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LOW-FLOW AND SEDIMENT CHARACTERIZATION STUDY OF MONOCACY CREEK

by

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December, 1995

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Page

ABSTRACT

The purpose of this thesis is to update a low-flow characterization study of Monocacy Creek performed by the Pennsylvania Department of Environmental Resources (DER) in 1977 that used flow records prior to 1972. Forty five years of average daily flow values for Monocacy Creek were obtained from the United States Geological Survey (USGS) gauging station off Illick's Mill Rd. in Bethlehem and used in this thesis to generate updated duration and frequency curves. The duration and frequency curves generated using the more recent data show higher flowrates versus percent exceedence and recurrence intervals, respectively.

Duration and frequency curves for Jordan Creek, Little Lehigh Creek and Aquashicola Creek, using data prior to 1972, are compared to the duration and frequency curves of Monocacy Creek to compare low-flow characteristics among watersheds of various geology. The Little Lehigh Creek sustains higher low-flow characteristics than the other creeks while the Jordan Creek sustains the lowest. The Monocacy Creek and the Aquashicola Creek have similar low-flow characteristics.

A base-flow recession analysis is also included in this low-flow characterization of Monocacy Creek. A characteristic base-flow recession constant of 0.985 describes how groundwater storage is depleted in the Monocacy Creek.

The sediment characterization study of the Monocacy Creek is limited to analyzing the stability of the deposited sediment and the geomorphology of the stream bed within the Archibald Johnston Conservation Area (Johnston Reach). Three core

samples were taken at a cross section of the Johnston Reach and a bulk density profile was determined for each sample using a Multi Sensor Core Logger (MSCL). Bulk density for the deepest sediment core sample increased significantly at approximately ten inches. This data implies that sediment in the Johnston Reach, to a depth of ten inches, is relatively unconsolidated and thus less stable than the deeper, more compacted sediment.

Chapter One: INTRODUCTION

1.1 General Watershed Characteristics

1.1.1 Land Use

Monocacy Creek, a tributary to the Lehigh River in eastern Pennsylvania, is located in seven Northampton County Municipalities and one Lehigh County Municipality as shown in Figure 1.1. The watershed has a drainage area of 49.3 square miles comprised of various land uses. The upper portion of the watershed (Lower Nazareth, Upper Nazareth, East Allen, Moore and Bushkill Townships) is mostly suburban and rural while the lower portion (Bethlehem Township and the City of Bethlehem, near its confluence with the Lehigh River) is mostly urban. The Monocacy flows through wooded areas in its headwaters, large open farmland through the middle of the watershed, and mostly urban land in the southern portion of the watershed. The land use of the watershed is approximately 50% urban/suburban and 50% rural/agricultural as determined by the Joint Planning Commission of Lehigh and Northampton Counties (1988).

1.1.2 Geology & Soils

Soil and geologic features of a watershed are important characteristics because they govern the recharge and discharge rates in the basin. The Martinsburg shale formation lies underneath the headwaters of the watershed. The upper Martinsburg section is composed of banded clay slate or shale with traces of sandstone. The middle

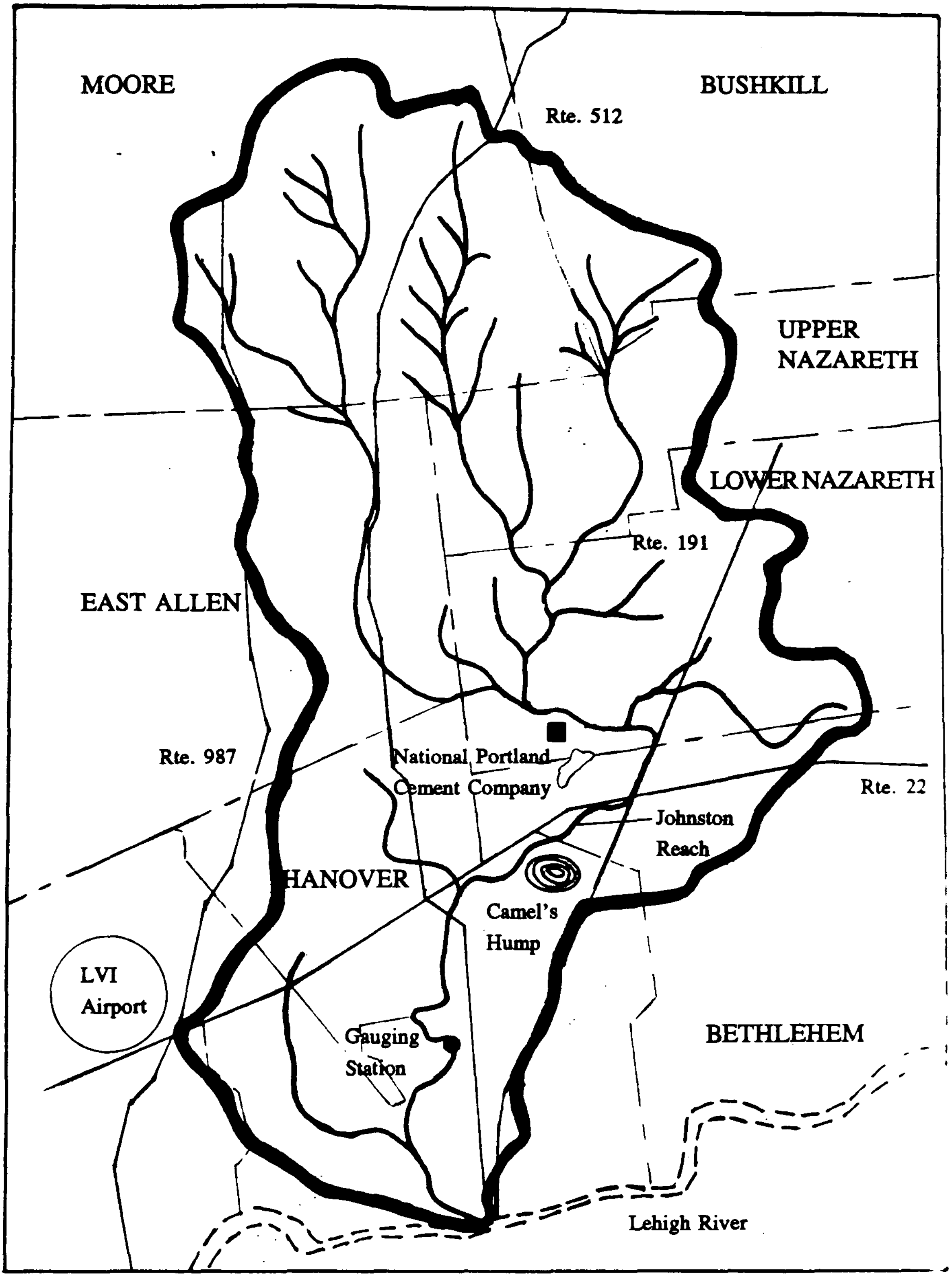


Figure 1.1 Monocacy Creek Watershed

section is mostly sandstone beds with some slate. The lower Martinsburg area is largely a shale region containing banded clay slate similar to the upper portion with more sand and thinner beds. The topography of the slate region is characterized by low, flat-topped hills divided by steep-sided valleys.

South of the Martinsburg formation the geology is predominantly limestone. Jacksonburg, Beekmantown, and Allentown limestone comprise about ninety percent of the geology in the lower two thirds of the watershed. The limestone area is flat with gently sloping valleys. Well-defined, underground channels have formed from solution of the limestone along joints. Sinkholes and closed depressions are a common occurrence throughout the limestone region. A detailed study was done by Kochanov (1987) to accurately define areas of carbonate bedrock that are susceptible to sinkhole development and identify areas that have had a history of sinkhole occurrence.

The soils of the watershed are formed from weathered shale and limestone. Staley (1974) divided the soils of Northampton County into associations. The soils from each association found in the Monocacy Creek watershed are further divided into specific soil series and characterized in Table 1.1. Most of the soils in the northern part of the watershed are part of the Berks-Bedington-Comly association with traces of Brinkerton, Weikart and Holly soils as well. These soils are gently sloping to steep, moderately deep and deep, well-drained to somewhat poorly drained and are underlain by acid, gray shale. Soils from the Holly series are found along the stream and in the flood plain in small patches along the entire span of the creek. The soils of the Duffield-Clarksburg-Ryder association are mainly found in the middle of the watershed from the north side of

ASSOCIATION	SERIES	GENERAL DESCRIPTION
Berks-Bedington-Comly		
	Berks	Nearly level to very steep; moderately deep; well-drained; moderately rapid permeability; moderate to low moisture capacity.
	Bedington	Nearly level to sloping and undulating to rolling; deep; well-drained; moderately slow permeability; moderate to high moisture capacity.
	Comly	Nearly level to gently sloping; Deep; moderately well drained & somewhat poorly drained; moderate moisture capacity; moderately slow permeability.
	Brinkerton	Nearly level to sloping; deep; poorly-drained; slow permeability; low moisture capacity.
	Weikart	Gently sloping to very steep; shallow; well-drained; low moisture capacity; moderately rapid permeability.
	Holly	Nearly level; deep; poorly to very poorly drained; high moisture capacity; moderate permeability.
Duffield-Clarksburg-Ryder		
	Duffield	Nearly level to gently sloping; deep; well-drained; high moisture capacity; moderate permeability.
	Clarksburg	Nearly level to gently sloping; deep; moderately well-drained; high moisture capacity; slow permeability.
	Ryder	Gently sloping to sloping; moderately deep; well-drained; moderate moisture capacity; moderate permeability.
Washington-Urban		
	Washington	Nearly level to very steep; deep; well-drained; high moisture capacity; moderate permeability.
	Urban	Bethlehem urban land used for homes, shopping centers, schools, factories, roads, cemeteries, golf courses, railroads, and other residential & industrial facilities.
Conestoga-Hollinger		
	Conestoga	Nearly level to very steep; deep; well-drained; high moisture capacity; moderate permeability.
	Hollinger	Nearly level to very steep; deep; well-drained; moderate moisture capacity; moderate permeability.

