .03             | .03                |
| 29                                | 61            | .11        | 1.00  | .89  | -                        | -              | .89             | .16                |
| 30                                | 66            | .13        | .22   | .09  | -                        | -              | .09             | .14                |
| 31                                | 72            | .17        | .04   | -.13 | -.13                     | -              | -               | .10                |
| Monthly<br>Total or<br>Average 58 |               |            |       |      |                          |                |                 |                    |
|                                   |               | 2.75       | 6.14  |      |                          |                |                 | 1.70               |

TABLE 12  
DAILY WATER BUDGET, JUNE 1976

| Date       | Mean<br>T, °F | Adj.<br>PE | Prec. | P-PE | Soil<br>Moist.<br>Change | Moist.<br>Def. | Moist.<br>Surp. | Observed<br>Runoff |
|------------|---------------|------------|-------|------|--------------------------|----------------|-----------------|--------------------|
| 1          | 69            | .16        | .27   | .11  | +.11                     | -              | -               | .07                |
| 2          | 65            | .13        | .41   | .28  | +.02                     | -              | .26             | .07                |
| 3          | 65            | .13        | .73   | .60  | -                        | -              | .60             | .17                |
| 4          | 67            | .14        | .10   | -.04 | -.04                     | -              | -               | .16                |
| 5          | 60            | .10        | .08   | -.02 | -.02                     | -              | -               | .12                |
| 6          | 60            | .10        | -     | -.10 | -.10                     | -              | -               | .08                |
| 7          | 63            | .12        | -     | -.12 | -.12                     | -              | -               | .06                |
| 8          | 66            | .13        | -     | -.13 | -.13                     | -              | -               | .05                |
| 9          | 68            | .15        | -     | -.15 | -.15                     | -              | -               | .04                |
| 10         | 69            | .16        | .09   | -.05 | -.05                     | -              | -               | .03                |
| 11         | 71            | .16        | .14   | -.02 | -.02                     | -              | -               | .02                |
| 12         | 70            | .16        | -     | -.16 | -.16                     | -              | -               | .02                |
| 13         | 72            | .17        | -     | -.17 | -.17                     | -              | -               | .02                |
| 14         | 73            | .18        | -     | -.18 | -.18                     | -              | -               | .02                |
| 15         | 73            | .18        | .02   | -.16 | -.16                     | -              | -               | .01                |
| 16         | 71            | .16        | .06   | -.10 | -.10                     | -              | -               | .01                |
| 17         | 71            | .16        | .03   | -.13 | -.13                     | -              | -               | .01                |
| 18         | 75            | .18        | .04   | -.14 | -.14                     | -              | -               | .01                |
| 19         | 67            | .13        | .48   | .35  | +.35                     | -              | -               | .01                |
| 20         | 64            | .12        | .77   | .65  | +.65                     | -              | -               | .03                |
| 21         | 62            | .11        | .69   | .58  | +.58                     | -              | -               | .10                |
| 22         | 63            | .12        | .30   | .18  | +.11                     | -              | .07             | .07                |
| 23         | 65            | .13        | .15   | .02  | -                        | -              | .02             | .05                |
| 24         | 72            | .17        | .01   | -.16 | -.16                     | -              | -               | .04                |
| 25         | 73            | .18        | .05   | -.13 | -.13                     | -              | -               | .03                |
| 26         | 73            | .18        | .52   | .34  | +.29                     | -              | .05             | .11                |
| 27         | 74            | .18        | .18   | 0.0  | -                        | -              | -               | .12                |
| 28         | 71            | .16        | .08   | -.10 | -.10                     | -              | -               | .07                |
| 29         | 72            | .17        | .28   | .11  | +.10                     | -              | .01             | .06                |
| 30         | 65            | .13        | .62   | .49  | -                        | -              | .49             | .08                |
| Monthly    |               |            |       |      |                          |                |                 |                    |
| Total or   |               |            |       |      |                          |                |                 |                    |
| Average 68 |               |            |       |      |                          |                |                 |                    |
|            |               | 4.34       | 6.10  |      |                          |                |                 | 1.69               |

TABLE 13  
DAILY WATER BUDGET, JULY 1976

| Date       | Mean<br>T, °F | Adj.<br>PE | Prec. | P-PE | Soil<br>Moist.<br>Change | Moist.<br>Def. | Moist.<br>Surp. | Observed<br>Runoff |
|------------|---------------|------------|-------|------|--------------------------|----------------|-----------------|--------------------|
| 1          | 64            | .12        | .05   | -.07 | -.07                     | -              | -               | .08                |
| 2          | 61            | .11        | -     | -.11 | -.11                     | -              | -               | .06                |
| 3          | 66            | .13        | .12   | -.01 | -.01                     | -              | -               | .05                |
| 4          | 66            | .13        | 1.26  | 1.13 | +.19                     | -              | .94             | .23                |
| 5          | 65            | .13        | .20   | .07  | -                        | -              | .13             | .30                |
| 6          | 63            | .12        | .02   | -.10 | -.10                     | -              | -               | .15                |
| 7          | 64            | .12        | .09   | -.03 | -.03                     | -              | -               | .11                |
| 8          | 69            | .16        | -     | -.16 | -.16                     | -              | -               | .07                |
| 9          | 72            | .17        | .07   | -.10 | -.10                     | -              | -               | .05                |
| 10         | 72            | .17        | -     | -.17 | -.17                     | -              | -               | .04                |
| 11         | 74            | .18        | -     | -.18 | -.18                     | -              | -               | .03                |
| 12         | 76            | .19        | .02   | -.17 | -.17                     | -              | -               | .02                |
| 13         | 70            | .16        | .19   | .03  | +.03                     | -              | -               | .02                |
| 14         | 68            | .14        | -     | -.14 | -.14                     | -              | -               | .02                |
| 15         | 77            | .19        | -     | -.19 | -.19                     | -              | -               | .02                |
| 16         | 72            | .17        | .31   | .14  | +.14                     | -              | -               | .01                |
| 17         | 66            | .13        | .38   | .25  | +.25                     | -              | -               | .01                |
| 18         | 65            | .13        | .00   | -.13 | -.13                     | -              | -               | .01                |
| 19         | 70            | .15        | -     | -.15 | -.15                     | -              | -               | .01                |
| 20         | 73            | .18        | -     | -.18 | -.18                     | -              | -               | .01                |
| 21         | 71            | .15        | -     | -.15 | -.15                     | -              | -               | .01                |
| 22         | 75            | .18        | .05   | -.13 | -.13                     | -              | -               | .007               |
| 23         | 77            | .19        | .28   | .09  | +.09                     | -              | -               | .007               |
| 24         | 78            | .20        | -     | -.20 | -.20                     | -              | -               | .006               |
| 25         | 78            | .20        | .11   | -.09 | -.09                     | -              | -               | .007               |
| 26         | 75            | .18        | .02   | -.16 | -.16                     | -              | -               | .006               |
| 27         | 76            | .19        | .21   | .02  | +.02                     | -              | -               | .004               |
| 28         | 74            | .18        | .50   | .32  | +.32                     | -              | -               | .005               |
| 29         | 78            | .20        | -     | -.20 | -.20                     | -              | -               | .008               |
| 30         | 72            | .16        | .33   | .17  | +.17                     | -              | -               | .009               |
| 31         | 73            | .18        | .05   | -.13 | -.13                     | -              | -               | .008               |
| Monthly    |               |            |       |      |                          |                |                 |                    |
| Total or   |               |            |       |      |                          |                |                 |                    |
| Average 71 |               | 4.97       | 4.47  |      |                          |                |                 | 1.37               |