Table 1.1 Description of Soils in the Monocacy Creek Watershed

Camel's Hump to just south of Bath. These soils are nearly level to sloping, deep and moderately deep, well-drained and moderately well drained, silty soils underlain by shaly limestone. The lower portion of the watershed is comprised of soils from the Washington-Urban association with a trace of soils from the Conestoga-Hollinger association in the vicinity of Camel's Hump. These soils are nearly level to sloping, deep, well-drained soils and land types underlain by thin glacial till over cavernous limestone.

1.1.3 Climate

In any hydrologic study, climate and weather are described to determine the likelihood of occurrence and nature of certain precipitation events. Daily weather reports from the National Weather Service (NWS) Office at the Lehigh Valley International Airport in Allentown, Pennsylvania are used to describe the temperate climate of the Monocacy Creek watershed. The airport is located less than one half mile outside of the southwest watershed boundary and is shown in Figure 1.1 as the Lehigh Valley International (LVI) Airport. Due to the close proximity of the airport to the watershed, climatological data obtained here is assumed to be representative of the entire drainage basin.

Air (and ground) temperatures may permit the storage of precipitation as snow and influences the evapotranspiration rate. Daily maximum and minimum values of air temperature have been recorded from 1951-1980 and are plotted as a monthly average taken over the 30 years of record as shown in Figure 1.2. Monthly normal temperatures

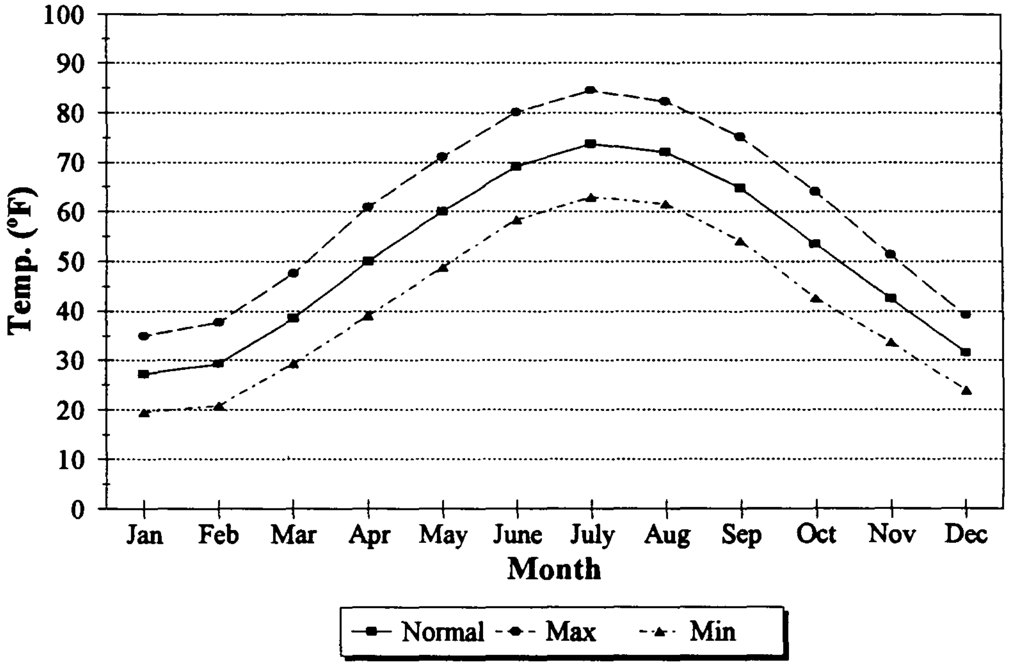


Figure 1.2 Climate: Mean Temperature

are also shown in Figure 1.2. Normal monthly temperature is calculated as an average of the daily maximum and minimum values for the entire period of record. Normal temperatures vary from approximately 30 degrees Faranheit (°F) during the winter months to roughly 70 °F in the summer months and change linearly in both the fall and spring. The Monocacy Creek watershed experiences an annual average temperature of 51 °F. Figure 1.3 shows the extreme maximum and minimum temperatures for each month over the past 50 years. The highest temperature recorded for the region is 105 °F which occurred in July of 1966. The lowest temperature for the 50 year period is -12 °F recorded in January of 1961.

Precipitation, another important parameter in assessing climate, includes both rain and snow and is measured as a water equivalent in inches. Frost, dew, and fog have a negligible effect on precipitation in humid climates and are, therefore, not included. The Monocacy Creek watershed experienced an average annual precipitation of 44.31 inches during the twenty nine years of record from 1951 to 1980. 44.31 inches is the sum of the mean monthly values averaged over the period of record. Mean monthly precipitation is plotted along with the monthly maximum and minimum values in Figure 1.4. Monthly maximum values vary considerably while monthly minimums are reasonably stable. Normal monthly precipitation is constant as well. Normal monthly precipitation does not significantly deviate from 4 water equivalent inches in any given month. The most precipitation for one month of record was 12.10 inches, occurring in August of 1955. The least amount of monthly precipitation on record was 0.09 inches recorded in May of 1964.

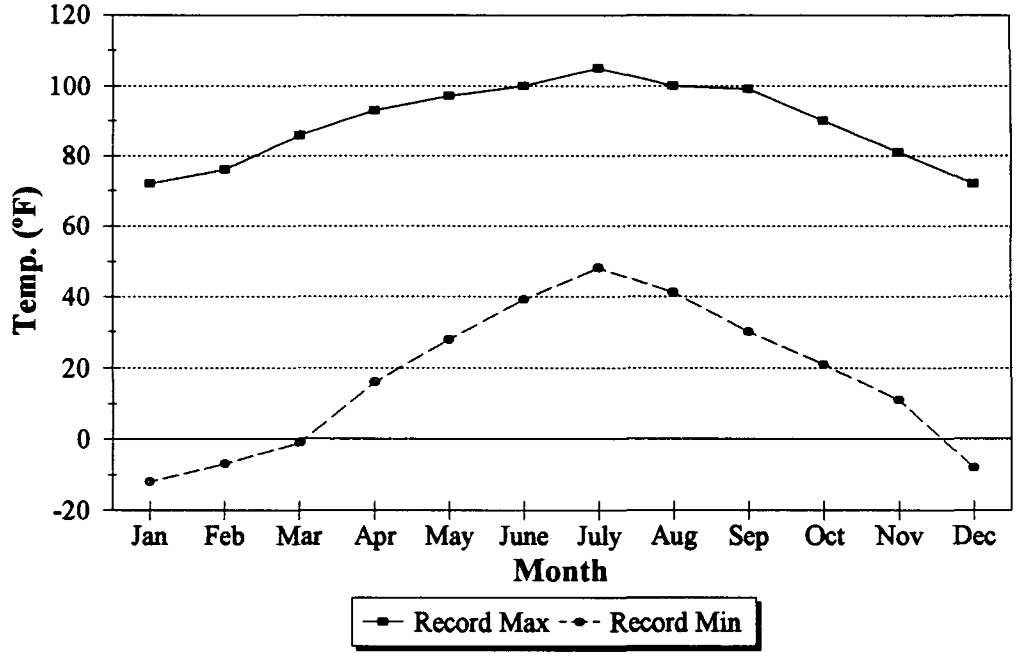


Figure 1.3 Climate: Extreme Temperature

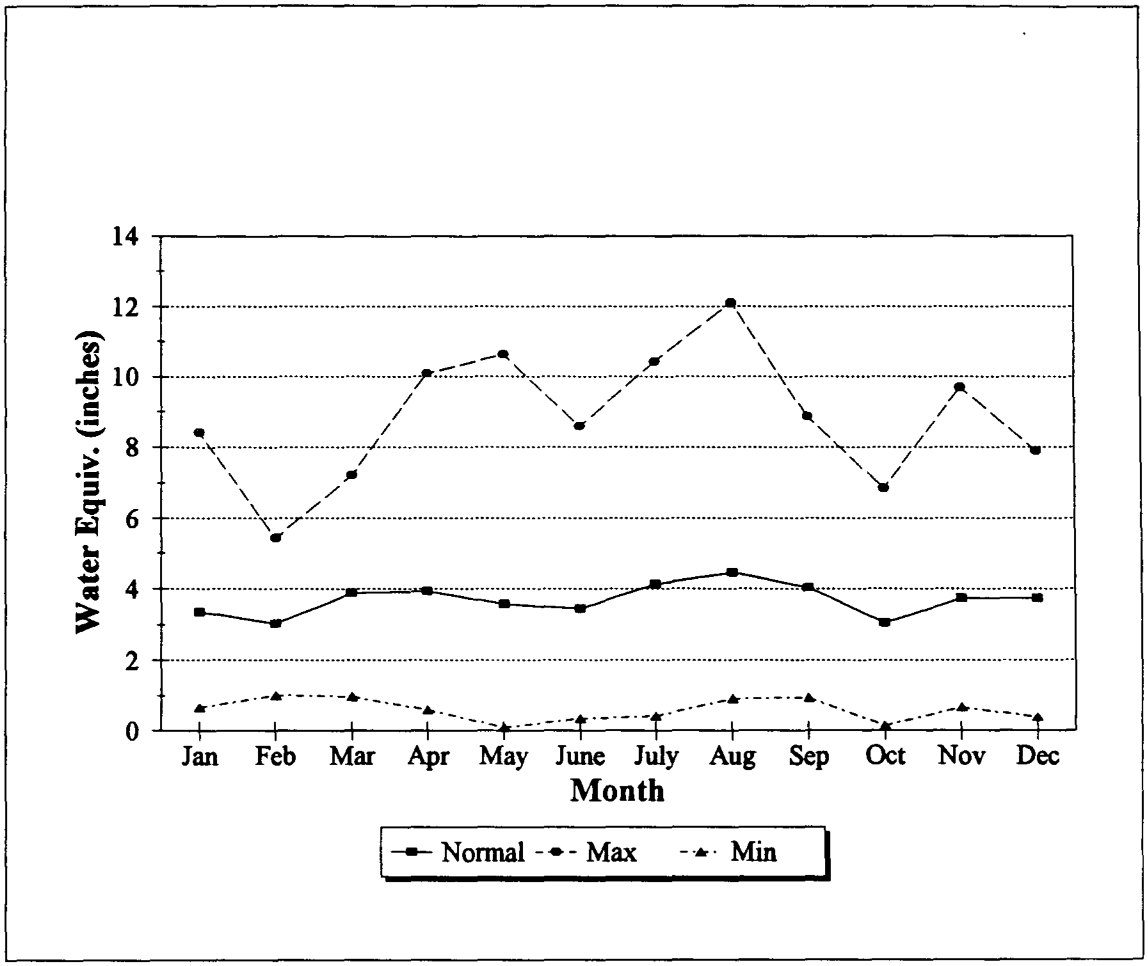


Figure 1.4 Climate: Precipitation

Wind and relative humidity characteristics help to provide a comprehensive description of climate. Mean monthly wind speed is plotted in Figure 1.5. Mean annual wind speed in the Lehigh Valley is 9.1 mph. The maximum monthly mean wind speed occurs in March and is about 11.5 mph while the minimum monthly mean is close to 7 mph in August. Winds come out of the west during most days of the year.