TABLE 14  
DAILY WATER BUDGET, AUGUST 1976

| Date     | Mean<br>T, °F | Adj.<br>PE | Prec. | P-PE | Soil<br>Moist.<br>Change | Moist.<br>Def. | Moist.<br>Surp. | Observed<br>Runoff |
|----------|---------------|------------|-------|------|--------------------------|----------------|-----------------|--------------------|
| 1        | 72            | .16        | -     | -.16 | -.16                     | -              | -               | .007               |
| 2        | 66            | .13        | -     | -.13 | -.13                     | -              | -               | .005               |
| 3        | 67            | .13        | -     | -.13 | -.13                     | -              | -               | .004               |
| 4        | 68            | .14        | -     | -.14 | -.14                     | -              | -               | .003               |
| 5        | 73            | .17        | -     | -.17 | -.17                     | -              | -               | .002               |
| 6        | 71            | .15        | .11   | -.04 | -.04                     | -              | -               | .002               |
| 7        | 72            | .16        | .76   | .60  | +.60                     | -              | -               | .003               |
| 8        | 66            | .13        | -     | -.13 | -.13                     | -              | -               | .003               |
| 9        | 65            | .13        | -     | -.13 | -.13                     | -              | -               | .003               |
| 10       | 69            | .15        | -     | -.15 | -.15                     | -              | -               | .004               |
| 11       | 71            | .15        | -     | -.15 | -.15                     | -              | -               | .003               |
| 12       | 75            | .17        | .01   | -.16 | -.16                     | -              | -               | .003               |
| 13       | 76            | .18        | -     | -.18 | -.18                     | -              | -               | .003               |
| 14       | 76            | .18        | -     | -.18 | -.18                     | -              | -               | .002               |
| 15       | 74            | .17        | .03   | -.14 | -.01                     | .13            | -               | .003               |
| 16       | 73            | .17        | 1.49  | 1.32 | +1.32                    | -              | -               | .005               |
| 17       | 71            | .15        | -     | -.15 | -.15                     | -              | -               | .006               |
| 18       | 70            | .15        | -     | -.15 | -.15                     | -              | -               | .006               |
| 19       | 71            | .15        | -     | -.15 | -.15                     | -              | -               | .005               |
| 20       | 68            | .13        | -     | -.13 | -.13                     | -              | -               | .003               |
| 21       | 72            | .16        | -     | -.16 | -.16                     | -              | -               | .002               |
| 22       | 74            | .17        | -     | -.17 | -.17                     | -              | -               | .002               |
| 23       | 74            | .17        | -     | -.17 | -.17                     | -              | -               | .001               |
| 24       | 78            | .19        | -     | -.19 | -.19                     | -              | -               | .001               |
| 25       | 77            | .18        | .01   | -.17 | -.05                     | .12            | -               | .001               |
| 26       | 75            | .17        | .01   | -.16 | -                        | .16            | -               | .001               |
| 27       | 75            | .16        | .21   | .05  | +.05                     | -              | -               | .001               |
| 28       | 75            | .16        | .20   | .04  | +.04                     | -              | -               | .001               |
| 29       | 71            | .14        | .20   | .06  | +.06                     | -              | -               | .002               |
| 30       | 67            | .12        | -     | -.12 | -.12                     | -              | -               | .003               |
| 31       | 68            | .13        | .02   | -.11 | -.03                     | .08            | -               | .002               |
| Monthly  |               |            |       |      |                          |                |                 |                    |
| Total or |               |            |       |      |                          |                |                 |                    |
| Average  | 71            | 4.63       | 3.05  |      |                          | .49            |                 | .10                |

TABLE 15  
DAILY WATER BUDGET, SEPTEMBER 1976

| Date       | Mean<br>T, °F | Adj.<br>PE | Prec. | P-PE | Soil<br>Moist.<br>Change | Moist.<br>Def. | Moist.<br>Surp. | Observed<br>Runoff |
|------------|---------------|------------|-------|------|--------------------------|----------------|-----------------|--------------------|
| 1          | 63            | .11        | .22   | .11  | +.11                     | -              | -               | .002               |
| 2          | 68            | .13        | .79   | .66  | +.66                     | -              | -               | .002               |
| 3          | 68            | .13        | .02   | -.11 | -.11                     | -              | -               | .002               |
| 4          | 68            | .13        | .03   | -.10 | -.10                     | -              | -               | .002               |
| 5          | 69            | .14        | .02   | -.12 | -.12                     | -              | -               | .002               |
| 6          | 67            | .12        | -     | -.12 | -.12                     | -              | -               | .002               |
| 7          | 69            | .14        | -     | -.14 | -.14                     | -              | -               | .002               |
| 8          | 73            | .16        | -     | -.16 | -.16                     | -              | -               | .002               |
| 9          | 71            | .14        | .26   | .12  | +.12                     | -              | -               | .002               |
| 10         | 58            | .07        | .20   | .13  | +.13                     | -              | -               | .002               |
| 11         | 57            | .07        | -     | -.07 | -.07                     | -              | -               | .002               |
| 12         | 62            | .09        | -     | -.09 | -.09                     | -              | -               | .002               |
| 13         | 61            | .08        | -     | -.08 | -.08                     | -              | -               | .002               |
| 14         | 64            | .10        | -     | -.10 | -.03                     | .07            | -               | .002               |
| 15         | 66            | .11        | .02   | -.09 | -                        | .09            | -               | .001               |
| 16         | 65            | .11        | .03   | -.08 | -                        | .08            | -               | .001               |
| 17         | 62            | .09        | -     | -.09 | -                        | .09            | -               | .001               |
| 18         | 64            | .10        | -     | -.10 | -                        | .10            | -               | .001               |
| 19         | 65            | .11        | -     | -.11 | -                        | .11            | -               | .001               |
| 20         | 62            | .09        | .07   | -.02 | -                        | .02            | -               | .001               |
| 21         | 58            | .07        | .38   | .31  | +.31                     | -              | -               | .001               |
| 22         | 55            | .06        | -     | -.06 | -.06                     | -              | -               | .001               |
| 23         | 59            | .08        | -     | -.08 | -.08                     | -              | -               | .001               |
| 24         | 64            | .10        | -     | -.10 | -.10                     | -              | -               | .001               |
| 25         | 66            | .11        | -     | -.11 | -.07                     | .04            | -               | .001               |
| 26         | 72            | .14        | .06   | -.08 | -                        | .08            | -               | .001               |
| 27         | 69            | .13        | .46   | .33  | +.33                     | -              | -               | .001               |
| 28         | 63            | .10        | .83   | .73  | +.73                     | -              | -               | .001               |
| 29         | 61            | .09        | .12   | .03  | +.03                     | -              | -               | .001               |
| 30         | 53            | .06        | .55   | .49  | +.49                     | -              | -               | .002               |
| Monthly    |               |            |       |      |                          |                |                 |                    |
| Total or   |               |            |       |      |                          |                |                 |                    |
| Average 64 |               | 3.19       |       |      |                          | .71            | 0               | .04                |