Mean monthly values of relative humidity for the period of record are plotted in Figure 1.6 for four different times during the day. Relative humidity is greatest, generally, at 7:00 a.m. and is lowest at 1:00 p.m. Mean monthly relative humidity reaches maximum values for given times of the day in late summer and early fall while the minimum values occur in the spring.

1.2 General History

Native Americans were the first inhabitants of the Monocacy Creek region and its surroundings and they did little to change the topography. The earliest recorded Native Americans were the Lenni-Lenape or simply the Lenape Indians of the Delaware Tribe. These Native Americans gave names to the geological features of the region that were later corrupted by early Quaker settlers. Monocacy Creek was originally called the Managassi, Menagassi, or Manakessi by the Lenape Indians which means "a stream with several large bends." This name remains an accurate description of the creek. Thirty six other spellings of Monocacy have been located on various old maps and old records and those spellings are listed in Miller et al. (1939). Menagachsink was the name given by the Delawares to the site of Bethlehem at the confluence of Monocacy Creek with the

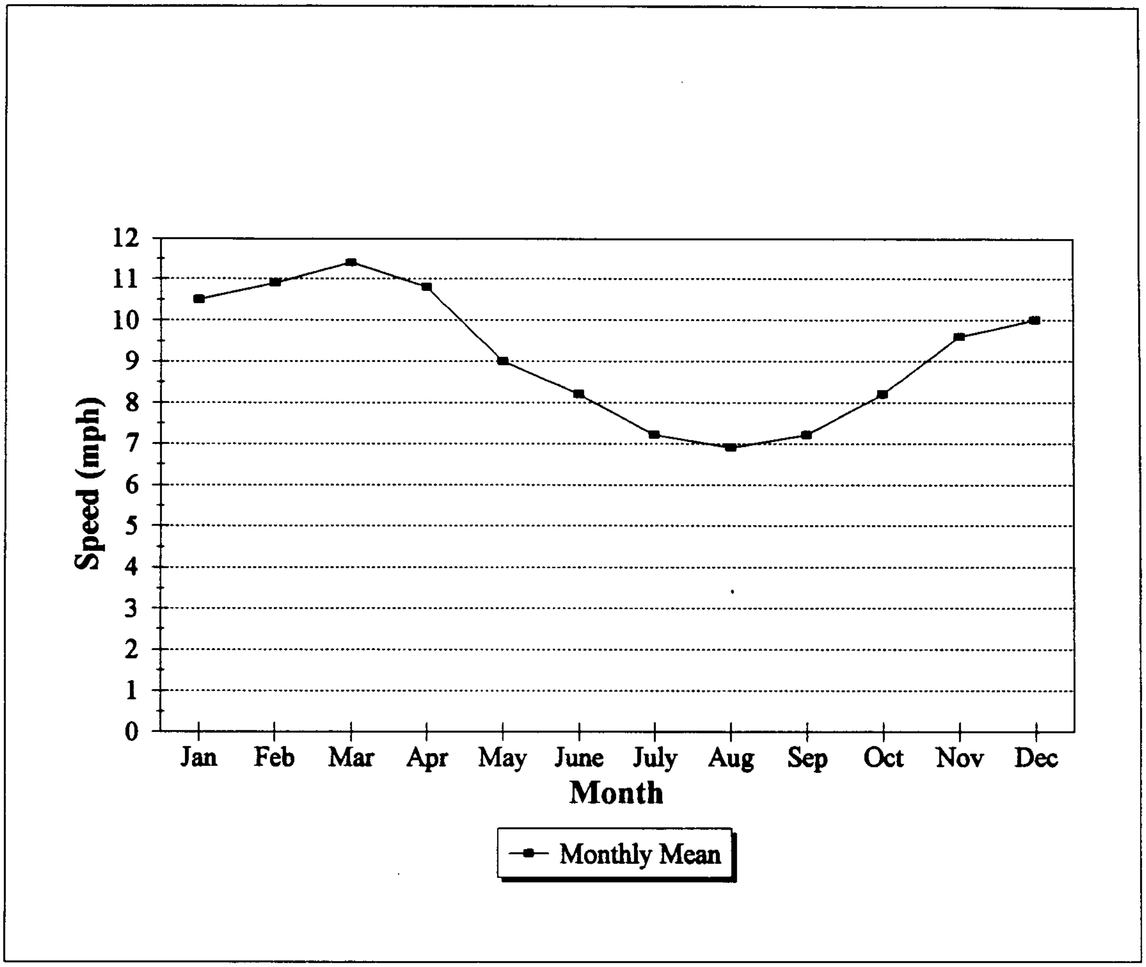


Figure 1.5 Climate: Wind Speed

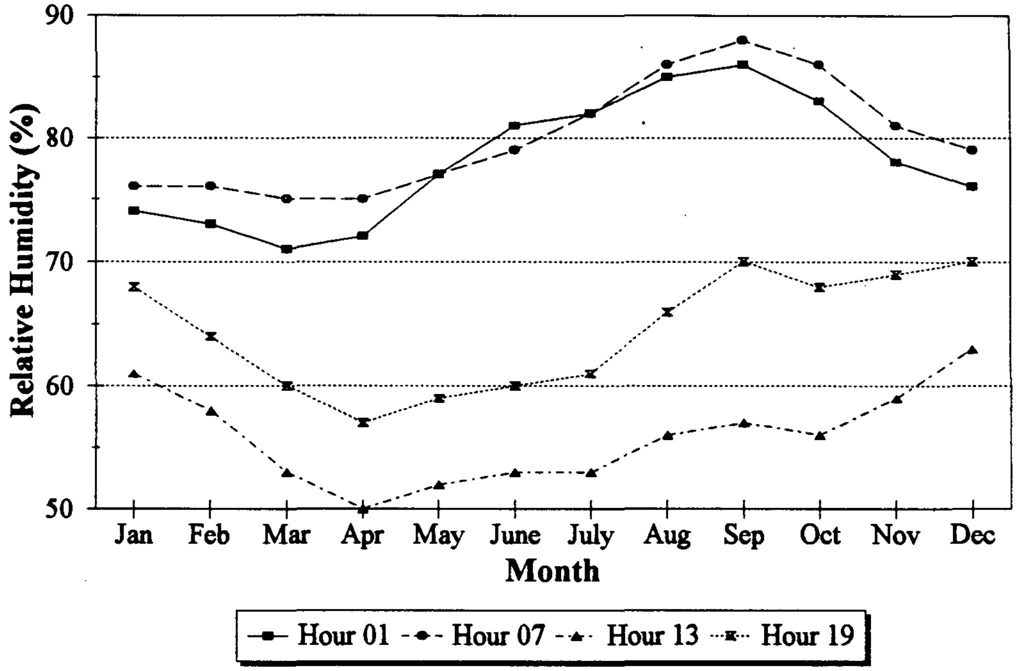


Figure 1.6 Climate: Relative Humidity

Lehigh River.

During the European settlement of the Lehigh Valley, Monocacy Creek was a source of municipal water supply and industrial power. Prior to 1973, the National Portland Cement Company, see Figure 1.1, discharged 10,000 gpm of water from its quarry near Bath to Monocacy Creek. This discharge sustained surface flow between the quarry and the Archibald Johnston Conservation Area (Johnston Reach) for many years prior to 1973. However, the large cone of depression which resulted from this pumping had adverse effects on the creek. Springs in the Johnston Reach were observed to have dried up during the pumping period according to Horner et al. (1981). When the pumping ended in 1973, springs in the lower reaches of the Monocacy were revitalized and, according to Horner et al. (1981), the creek between the quarry and the Johnston Reach was observed dry during extended periods of low flow.

Most of the eastern United States experienced a prolonged drought period during the mid 1960's. The average daily flow of the Monocacy Creek on January 1, 1966 was 5.2 cfs, the lowest recorded flowrate at the USGS gauging station. From the spring of 1965 to the beginning of 1966 average daily flowrates in the Monocacy never rose above 20 cfs compared to an average daily flowrate of 53 cfs for the entire period of record. Average annual precipitation for 1965 was equal to 30.55 water equivalent inches, the second lowest annual average rainfall for the entire period of record. The lowest average annual rainfall in water equivalent inches occurred in 1980 and had a value of 29.82. An average annual flowrate of 45.3 cfs was sustained in Monocacy Creek during 1980 with a minimum daily flowrate of 17 cfs. During 1965, however, the lowest average daily flowrate was 5.5 cfs and the annual average was only 17 cfs. This drought period has a significant impact on the duration and frequency curves generated in Chapter 2.