TABLE 16  
DAILY WATER BUDGET, OCTOBER 1976

| Date       | Mean<br>T, °F | Adj.<br>PE | Prec. | P-PE | Soil<br>Moist.<br>Change | Moist.<br>Def. | Moist.<br>Surp. | Observed<br>Runoff |
|------------|---------------|------------|-------|------|--------------------------|----------------|-----------------|--------------------|
| 1          | 60            | .08        | .30   | .22  | +.22                     | -              | -               | .005               |
| 2          | 60            | .08        | -     | -.08 | -.08                     | -              | -               | .007               |
| 3          | 62            | .09        | -     | -.09 | -.09                     | -              | -               | .006               |
| 4          | 65            | .11        | -     | -.11 | -.11                     | -              | -               | .005               |
| 5          | 66            | .11        | -     | -.11 | -.11                     | -              | -               | .004               |
| 6          | 58            | .07        | .23   | .16  | +.16                     | -              | -               | .004               |
| 7          | 52            | .05        | .46   | .39  | +.39                     | -              | -               | .004               |
| 8          | 53            | .06        | .16   | .10  | +.10                     | -              | -               | .003               |
| 9          | 46            | .03        | .38   | .35  | +.35                     | -              | -               | .005               |
| 10         | 50            | .05        | -     | -.05 | -.05                     | -              | -               | .008               |
| 11         | 53            | .06        | -     | -.06 | -.06                     | -              | -               | .008               |
| 12         | 57            | .07        | -     | -.07 | -.07                     | -              | -               | .008               |
| 13         | 60            | .08        | -     | -.08 | -.08                     | -              | -               | .008               |
| 14         | 56            | .07        | -     | -.07 | -.07                     | -              | -               | .006               |
| 15         | 57            | .07        | -     | -.07 | -.07                     | -              | -               | .005               |
| 16         | 51            | .05        | .02   | -.03 | -.03                     | -              | -               | .004               |
| 17         | 57            | .07        | .19   | .12  | +.12                     | -              | -               | .004               |
| 18         | 58            | .07        | -     | -.07 | -.07                     | -              | -               | .003               |
| 19         | 55            | .06        | -     | -.06 | -.06                     | -              | -               | .003               |
| 20         | 51            | .05        | .49   | .44  | +.44                     | -              | -               | .003               |
| 21         | 51            | .05        | .15   | .10  | +.10                     | -              | -               | .003               |
| 22         | 58            | .07        | -     | -.07 | -.07                     | -              | -               | .004               |
| 23         | 63            | .09        | .01   | -.08 | -.08                     | -              | -               | .004               |
| 24         | 57            | .07        | .40   | .33  | +.33                     | -              | -               | .004               |
| 25         | 58            | .07        | 1.31  | 1.24 | +.30                     | -              | .94             | .075               |
| 26         | 47            | .04        | 1.16  | 1.12 | -                        | -              | 1.12            | .266               |
| 27         | 47            | .04        | -     | -.04 | -.04                     | -              | -               | .109               |
| 28         | 52            | .05        | -     | -.05 | -.05                     | -              | -               | .057               |
| 29         | 61            | .08        | -     | -.08 | -.08                     | -              | -               | .039               |
| 30         | 53            | .05        | .37   | .32  | +.17                     | -              | .15             | .034               |
| 31         | 46            | .03        | .65   | .62  | -                        | -              | .62             | .102               |
| Monthly    |               |            |       |      |                          |                |                 |                    |
| Total or   |               |            |       |      |                          |                |                 |                    |
| Average 51 |               |            |       |      |                          |                |                 |                    |
|            |               | 1.88       | 6.26  |      |                          |                | 3.28            | .790               |

TABLE 17  
DAILY WATER BUDGET, NOVEMBER 1976

| Date       | Mean<br>T, °F | Adj.<br>PE | Prec. | P-PE | Soil<br>Moist.<br>Change | Moist.<br>Def. | Moist.<br>Surp. | Observed<br>Runoff |
|------------|---------------|------------|-------|------|--------------------------|----------------|-----------------|--------------------|
| 1          | 43            | .02        | -     | -.02 | -.02                     | -              | -               | .099               |
| 2          | 43            | .02        | -     | -.02 | -.02                     | -              | -               | .066               |
| 3          | 41            | .02        | -     | -.02 | -.02                     | -              | -               | .049               |
| 4          | 31            | .00        | -     | -    | -                        | -              | -               | .039               |
| 5          | 34            | .00        | -     | -    | -                        | -              | -               | .031               |
| 6          | 43            | .02        | -     | -.02 | -.02                     | -              | -               | .027               |
| 7          | 42            | .02        | -     | -.02 | -.02                     | -              | -               | .023               |
| 8          | 31            | .00        | -     | -    | -                        | -              | -               | .020               |
| 9          | 46            | .03        | -     | -.03 | -.03                     | -              | -               | .018               |
| 10         | 46            | .03        | -     | -.03 | -.03                     | -              | -               | .016               |
| 11         | 35            | .00        | .05   | .05  | +.05                     | -              | -               | .016               |
| 12         | 31            | .00        | .22   | .22  | +.11                     | -              | .11             | .015               |
| 13         | 30            | .00        | -     | -    | -                        | -              | -               | .014               |
| 14         | 32            | .00        | -     | -    | -                        | -              | -               | .014               |
| 15         | 40            | .02        | .11   | .11  | -                        | -              | .11             | .014               |
| 16         | 41            | .02        | -     | -.02 | -.02                     | -              | -               | .014               |
| 17         | 44            | .03        | -     | -.03 | -.03                     | -              | -               | .015               |
| 18         | 50            | .04        | -     | -.04 | -.04                     | -              | -               | .015               |
| 19         | 55            | .05        | -     | -.05 | -.05                     | -              | -               | .013               |
| 20         | 44            | .03        | -     | -.03 | -.03                     | -              | -               | .013               |
| 21         | 36            | .00        | -     | -    | -                        | -              | -               | .012               |
| 22         | 29            | .00        | -     | -    | -                        | -              | -               | .012               |
| 23         | 27            | .00        | -     | -    | -                        | -              | -               | .011               |
| 24         | 42            | .02        | -     | -.02 | -.02                     | -              | -               | .010               |
| 25         | 47            | .03        | -     | -.03 | -.03                     | -              | -               | .009               |
| 26         | 51            | .04        | .12   | .08  | +.08                     | -              | -               | .009               |
| 27         | 59            | .07        | .47   | .40  | +.16                     | -              | .24             | .012               |
| 28         | 37            | .01        | .24   | .23  | -                        | -              | .23             | .024               |
| 29         | 19            | .00        | .45   | .45  | -                        | -              | .45             | .057               |
| 30         | 19            | .00        | .04   | .04  | -                        | -              | .04             | .073               |
| Monthly    |               |            |       |      |                          |                |                 |                    |
| Total or   |               |            |       |      |                          |                |                 |                    |
| Average 36 |               |            |       |      |                          |                |                 |                    |
|            |               | .44        | 1.70  |      |                          |                | 1.18            | .746               |