In recent history, the Monocacy has become a valuable aesthetic and recreational resource. Meandering through urbanized Bethlehem, the banks of the Monocacy are lined with parks, conservation land, and lush vegetation. The Monocacy supports a large population of natural brown trout. Monocacy Creek is a Trophy Trout, limestone creek designated by the DER as a HQ-CWF (High Quality - Cold Water Fishery). A "high quality" description, according to the DER, is considered to be a stream or watershed with excellent quality water and environmental features that require special protection.

1.3 Purpose and Scope

Page and Shaw (1977) generated flow duration curves and frequency analyses for several eastern Pennsylvania creeks, including Monocacy Creek, using data prior to 1972. The purpose of this flow characterization study is to update Page and Shaw (1977) by analyzing forty five years of average daily flowrates for Monocacy Creek and present the results of those analyses in a useable form. Flow duration curves and frequency analyses are generated and a comparison is made between two time periods within the flow record. Only using data prior to 1972, a comparison among low-flow characteristics of the Monocacy Creek and other eastern Pennsylvania creeks is also made. A base-flow recession analysis provides yet another description of the low-flow characteristics of Monocacy Creek.

The purpose of a sediment characterization study within the Johnston Reach is to analyze the stream bed stability and geomorphology. A determination of the stability of the sediment in the Johnston Reach provides information as to the possibility of increased sedimentation throughout the lower reaches of the Monocacy Creek. An assessment of the sediment characteristics within the Johnston Reach also provides information which may be useful in an attempt to excavate the sediment that has deposited in this reach.

Chapter Two: LOW-FLOW CHARACTERISTICS

2.1 Flow Records

Flow records were obtained for the USGS gauging station #00145500 in Monocacy Park just downstream from Illick's Mill Road in Bethlehem. The records consist of average daily flow values for 45 years from 1949 to 1993. Monocacy Creek had an average daily flowrate of 52.9 cfs for the 45 years of record with an average daily maximum of 1,160 cfs occurring on January 25, 1979 and an average daily minimum of 5.2 cfs occurring on January 1, 1966. The instantaneous maximum flowrate on record occurred January 25, 1979 and had a magnitude of 3,490 cfs while, on the other hand, sections of the creek have stopped flowing during extended low-flow periods. On October 3, 1995 this writer observed a section of the creek extending from the north end of the Johnston Reach to approximately 500 yards east of the old National Portland Cement Company to be dry.

2.2 Flow Duration Analysis

2.2.1 Introduction

A flow duration curve is a cumulative frequency curve that shows the percentage of time during which specified discharges are equalled or exceeded during the period of record. The flow duration curve is one of the simplest analytical tools used in investigating low-flow stream characteristics. The low-flow portion of the curve can be used as an index of the amount of groundwater being contributed to streamflow from natural catchment storage (McMahon, 1976). Flow duration curves can also be used in stream pollution studies, in stream quality-of-water studies and in investigations of the continuous power of a stream (Searcy, 1959).

A report prepared by an ASCE Task Committee (1980) surveyed a sample of organizations, agencies, and institutions to assess low-flow activities from various perspectives. According to the report, water supply problems are not the only concern which stimulate low-flow analyses. The paper states that low-flow situations generate concern over water quality degradation, the increase of water temperatures during summer months, the decrease in reaeration capability, and the increase in time-of-travel of a conservative pollutant. The results of the analyses performed in this low-flow characterization study may be used at a later date to address those issues as they relate to Monocacy Creek but are not considered in this study.

2.2.2 Theory and Methodology

Flowrate events used in a duration analysis are assumed to be non-random and non-homogenous. Time homogeneity requires that identical events in a series are equally likely to occur at all times (McMahon, 1976).

In this report flow duration curves are generated using the following method:

1. Arbitrarily identify a range of discharge values which appropriately represents the spectrum of flowrates on record. Discharge values of 5, 10, 15, 20, 30, 50, 75, 100, 150, and 200 cfs were chosen for this study.

2. Calculate the number of times each selected discharge value is equalled or exceeded within the period of record.

3. Calculate a percentage of exceedence for each discharge based on the total number of values in the period of record.

4. Plot the results as a flowrate versus percent of the time exceeded.

2.2.3 Results

A flow duration curve was generated for the Monocacy Creek using flow records from 1949 to 1993 as shown in Figure 2.1. Separate duration curves for the period from 1949 to 1972 and then 1973 to 1993 were generated to compare the differences between the duration curve generated in Page and Shaw (1977), which used data prior to 1972, and the duration curve generated using the more recent data. These curves are also shown in Figure 2.1. The duration curves for the two time periods are significantly different. The difference can be attributed to the drought of the 1960's generating an overall lower duration curve for the earlier record. During most of 1965 and the beginning of 1966 the average daily flowrate was less than or equal to 17 cfs. The lowest average daily flowrates from 1973 to 1993 were between 15 and 20 cfs but never lasted more than one month. Because the flow data from 1973 to 1993 does not contain a low-flow period of comparable magnitude to the 1960's drought, the Monocacy was

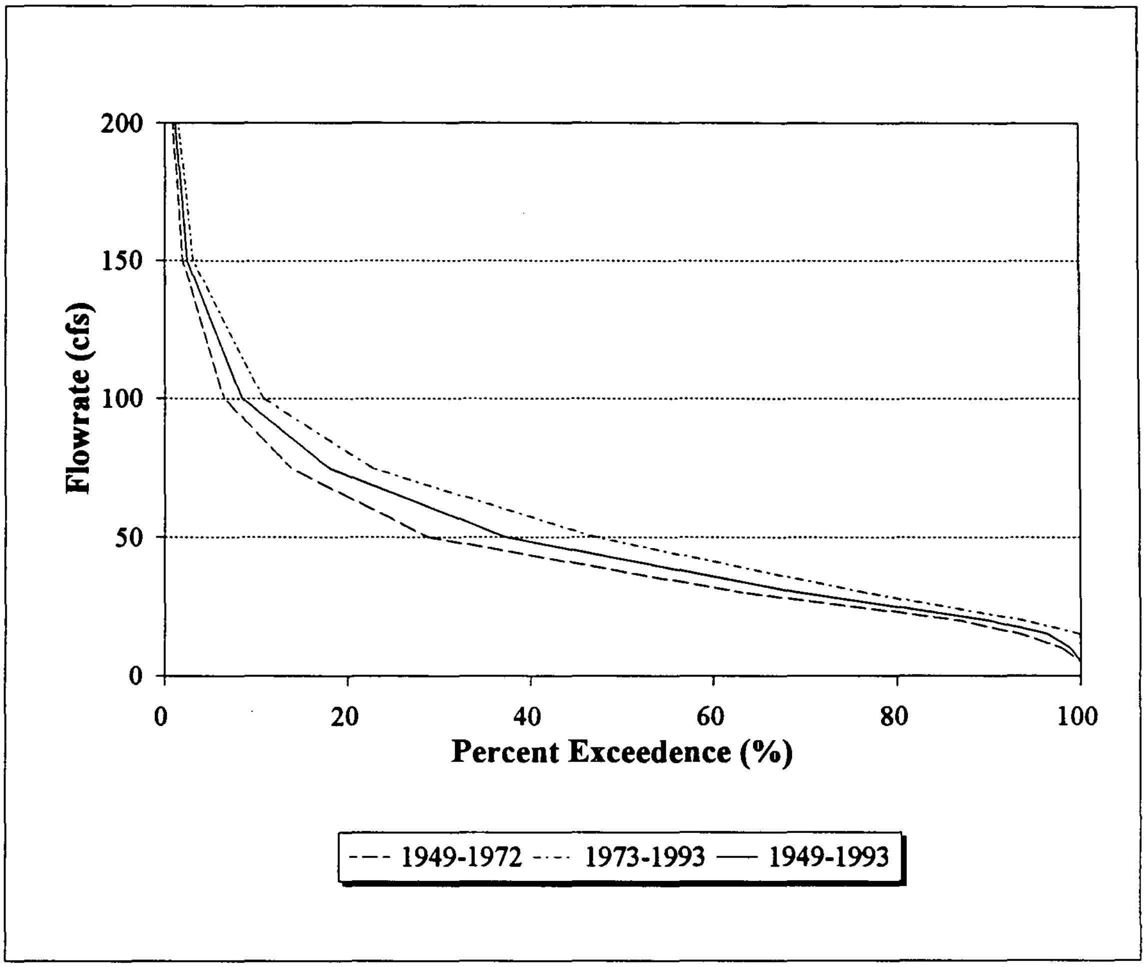


Figure 2.1 Duration Curves: Monocacy Creek

able to sustain a higher flowrate from 1973 to 1993 as shown in Figure 2.1. According to the records obtained from the National Weather Service Office at the Lehigh Valley International Airport, average annual rainfall increased from 43.4 inches between 1949 and 1972 to only 44.9 inches between 1973 and 1993. This increase is insignificant relative to the large shift in the duration curve.

2.2.4 Comparison with Other Watersheds

The duration curves generated in Page and Shaw (1977) for several eastern Pennsylvania creeks are compared in this study to the duration curve of Monocacy Creek as shown in Figure 2.2. Duration curves for Jordan Creek, Little Lehigh Creek and Aquashicola Creek are compared to the duration curve of Monocacy Creek to observe similarities or differences in flow characteristics among watersheds of various geology. These particular creeks were chosen based on the availability of flow records, proximity to the Monocacy Creek and their geological compositions. The values of flowrate for each stream were normalized by dividing flowrates by the respective drainage areas to account for basin size. Table 2.1 provides a brief description of each watershed including the period of record used by Page and Shaw (1977) to generate the duration curves.

Flowrates equalled or exceeded 90% of the time are considered by Cross (1949) to be a measure of groundwater contribution to streamflow and Searcy (1959) used the same value as a measure of run-of-the-river power stations. This low flowrate can be used as a basis for comparing one low-flow characteristic among the specified eastern

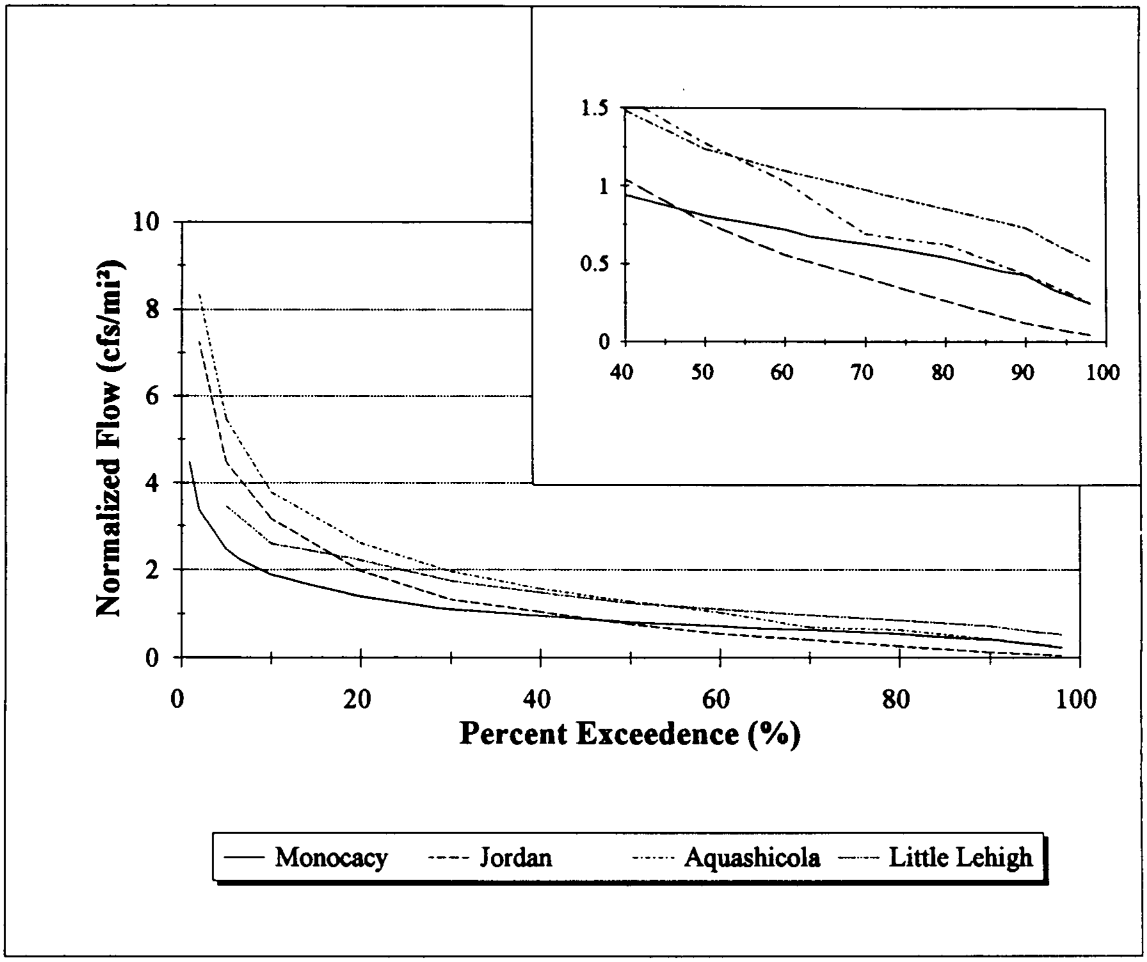


Figure 2.2 Duration Curves: Comparing Eastern Pennsylvania Creeks

Pennsylvania creeks. Normalized flows equalled or exceeded 90% of the time are greatest for Little Lehigh Creek and least for Jordan Creek. The Monocacy and the Aquashicola have very similar normalized 90% exceedence values of discharge despite the contrast in geological characteristics. Table 2.2 shows a comparison of 90% exceedence values among the chosen eastern Pennsylvania creeks.

WATERSHED	AREA ABOVE GAGE (mi^2)	GEOLOGY	PERIOD OF RECORD
Monocacy	44.5	Upper portion is shale and slate Lower portion is limestone	1949 - 1972
Jordan	75.8	Mostly sandstone and siltstone Partly slate Some limestone and dolomite	1945 - 1972
Little Lehigh	80.8	Almost completely limestone	1947 - 1972
Aquashicola	76.7	Almost completely underlain by the Blue Mountain slate belt	1940 - 1972

Table 2.1 Description of Compared Streams

Creek	Normalized 90% Exceedence Flowrates (cfs/mi^2)	Actual 90% Exceedence Flowrates (cfs)
Monocacy	0.44	20
Jordan	0.10	8
Little Lehigh	0.75	61
Aquashicola	0.45	35

Table 2.2 Comparison of 90% Exceedence Flowrates

2.3 Low-Flow Frequency Analysis

2.3.1 Introduction

An annual or seasonal low-flow can be defined as either the instantaneous minimum discharge or the minimum mean discharge averaged over a selected period of time. Low-flow frequency curves are generated to show the magnitude and frequency of annual minimum flow events for specified time intervals. Time intervals of 7, 14, 30, and 60 days are typical values used to generate frequency curves. As well as estimating the recurrence intervals of low flows for a specified time interval, frequency curves are used in storage-yield analyses and stream quality studies. McMahon (1976) describes the detailed procedure and the limitations of a storage-yield analysis. Some governmental agencies base their water quality standards on the Q-7,10 flowrate, the average flow that occurs over a consecutive seven day period with a recurrence interval of ten years.

2.3.2 Theory and Methodology

Two methods were used to generate low-flow frequency information: Weibull plotting positions and an Extreme Value Type III probability distribution.

Weibull Plotting Positions

The procedure for generating low-flow frequency information using the Weibull plotting position formula as presented by Riggs (1972) is as follows:

1. Calculate the lowest mean discharge for 7, 14, 30, and 60 consecutive days for each year of the record.

2. Array the values in order of magnitude and assign a rank to each number with the smallest value having a rank of 1.

3. Compute the recurrence interval, T, of each value by the formula:

   $$T = \frac{(n+1)}{m} \tag{1}$$

   where n is the number of years in the record and m is the rank assigned to each value.

4. Plot each consecutive day low-flow value versus recurrence interval.

Extreme Value Type III Distribution

Gumbel applied the Extreme Value Type III (EVTIII) probability distribution in Gumbel (1954) to low-flow frequency analysis and the EVTIII is therefore referred to by some hydrologists as the Gumbel distribution. Others refer to the EVTIII as the Weibull Distribution since Weibull first applied it to the description of the strength of brittle materials according to Chow (1964). The Extreme Value Type III probability distribution will be referred to in this thesis as the EVTIII.

Several probability distributions have been used to identify the magnitude and frequency of low flows and include the following: EVTIII, the log normal, the three-parameter log normal, Pearson Type III, and Pearson Type IV. The Pearson Type III and the EVTIII probability distributions were found to be about equal in their ability to match the Weibull plotting positions according to Matalas (1963). O'Conner (1964) made a graphical comparison between the Logarithmic Normal, Pearson Type III and EVTIII distributions. He concluded that neither method was more appropriate and that all methods yielded equivalent results in the majority of cases. Only the EVTIII distribution is used in this study along with the Weibull plotting position method. The EVTIII distribution is used to generate frequency curves according to the following procedure as presented by Gumbel (1954):

1. Calculate the lowest mean discharge for 7, 14, 30, and 60 consecutive days for each year of the record.

2. Compute the logarithms (logs) of each low-flow value and then determine the mean of the logs, $\overline{\log x}$, and standard deviation of the logs, $s(\log x)$.

3. A characteristic value of the low flows, u, is obtained from the following equation:

$$\log u = \overline{\log x} + \frac{\overline{y}_N}{\alpha'} \tag{2}$$

where $\overline{y_N}$ is the reduced mean depending only on the sample size, *N*, and is given in Table II of Gumbel (1954). The parameter *1/α′* is calculated using the following equation:

$$\frac{1}{\alpha'} = \frac{s(\log x)}{\sigma_N} \tag{3}$$

where σ_N is the reduced standard deviation which depends only on the sample size, *N*, and is given in Table II of Gumbel (1954).

4. Assuming a lower limit of zero, the non-exceedence probability, *P(x)* is:

$$P(x) = \exp[-(\frac{x}{u})^{\alpha}] \tag{4}$$

where *x* is equal to the low-flow values in cubic feet per second (cfs), and α is a parameter which is a function of *s(log x)* and σ_N. α and α′ are related by the following equation:

$$\alpha' = 2.30259\ \alpha \tag{5}$$

5. The relationship of probability, *P(x)*, to return period, *T(x)* is as follows:

$$T(x) = \frac{1}{[1 - P(x)]} \tag{6}$$

6. Plot each consecutive day low-flow value versus recurrence interval.

A tabulation of the low-flow data used to generate the frequency analyses is shown in Table 2.3.

2.3.3 Results

The low-flow frequency curves presented in Figures 2.3 through 2.6 show the magnitude and frequency of annual minimum flow events for periods of 7, 14, 30, and 60 consecutive days calculated using Weibull plotting positions. The Weibull plotting positions were constructed for the same two time periods (1949-1972 and 1973-1993) as the duration curves. The plotting positions are very similar for recurrence intervals less than four years but start to spread apart for the higher return periods. This significant spread in the data from the earlier record, due to the drought of the 1960's, is again apparent.

The EVTIII results are plotted along with the Weibull plotting positions for the entire length of record in Figures 2.7 through 2.10. The analytical EVTIII distribution and the Weibull plotting positions match closely in all cases. The similarity between the solutions provides confidence in the use of either technique to describe the frequency of low-flow events.