TABLE 18  
DAILY WATER BUDGET, DECEMBER 1976

| Date     | Mean<br>T, °F | Adj.<br>PE | Prec. | P-PE | Soil<br>Moist.<br>Change | Moist.<br>Def. | Moist.<br>Surp. | Observed<br>Runoff |
|----------|---------------|------------|-------|------|--------------------------|----------------|-----------------|--------------------|
| 1        | 36            | .00        | -     | -    | -                        | -              | -               | .058               |
| 2        | 32            | .00        | -     | -    | -                        | -              | -               | .049               |
| 3        | 35            | .00        | -     | -    | -                        | -              | -               | .044               |
| 4        | 41            | .02        | -     | -.02 | -.02                     | -              | -               | .039               |
| 5        | 40            | .02        | -     | -.02 | -.02                     | -              | -               | .034               |
| 6        | 43            | .02        | .12   | .10  | +.04                     | -              | .06             | .033               |
| 7        | 35            | .00        | .87   | .87  | -                        | -              | .87             | .143               |
| 8        | 21            | .00        | .09   | .09  | -                        | -              | .09             | .184               |
| 9        | 28            | .00        | .01   | .01  | -                        | -              | .01             | .119               |
| 10       | 44            | .02        | -     | -.02 | -.02                     | -              | -               | .088               |
| 11       | 52            | .04        | .07   | .03  | +.02                     | -              | .01             | .073               |
| 12       | 44            | .02        | .42   | .40  | -                        | -              | .40             | .098               |
| 13       | 33            | .00        | .06   | .06  | -                        | -              | .06             | .146               |
| 14       | 38            | .01        | -     | -.01 | -.01                     | -              | -               | .116               |
| 15       | 43            | .02        | .20   | .18  | +.01                     | -              | .18             | .098               |
| 16       | 39            | .01        | -     | -.01 | -.01                     | -              | -               | .092               |
| 17       | 42            | .02        | -     | -.02 | -.02                     | -              | -               | .078               |
| 18       | 48            | .03        | -     | -.03 | -.03                     | -              | -               | .066               |
| 19       | 52            | .04        | -     | -.04 | -.04                     | -              | -               | .055               |
| 20       | 36            | .00        | .22   | .22  | +.10                     | -              | .12             | .050               |
| 21       | 14            | .00        | .12   | .12  | -                        | -              | .12             | .053               |
| 22       | 21            | .00        | -     | -    | -                        | -              | -               | .048               |
| 23       | 30            | .00        | -     | -    | -                        | -              | -               | .044               |
| 24       | 28            | .00        | -     | -    | -                        | -              | -               | .041               |
| 25       | 36            | .00        | .08   | .08  | -                        | -              | -               | .038               |
| 26       | 32            | .00        | .41   | .41  | -                        | -              | .41             | .055               |
| 27       | 37            | .01        | -     | -    | -                        | -              | -               | .068               |
| 28       | 36            | .00        | -     | -    | -                        | -              | -               | .065               |
| 29       | 21            | .00        | .01   | .01  | -                        | -              | .01             | .060               |
| 30       | 33            | .00        | .12   | .12  | -                        | -              | .12             | .051               |
| 31       | 14            | .00        | .36   | .36  | -                        | -              | .36             | .054               |
| Monthly  |               |            |       |      |                          |                |                 |                    |
| Total or |               |            |       |      |                          |                |                 |                    |
| Average  | 34            | .28        | 3.16  |      |                          | 0              | 2.92            | 2.240              |

Some runoff did occur at times when the water budget indicates that soil moisture storage was not full. This might be explained by factors such as irregularity of precipitation, locally intense precipitation causing Horton overland flow, rapid near-surface throughflow, and precipitation falling directly into stream channels. Some parts of the basin will receive more precipitation than others or will have lower storage capacity than others, so that soil saturation and through-flow could occur even though the "average" soil of the basin is still well below field capacity. The possibility of runoff from soils not at field capacity must be considered also.

In general, however, the daily water budget does seem to back up Thornthwaite's assumption that runoff does not occur until the soils in the basin are at field capacity. For example, on August 16, 1976, the basin had an average of 1.49 inches of precipitation, yet no significant amount of runoff was generated, because the soils were extremely dry at the time. Another 1.64 inches fell between August 27 and September 2 with no significant runoff resulting.

The most evident discrepancy in the daily water budget of 1976 is that for the October 23-30 period. Average total rainfall over the basin for this period was 2.88 inches. Even though the soil was already near field capacity, only .58 inches of runoff were generated over the next six days. One possible explanation is that the precipitation data are non-representative for the basin as a whole.

In almost every case, peak runoff rates occurred not on the day of maximum precipitation, but on the following day. This might indicate that direct surface runoff is not responsible for peak flows, although

this delay is at least partially explained by the time lag required for the water to reach the end of the basin, where the gage is located.

The relatively smooth topography, the dense vegetation, the sandy soils, and the small amount of urban development in the basin should all contribute to high infiltration relative to surface runoff. The low degree of dissection (i.e., low drainage density) indicates a large amount of infiltration and little surface runoff. If surface runoff were common, channels to move it would be required, as Carlston stated.<sup>8</sup> In most cases, conditions favoring low surface runoff produce highly stable streamflow. The extremely peaked flow for the Emory River is quite unusual for a stream with the basin characteristics just described.

Application of water budget analysis to the Emory River basin accounts for the overall volume and seasonal pattern of runoff. The required adjustments to Thornthwaite's runoff equation reinforce the observation that the peaked discharge of the Emory River is anomalous.

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<sup>8</sup> Charles W. Carlston, Drainage Density and Streamflow, U.S. Geological Survey Professional Paper 422-C (U.S. Government Printing Office, Washington, D.C., 1963).

## CHAPTER 4

### A COMPARISON OF THREE BASINS

The degree to which the seasonal flow regime of the Emory River deviates from the general pattern of streams in southern Appalachia, or from the pattern that might be expected of a stream with its basin characteristics, can best be understood by comparing the Emory to other streams in East Tennessee. The Nolichucky River above the gaging station at Embreeville and the Collins River above McMinnville are used for the comparison (See Figure 1, pg. 2). These streams are reasonably near the Emory, are of similar size, are also free-flowing, and afford comparable streamflow data. The Nolichucky drains an area of 805 square miles, most of which lies in the Unaka Mountains of Tennessee and North Carolina, a subsection of the Blue Ridge physiographic province. The Collins drains parts of the Cumberland Plateau and the Highland Rim south and west of the Emory basin. Its basin area above the McMinnville gage is 640 square miles. These and other characteristics of the three basins are summarized in Table 19.

The general seasonal runoff regime is similar in all three basins, although the Nolichucky differs somewhat from the other two by having greater summer flows, reflecting the higher summer precipitation and lower evapotranspiration in that mountainous drainage basin. The Collins resembles the Emory more closely than the Nolichucky, but its summer base flows, on a monthly basis, are higher, and its spring discharges are lower.

TABLE 19  
STREAMFLOW CHARACTERISTICS

|                                                 | Emory   | Nolichucky | Collins |
|-------------------------------------------------|---------|------------|---------|
| Mean Annual Flood,<br>c.f.s./mile <sup>2</sup>  | 60.1    | 23.6       | 36.6    |
| Peak Flow, 2-year<br>Recurrence                 | 45,900  | 19,000     | 23,400  |
| 5-year Recurrence                               | 72,800  | 30,100     | 36,200  |
| 10-year Recurrence                              | 92,500  | 38,900     | 44,900  |
| 25-year Recurrence                              | 119,000 | 51,700     | 56,100  |
| 50-year Recurrence                              | 140,000 | 62,700     | 64,500  |
| 100-year Recurrence                             | 162,000 | 74,900     | 72,900  |
| Average 7-day Low<br>Flow, 2-year<br>Recurrence | 5.0     | 350        | 87.6    |
| 10-year Recurrence                              | .32     | 211        | 62.6    |
| Standard Deviation of<br>Mean Annual Flow       | 376.8   | 276.6      | 305.7   |
| Mean Discharge                                  | 1458    | 1348       | 1168    |

All Values in Cubic Feet per Second

Source: V. Jeff May, George H. Wood, and Donald R. Rima, A Proposed Streamflow-Data Program for Tennessee. U.S. Geological Survey (Nashville, 1970)

In flood-flow characteristics, on the other hand, the Collins is nearly a duplicate of the Nolichucky; the standard flood for each is only about one-half that of the Emory.

Clearly the Emory River system differs from nearby streams of comparable size with respect to several hydrographic characteristics, especially the height of its flood peaks and the small volume of base flow. In order to approach an explanation for these peculiarities, a number of factors believed to affect high and low-water flows will be examined as they relate to observed flow characteristics of the three basins. In order of treatment, the factors considered are precipitation, vegetation cover, surface storage capacity, basin relief, channel slope, drainage density, infiltration capacity of the soil, groundwater storage, and lateral transmission capacity of the soil, regolith, and bedrock (Table 20).

Average annual precipitation in the Nolichucky basin is, at 51 inches, slightly below the the 53-inch figure for the Emory and Collins basins. On the other hand, the Obed-Emory basin is subject to somewhat more intense rainfall than either of the other two. Two-year, 24-hour rainfall events are 3.5 inches for the Emory basin and only 3.0 inches for both the Nolichucky and Collins. This slightly higher storm event value may contribute to the higher flood flows on the Emory River, but clearly it does not wholly explain them. The two-year precipitation events in the Emory basin exceed those in the other basins by only 17%, whereas the Obed-Emory's flood flows are roughly twice as great as those of the Nolichucky and Collins.

Although all three drainage basins are extensively forested, the percentage of forested land is somewhat higher in the Obed-Emory basin

TABLE 20  
A COMPARISON OF RIVER BASIN CHARACTERISTICS

| Characteristic                      | River |            |         |
|-------------------------------------|-------|------------|---------|
|                                     | Emory | Nolichucky | Collins |
| Drainage Area, Mile <sup>2</sup>    | 764   | 805        | 640     |
| Main Channel Slope,<br>Feet/Mile    | 24    | 47         | 26      |
| Mean Elevation, Feet                | 1630  | 3070       | 1370    |
| % Forest Cover                      | 87.9  | 82.0       | 65.4    |
| % Area in Lakes<br>and Ponds        | .11   | 0.0        | .01     |
| Soils Infiltration<br>Index, Inches | 3.89  | 3.00       | 3.50    |
| Annual Precipitation,<br>Inches     | 53    | 51         | 53      |
| 2-year 24-hour Rainfall,<br>Inches  | 3.5   | 3.0        | 3.0     |
| Basin Relief, Feet                  | 2563  | 5165       | 1535    |
| Drainage Density                    | 3.73  | 4.70       | 4.58    |

Source: V. Jeff May, George H. Wood, and Donald R. Rima, A Proposed Streamflow-Data Program for Tennessee. U.S. Geological Survey (Nashville, 1970)

than in the Nolichucky basin and far greater than in the Collins basin. Other things being equal, a cleared basin should yield higher flood peaks than a more heavily forested basin. Here, however, the basin with the largest percentage of forested area has the highest floods.

None of the basins has large storage capacity in lakes and ponds, although the Obed-Emory has more than the others. Recreational development and the lack of dependable sources of domestic and agricultural water supplies have led to the construction of numerous small reservoirs on the Cumberland Plateau in recent years. Although increased storage capacity lowers flood peaks, the small amount available in these basins is hardly enough to affect their flood hydrographs significantly.

Basin relief has been shown to be an important factor in the determination of peak flows. With increasing relief, as a rule, come steeper hillslopes, higher stream gradients, and reduced time of concentration.<sup>1</sup> These secondary features generally result in higher and more immediate peaking of the flood hydrograph. Basin reliefs are 2563 feet for the Obed-Emory, 5165 feet for the Nolichucky, and 1535 feet for the Collins. It is evident that basin relief is not the decisive factor in the distinctively high peaks characteristic of the Emory River.

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<sup>1</sup>Peter Patton and Victor Baker, "Morphometry and Floods in Small Drainage Basins Subject to Hydrogeomorphic Controls," Water Resources Research, Vol. 12 (October, 1976), pp. 941-952.

Benson and others have found that main channel slope is an important determinant of flood peaks.<sup>2</sup> In studies of basins representing numerous sections of the United States, Benson found, in a regression analysis, that main channel slope was second only to drainage area in explaining peak flows; the steeper the channel slope, the greater the flood peak.<sup>3</sup> This relationship is presumably due to the ability of a steeper channel to deliver surplus water from all parts of the basin to the gage more rapidly.

Measured from stream gage to drainage divide, the main channel of the Obed-Emory is 47 miles long and drops from 1,900 feet elevation at the divide to 761 feet at the gaging station, for an average channel slope of 24 feet per mile. The Nolichucky falls 3,473 feet over a distance of 74 miles, for an average channel slope of 47 feet per mile. The slope of the Obed-Emory, but approximately one-half of the basin, lying on the Highland Rim, is drained by the Barren Fork, which joins the Collins just above the gage and which has a much gentler channel slope. According to the findings of Benson, Shelton, and others, the Nolichucky should have the highest flood flows and the Collins the least. In fact, however, those of the Collins and Nolichucky are much the same, and those of the Obed-Emory roughly twice as great.

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<sup>2</sup>Manuel A. Benson, Factors Influencing the Occurrence of Floods in a Humid Region of Diverse Terrain, U.S. Geological Survey Water-Supply Paper, 1580-B (Washington, D.C.: U. S. Government Printing Office, 1962); and Curtis Shelton, J. H. Lilliard, J.I. Sewell, and T.V. Wilson, Field Procedures for Predicting Water Yields and Peak Runoff Rates from Small Watersheds, Southern Regional Research Project S-53, Series Bulletin No. 202, 1975.