	Consecutive Day Mean Low Flows (cfs)			
YEAR	**Q-7**	**Q-14**	**Q-30**	**Q-60**
1949	18.57	18.93	19.67	20.50
1950	20.86	21.71	26.53	26.73
1951	32.14	33.00	35.00	38.33
1952	39.00	40.36	41.33	45.05
1953	32.71	35.36	36.90	37.45
1954	19.00	20.50	21.37	21.97
1955	16.86	17.21	17.87	20.73
1956	17.00	18.50	20.27	21.02
1957	14.29	16.43	19.60	21.08
1958	21.71	24.00	26.13	28.10
1959	20.57	21.36	22.60	23.37
1960	29.71	31.29	32.13	37.70
1961	27.86	30.07	31.60	32.30
1962	18.71	21.21	23.03	24.73
1963	13.71	13.86	14.27	15.13
1964	12.57	13.93	14.03	15.28
1965	6.36	6.54	6.89	8.39
1966	6.71	6.80	7.12	11.98
1967	13.14	13.79	19.27	21.27
1968	26.86	28.71	29.60	31.00
1969	20.71	21.21	21.53	22.63
1970	21.71	22.57	24.20	27.47
1971	32.43	33.36	36.83	37.90
1972	43.00	43.71	44.60	45.98
1973	40.43	45.00	46.13	48.35
1974	36.57	38.21	43.27	47.85
1975	26.57	33.93	36.93	44.17

Table 2.3 Continued

Table 2.3 Continued

1976	24.71	25.86	30.13	34.22
1977	18.00	18.50	19.67	30.83
1978	32.00	32.86	34.53	38.05
1979	35.86	36.29	40.33	45.47
1980	17.71	17.86	18.27	21.03
1981	15.43	15.71	16.23	16.67
1982	17.00	17.07	24.10	26.60
1983	23.86	24.43	27.07	27.72
1984	30.29	30.50	32.37	35.55
1985	17.00	17.86	20.17	23.22
1986	21.00	22.50	24.33	27.85
1987	31.14	32.29	35.50	35.92
1988	21.00	22.71	23.13	25.12
1989	20.00	20.86	23.80	29.72
1990	30.14	32.00	36.50	40.38
1991	17.14	17.79	18.27	20.92
1992	17.71	18.14	18.90	20.27
1993	25.43	28.50	28.80	30.65
Mean of Low Flows (cfs)				
	23.23	24.52	26.46	29.04
Standard Deviation of Low Flows (cfs)				
	8.59	9.19	10.07	11.62
Mean of Logarithms of Low Flows (cfs)				
	1.33	1.36	1.39	1.43
Standard Deviation of the Logarithms of Low Flows (cfs)				
	0.179	0.181	0.180	0.165