<sup>3</sup>Benson, op.cit., p. B-23.

Carlston has studied the relationship of streamflow to drainage density, which is defined, for a given drainage basin, as the ratio of total channel length to basin area. He states that flood runoff is difrectly proportional to drainage density, in the form  $Q_{2.33} \text{ per mi}^2 = 1.3 D^2$ , where  $Q_{2.33}$  is the mean annual flood and D is the drainage density as measured from 1:24,00 topographic maps. He interprets this relationship in the statement, "Drainage density is adjusted to the most efficient removal of flood runoff."<sup>4</sup> Carlston also states that base flow is directly proportional to the inverse square of the drainage density. By these rules, a basin with a high drainage density should have high flood flows and low base flows.

In order to compare drainage densities among the basins, Donahue's method of drainage density computation was employed.<sup>5</sup> Several 1:24,000 topographic maps from each basin were selected and each map divided into 9 equal areas. Within selected areas on each map, all drainage lines that were indicated by blue lines or by consecutive crenulations in contour lines were drawn in with a number 1 Rapidograph pen. A dot planimeter was overlaid in order to estimate drainage intensity. These measurements were made twice for each chosen section, with different orientations of the dot screen. Drainage intensity, (I), can be converted to stream lengths and thus into drainage density by the transformation:

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<sup>4</sup> Charles Carlston, Drainage Density and Streamflow, U.S. Geological Survey Professional Paper 422-C (Washington, D.C.: U.S. Government Printing Office, 1963).

<sup>5</sup> John Donahue, "Measuring Drainage Density with a Dot Planimeter," The Professional Geographer, Vol. 26 (Sugust, 1974), pp. 317-319.

$L = \frac{na}{NW}$ , where  $L$  = stream lengths within the measured area,  $n$  = the number of dots that intersect stream lines,  $N$  = the total number of dots that within the sample area,  $A$  = sample area in square inches, and  $W$  = width of two dot radii and included drainage line in fractions of an inch.

In almost all samples, drainage density values from the Obed-Emory basin were lower than those from the Nolichucky. The average value for the Obed-Emory was 3.73, as compared with 4.70 for the Nolichucky. A smaller sample drawn from the Collins basin yielded an average density of 4.58. By Carlston's principles, peak flows on both the Nolichucky and the Collins should exceed those of the Emory, and their base flows should be lower. In reality the opposite is true. Each of the standard recurrence-interval floods on the Emory River is more than twice the value of the same flood on the Nolichucky and Collins Rivers (Table 19). Applying Carlston's equation to the Obed-Emory basin, the predicted mean annual flood is about 11,000 c.f.s., yet the measured mean annual flood exceeds 46,000 c.f.s. On the other hand, Carlston's formula gives a reasonably accurate value for the mean annual flood ( $Q_{2.33}$ ) on the Nolichucky, 18,000 c.f.s., compared to the observed value of 19,000 c.f.s. The Carlston formula predicts an annual flood of approximately 17,500 c.f.s. for the Collins River, against a measured value of 24,000. Clearly it is the Emory that is anomalous.

To this point, brief examination of several factors believed to be partial determinants of flood peaks and base flows in streams, namely precipitation, vegetation cover, surface storage capacity, basin relief, channel slope, and drainage density, has indicated that none of these can be used to explain the unusually high peaks and low base flows

in the Obed-Emory basin. Attention must, therefore, be focused more specifically upon the actual routes and processes by which precipitation water reaches the stream channels.

Perhaps the single most important determinant of flood runoff volumes and concentrations is the relationship between the intensity of precipitation and the ability of the terrain to transmit water. Any soil unit under given conditions can absorb water at only a limited rate. If water is supplied by precipitation at a greater rate, some of it must be routed overland. That excess water quickly collects in channels and moves rapidly to the basin outlet. Such flow, termed "direct surface runoff," has commonly been regarded as the portion of the runoff that produces peak flows. Wherever direct surface runoff occurs, drainage channels must form to carry the water.

In a study conducted by the U.S. Geological Survey, the predominantly sandy and stony soils of the Obed-Emory basin were found, on the average, to have the capacity to accommodate through infiltration 3.89 inches of precipitation in a single storm.<sup>6</sup> For the soils of the Collins basin, the correspondence figure was 4.08 inches per storm, and for the finer textured soils of the Nolichucky basin, 3.51 inches. Studies by Longwell, Parks, and Springer indicate that in soils of the Hartsells series, the most widespread series in the Obed-Emory basin, saturated permeabilities of the A horizons range from 6.8 to 10.4 inches per hour, and those of the

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<sup>6</sup>V. Jeff May, George H. Wood, and Donald R. Rima, A Proposed Streamflow Data Program for Tennessee, U.S. Geological Survey Open File Report (Nashville, 1970).

B horizons from 3.3 to 8.8 inches per hour.<sup>7</sup> Comparable figures for the Collins basin are 1.48 to 17.25 inches per hour for A horizons and 2.97 to 19.21 for B horizons. Data are not available for the Nolichucky basin. These figures were derived from laboratory tests on prepared soils, which would not all benefit from naturally occurring macropores. The same soils should have even higher permeabilities in the field, where decayed root channels and animal burrows exist. On the basis of these data, it is doubtful that precipitation rates ever exceed infiltration rates in any of the three basins except, perhaps, very locally for very brief periods on rare occasions. Hence even the storm flows in these basins, to the extent that they are not accounted for by precipitation directly in the channels, must be fed largely by subsurface movement of water, either throughflow in the soil or deep outflow in the deeper regolith or bedrock.

The sandy, permeable soils of the Obed-Emory basin overlie a well indurated sandstone formation interbedded with thin shale layers. Low permeability of these shales is suggested by the artesian pressure encountered by wells in the Rockcastle formation. Low intergranular permeability of the sandstone is indicated by the low rates of delivery from wells. Of the wells tested in the Obed-Emory basin, one-half yield less than 10 gallons per minute, and only 6% will deliver as much as 25 gallons per minute.<sup>8</sup>

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<sup>7</sup>T.J. Longwell, W.L. Parks, and M.E. Springer, Moisture Characteristics of Tennessee Soils, University of Tennessee Agricultural Experiment Station Bulletin 367, (Knoxville, TN, 1963).

<sup>8</sup>Tennessee Department of Conservation, Division of Water Resources, Summary of Ground Water Data for Tennessee through May, 1972 (Nashville, TN, 1972), p. 86.