Table 2.3 Low-Flow Data

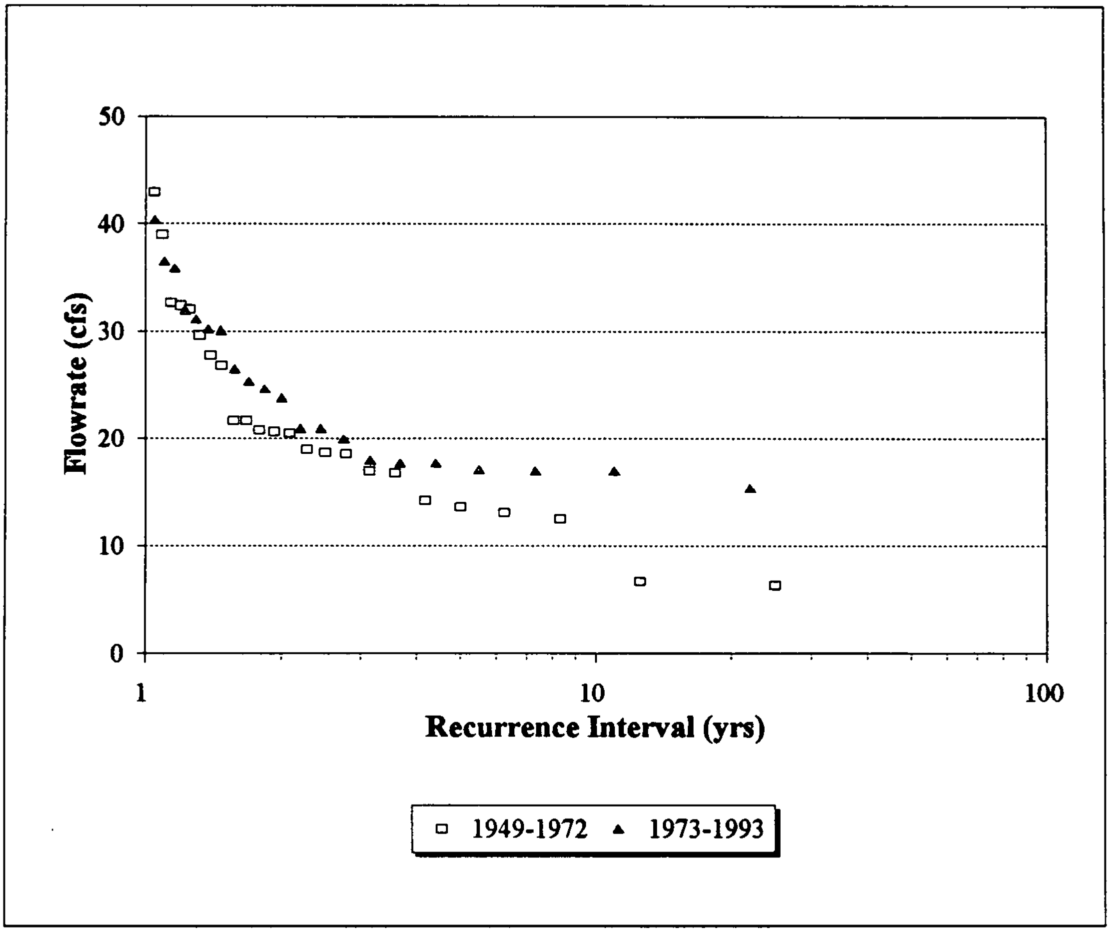


Figure 2.3 Frequency Analysis: Weibull Q-7

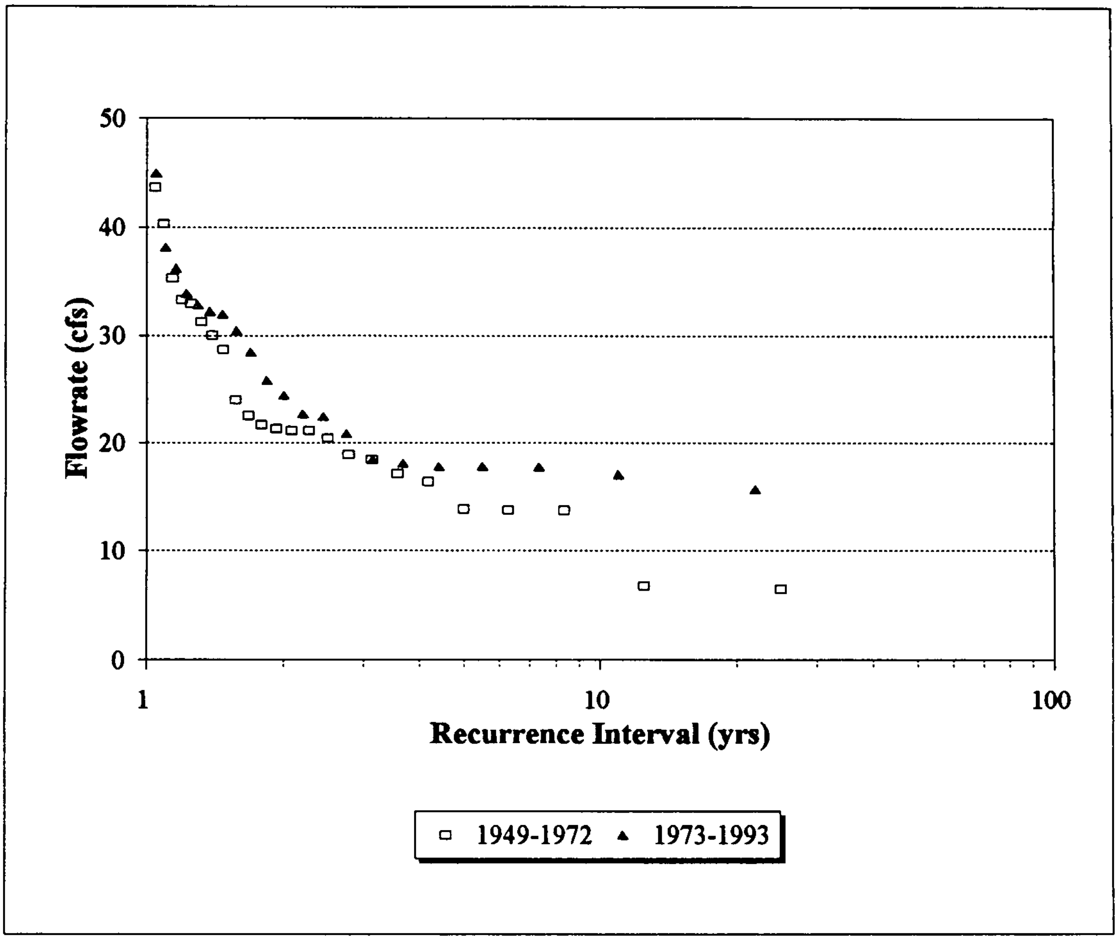


Figure 2.4 Frequency Analysis: Weibull Q-14

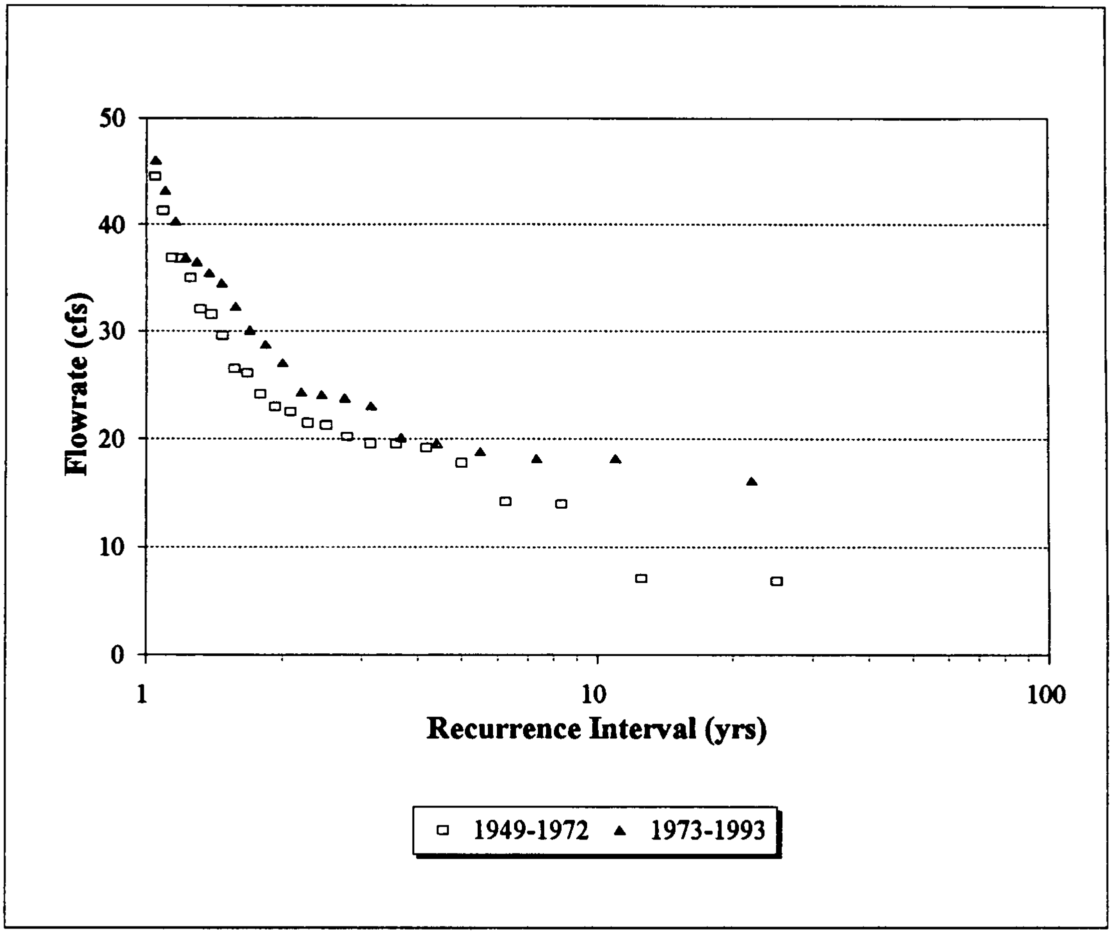


Figure 2.5 Frequency Analysis: Weibull Q-30

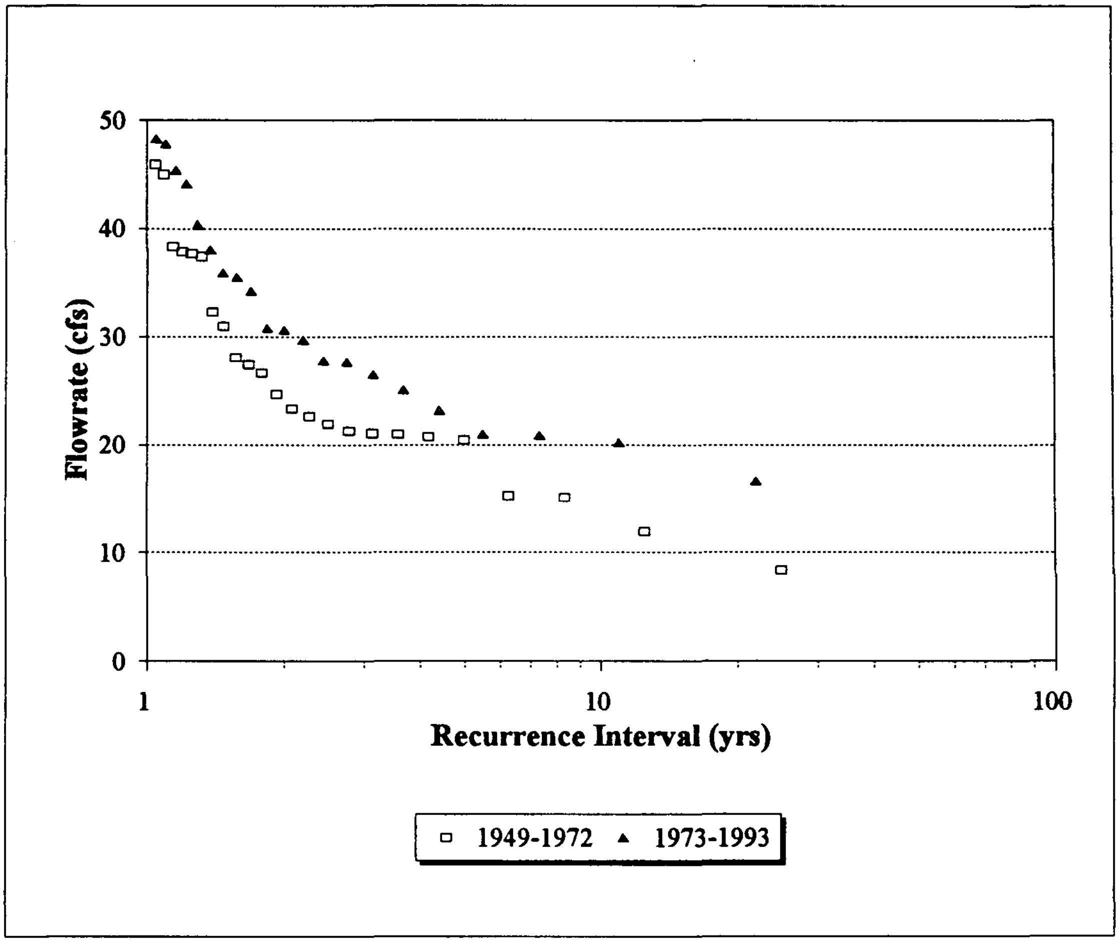


Figure 2.6 Frequency Analysis: Weibull Q-60

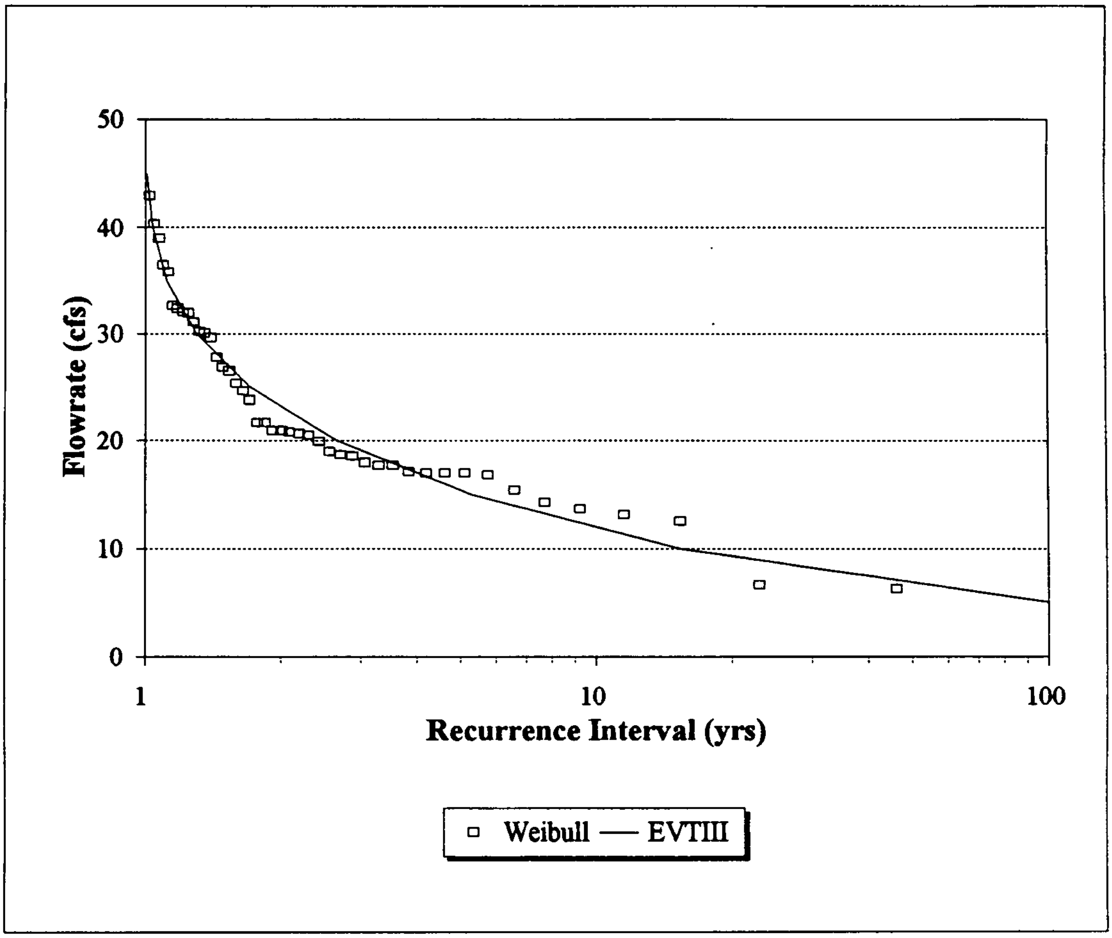


Figure 2.7 Frequency Analysis: Q-7, 1949-1993

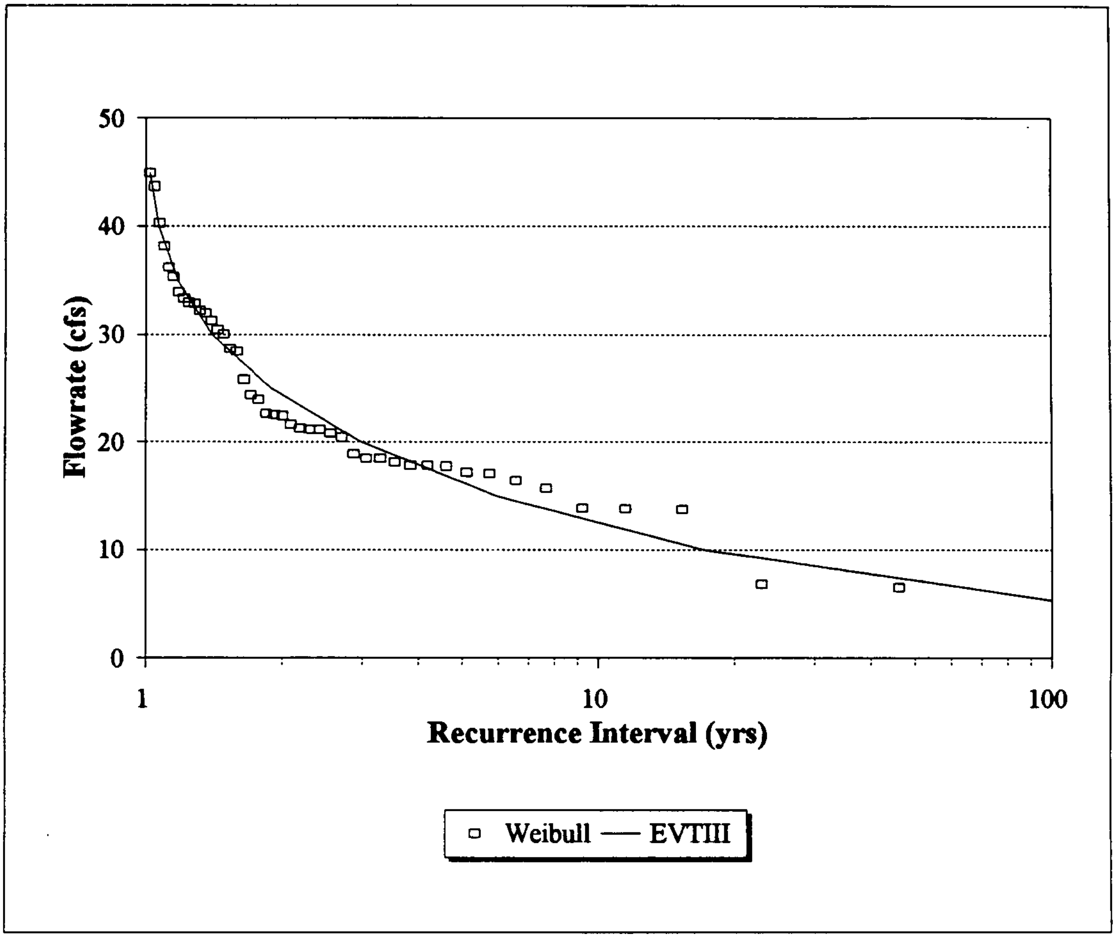


Figure 2.8 Frequency Analysis: Q-14, 1949-1993