Soils in the Nolichucky basin are deeper and somewhat lower in permeability. Beneath them a thick layer regolith, more than 100 feet deep on many lower slopes, overlies the bedrock. Zurawski has noted that this regolith, "stores large amounts of water, releasing it slowly to the underlying fractures and to springs and streams."<sup>9</sup> The underlying bedrock, largely schists and phyllites, is strongly fractured. Although the amount of water stored in the fractures and foliations is not great, they do lead considerable amounts of water from the soil and regolith to greater depth and convey it slowly to points of discharge. The section of the Collins basin lying on the Cumberland Plateau has subsurface conditions generally similar to those in the Emory basin, although soils are slightly deeper.<sup>10</sup> The remainder of the basin, however, lies upon the limestone upland of the Highland Rim. Here weathering yields a "deep chert regolith typically having a 'rubble zone' at the base."<sup>11</sup> This thick accumulation stores significant amounts of water, thus helping to sustain low stream flows and reduce flood peaks. Solution cavities in the bedrock provide additional subsurface storage capacity. Hence both the Nolichucky and the Collins basins offer ample opportunity for infiltrated water to percolate to greater depth and thus to move deviously and slowly toward stream channels.

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<sup>9</sup> Ann Zurawski, Summary Appraisals of the Nation's Groundwater Resources - Tennessee Region, including Tennessee and Adjacent States, U.S. Geological Survey Professional Paper 813 (Washington D.C.: U.S. Government Printing Office, 1978).

<sup>10</sup> U.S. Soil Conservation Service, Soil Survey: Warren County, Tennessee, (Washington D.C.: U.S. Government Printing Office, 1967). p. 5.

<sup>11</sup> Zurawski, op. cit., pg. L-15.

## CHAPTER 5

### CONCLUDING ARGUMENTS

It has been shown in the previous chapters that streamflow in the Obed-Emory basin is anomalous; peak flows are usually high and base flow is minimal.

The usual explanation for high peak flow rates is that overland flow is dominant. In the Obed-Emory Basin, however, the conditions which generally are thought to contribute to overland flow are absent. The predominantly sandy soils of the basin have been shown to have infiltration rates that are markedly higher than rates of storm water supply via precipitation. Given these high infiltration rates, most rainfall should be expected to enter into the soil readily. The majority of the basin is forested, yet it is deforested basins that are usually expected to yield extreme flow rates. Slopes in the basin are gentle to moderate, while steep slopes have been shown to be usually responsible for increasing peak flows. Perhaps the most convincing evidence of a scarcity of overland flow is the low drainage density values in the basin. If overland flow were common, channels would have developed to move it.

Newcombe and Smith stated that "Rain, falling on the outcrop areas, recharges the sandstone beds . . . water, flowing downdip in the fractured sandstones, is confined by overlying shale beds. . . Groundwater is discharged through springs, which are common in the walls of the many deep, narrow stream valleys . . . The springs in the Plateau generally

issue from sandstones near their contact with shale beds . . ."<sup>1</sup>

These statements and the observation of ice accumulation along bedding planes of the caprock in roadcuts led to the thesis that deep outflow through fractures in the rock was delivering large volumes of stormwater to the stream channels, resulting in rapid, concentrated runoff (See Figure 10). Overhung, or undercut, rock faces in the stream bluffs were seen as possible collaborating evidence of deep outflow in that they may have been formed by sapping.

Field investigation during times of high streamflow revealed, however, that these "caves" remain extremely dry even during the larger storms, eliminating sapping as a possible origin. Field investigation also revealed that the contact springs noted by Newcombe and Smith issue such small volumes of water that their contribution to flood flows must be considered as insignificant.

Well drilling records reveal that in the Rockcastle Formation, which makes up the caprock, water is under considerable artesian pressure. Water in wells drilled into the aquifer rises as much as 200 feet when the aquifer is penetrated, with rises of 40 to 80 feet being typical.<sup>2</sup> If open passages did exist through which large volumes of deep outflow could move, such high artesian pressure would not be possible.

The numerous small reservoirs and ponds that have proliferated on the upland surface of the Cumberland Plateau in recent years are at

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<sup>1</sup>Roy Newcombe, Jr., and Ollie Smith, Jr., Groundwater Resources of the Cumberland Plateau in Tennessee, State of Tennessee Department of Conservation, Division of Water Resources (Nashville, TN, 1958), pg. 9-10.

<sup>2</sup>Newcombe, op. cit., pg. 9.



Figure 10. Water seepage along bedding planes in a roadcut on Interstate 40.

the same time evidence of the seasonal scarcity of water from ground-water and streams and of the fallacy of the deep outflow thesis. If the caprock were sufficiently permeable or fractured to allow rapid transmission of storm waters, these small lakes would not be able to fill. It is likely that the thin intermittent layers of shale within the sandstone caprock are responsible for the exclusion of water. Analysis of a thin section of caprock revealed that permeability of the sandstone itself is also quite low.

The applicability of the traditional Horton model of inadequate infiltration rates yielding overland flow has been increasingly questioned by hydrologists in recent years.<sup>3</sup> Beasley, Whipkey, Hewlett and Hibbert, Kirkby and Chorley, Nutter, and Aubertin have argued that subsurface flows contribute greatly to streamflow.<sup>4</sup> Others, including Dunne and

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<sup>3</sup>Robert E. Horton, "Erosional Development of Streams and Their Drainage Basins: Hydrophysical Approach to Quantitative Morphology," Geological Society of America Bulletin, Vol. 56, 1945, pp.

<sup>4</sup>R.S. Beasley, "Contributions of Subsurface Flows from Upper Slopes of Forested Watersheds to Channel Flow," Soil Science Society of America Bulletin, Vol. 40, 1976, pp. 955-957; Ronald Z. Whipkey, "Theory and Mechanics of Subsurface Stormflow," in W.E. Sopper and H.W. Lull, eds., International Symposium on Forest Hydrology (Oxford: Pergamon Press, 1967), pg. 257; John D. Hewlett and Alden R. Hibbert, "Factors Affecting the Response of Small Watersheds to Precipitation in Humid Areas," in Sopper and Lull, op. cit., pg. ; M.J. Kirkby and R.J. Chorley, "Through-flow, Interflow, and Erosion," Bulletin of the International Association of Scientific Hydrology, Vol. 12, pp. 5-21; Wade L. Nutter, "The Role of Soil Water in the Hydrologic Behavior of Upland Soils," in Field Soil Water Regime, Soil Science Society of America Special Publication Series No. 5 (Madison, Wisconsin: SSA, Inc., 1973); Gerald M. Aubertin, "Nature and Extent of Macropores in Forest Soils and their Influence on Subsurface Water Movement," U.S. Department of Agriculture Forest Service Research Paper NE-192 (Washington, D.C.: U.S. Government Printing Office, 1971).

Black, have reported findings that agree with Horton's previous work.<sup>5</sup>

In his article on "The Role of Soil Water in the Hydrologic Behavior of Upland Soils," Nutter noted the persistence of the overland flow concept in spite of a lack of corroborative evidence and made these statements:

Except during the most extreme storms, all the precipitation falling on well-vegetated slopes infiltrates . . . On permeable upland slopes in humid regions, overland flow is rarely observed and subsurface flow in the vicinity of the stream channel accounts for much of the storm runoff (stormflow).<sup>6</sup>

In their 1967 study of runoff in small watersheds, Hewlett and Hibbert challenged the traditional Hortonian approach to runoff production in humid forest lands:

For example, the statements or assumption that all floods are due to surface runoff has persisted in hydrology papers and even in some hydrology textbooks despite much evidence to the contrary in forestry and agriculture research. Virtually all techniques now in general use for estimating flood peaks and volumes are based on the assumption that a quick rise in streamflow proves that rainfall is failing to infiltrate and is running over the surface of the ground to stream channels . . . The term interflow was proposed to refer to subsurface flows which contribute floodwaters in some cases, but there has been no general agreement as to what interflow is or how it works.

Usually a discussion of the runoff from a watershed begins with the assumption that direct runoff is the product of overland flow and that other types of flow are mere exceptions to the general rule. Perhaps the opposite approach is more logical in the case of the forest; that is, to begin with the assumption that all flow is subsurface until there is evidence otherwise.<sup>7</sup>

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<sup>5</sup> Thomas Dunne and Richard D. Black, "Partial Area Contributions to Storm Runoff in a Small New England Watershed," Water Resources Research Vol. 6, 1970, pp. 1296-1311.

<sup>6</sup> Nutter, op. cit., p. 181.

<sup>7</sup> Hewlett and Hibbert, op. cit., p. 275.

Whipkey has noted "the importance of subsurface stormflow from forested slopes of the Allegheny-Cumberland Plateau," which is the physiographic province in which the Obed-Emory basin is located.<sup>8</sup>

The most basic argument that has been leveled against the concept of subsurface flows as a source of peak flows is that water is incapable of traveling at sufficiently high velocities over long distances through the soil fabric to contribute to flood peaks. Two explanations for the mechanics of subsurface stormflow have been presented in the recent literature. The first is that water in the saturated zone of the soil is displaced by water that infiltrates farther upslope. A modified version of this hypothesis suggests that most runoff is generated by subsurface flow from narrow zones adjacent to the stream channels. Under these circumstances, lateral subsurface travel of storm water would not be great, and unrealistically high subsurface velocities would not be required in order to deliver large volumes of water rapidly.

The second hypothesis for explaining rapid rates of subsurface flows is that interconnected macrochannels in the soil formed by plants and burrowing animals do in fact enable water to move rapidly through the soil to stream channels. Aubertin reports that:

Rain, falling on a sloping forested soil, may enter the soil quickly and move considerable distances through the soil by way of macropores . . . The root channels within the forest floor form a network of relatively large, continuous, interconnected, open or partially filled channels that serve as pathways for the rapid movement of free water into and through the forest soil profiles.

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<sup>8</sup>Whipkey, op. cit., p. 275.

<sup>9</sup>Aubertin, op. cit., p. 1.

Beasley found that in a forested basin with sandy soils underlain by an impermeable substratum, subsurface flows contributed the majority of channel flow and that contributions from upper slopes (slopes not adjacent to stream channels) can be significant.<sup>10</sup> Beasley attributed this subsurface flow to movement of water through biologically-derived macrochannels. The soils of the Obed-Emory basin are predominantly sandy, the great majority of the basin is forested, and the bedrock is largely impervious, so one would expect Beasley's findings to be highly applicable to the Obed-Emory basin.

Subsurface movement of water through the soil does then seem to provide the best explanation for runoff mechanism in the Obed-Emory basin. It does not necessarily explain the extremely peaked flow in the basin, however.

If the streams are being fed primarily by subsurface flow even in times of storm floods, factors such as lateral permeability, depth of water penetration, and detention of water in underground storage become critical. One would expect, with Beasley, that rapid delivery would be favored by permeable soils overlying an impermeable substratum and that ready access to groundwater storage would effectively reduce flood peaks. The three East Tennessee basins may be examined with these considerations in mind.

In the Nolichucky basin, the somewhat deeper soils and the thick regolith accumulation on the lower slopes provide storage of water that is not available in the Obed-Emory basin. The fractured and

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<sup>10</sup>Beasley, op. cit., p. 955.

foliated bedrock also stores and slowly transmits excess water over extended periods of time. The "deep chert regolith" of the Highland Rim portion of the Collins basin provides a large amount of detention storage of water.<sup>11</sup> The limestone bedrock, being interspersed with interconnected solution openings, provides additional storage and favors delayed delivery of water to the stream channels.

Unlike the Nolichucky and Collins basins, the Obed-Emory provides little opportunity for deep infiltration and little capacity for deep storage. The thin, sandy soils of the basin overlies a well indurated sandstone interbedded with thin shale layers. The dense, well cemented sandstone and the shale layers act jointly to exclude or make difficult the downward movement of water, while the highly permeable soils facilitate lateral transmission near the surface. The result of this proclivity towards shallow subsurface flow is that most of the excess water from an individual storm event is forced to move laterally through the soil until a stream channel is encountered. Once the water enters a channel, runoff proceeds rapidly; water that has reached a stream channel at the most remote part of the basin could reach the mouth of the basin in only 24 hours at an average velocity of three miles per hour. Because very little water enters the bedrock, and because the bedrock has small storage capacity, there is little sustenance of base flow from deep outflow. Because the water is forced to move rapidly into stream channels, it is concentrated in the channels over a short period

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<sup>11</sup>Zurawski, op. cit.

of time. Thus, the flood peaks are high, the dropoff in flow is relatively rapid, and base flows are small.

The conclusions reached in this paper suggest several possibilities for future study. One is to expand the study area to include all of the tabular section of the Cumberland Plateau of Tennessee and Alabama, to determine if the other streams of this region behave similarly to the Obed-Emory system. A minor problem with this approach is that there are no other gaged streams of even one-half the basin area of the Obed-Emory. Some of the larger streams to the south of the Obed-Emory system are White's Creek, the Piney River, Chickamauga Creek, Caney Fork, Moccasin Creek, Calfkiller Creek, the upper Collins River, and the Little River of Alabama. To the north, in the somewhat more dissected terrain, lie the Obey River, Clear Creek, the New River, and the Big South Fork of the Cumberland River. The small amount of research that I have done on the runoff of these streams indicates that their hydrology is similar to that of the Obed-Emory in several important aspects.

It might also be desirable to look at runoff processes within the Obed-Emory basin at a much larger scale. Some of the techniques developed by hydrologists and soil scientists to determine the relative contributions of surface and subsurface flows could be used to gain a better understanding of hydrologic processes in the basin. Research currently under way at the University of Tennessee's Grassland Research Station near Crab Orchard may help to fill this need.

It is well known that water availability on the Plateau is poor or seasonally inadequate for even domestic needs in many cases. The

findings of this paper help to explain why this is so, but do not offer help toward a solution. Future research into possible sources of water supply on the Plateau should be able to make use of these findings, however.

The apparent paradox of low drainage densities and high flood peaks in the basin suggests that more research is needed regarding the relationship between drainage density and streamflow, not only in this study area, but in others as well.

Since running water is the primary sculptor of the landscape in the Southeast, any unusual runoff regime or process should be expected to result in different landscape forms or processes. One of the most intriguing aspects of the geomorphology of the Plateau is the question of the origin and persistence of the gently sloping uplands in an area with nearly 2,000 feet of local relief. The findings of this paper should be pertinent to this question. One possible answer is that the general lack of dissection is due more to a lack of overland flow than to the durability of the sandstone caprock.

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