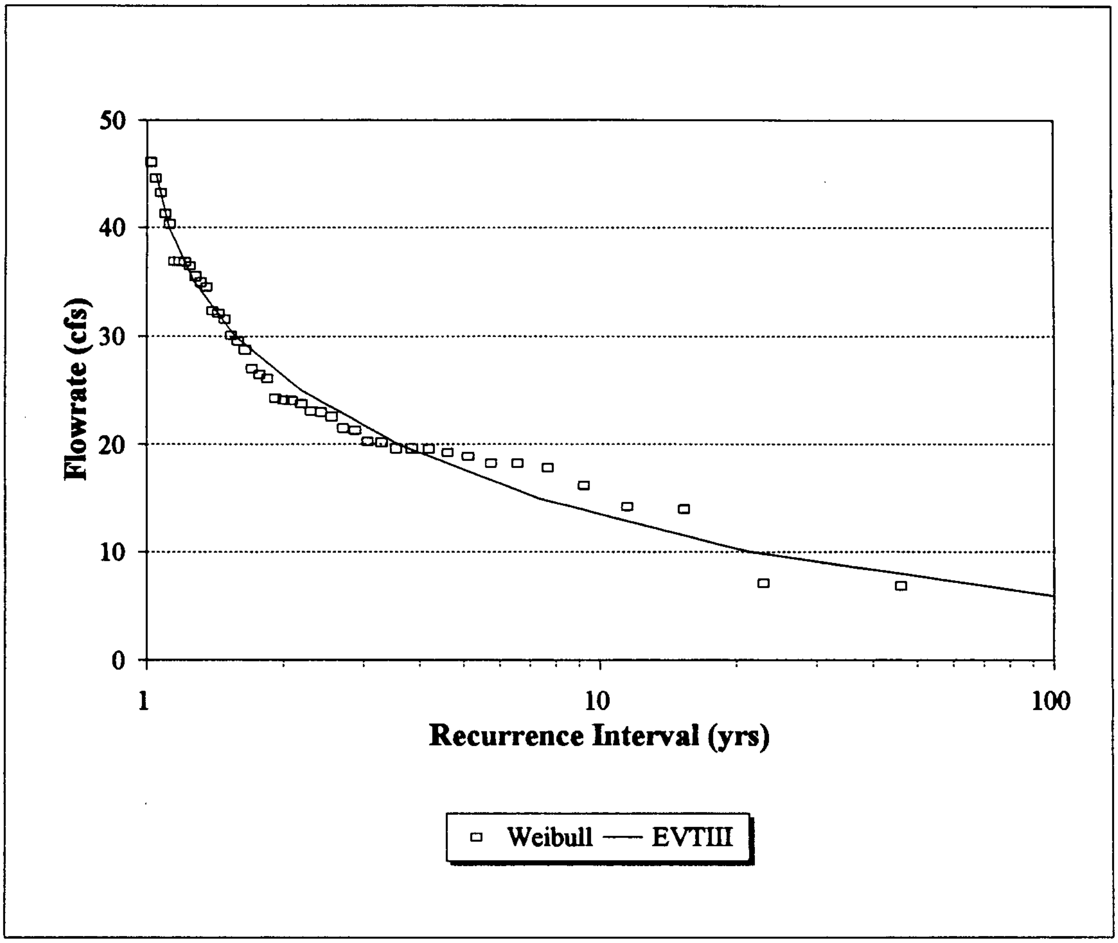


Figure 2.9 Frequency Analysis: Q-30, 1949-1993

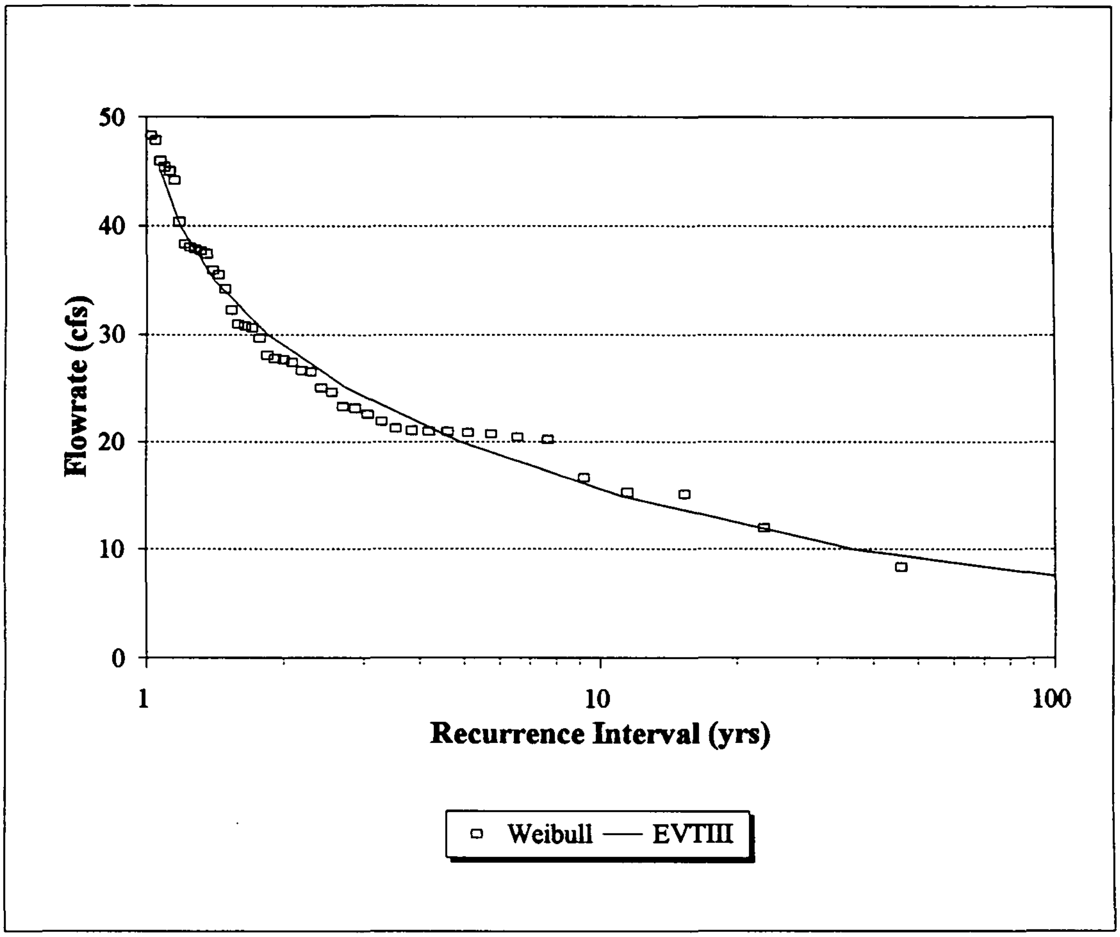


Figure 2.10 Frequency Analysis: Q-60, 1949-1993

2.3.4 Comparison with Other Watersheds

Weibull plotting positions were generated in Page and Shaw (1977) for Jordan Creek, Aquashicola Creek, and the Little Lehigh Creek. The plotting positions for these creeks are shown relative to the Monocacy Creek plotting positions using normalized flowrates with respect to drainage area in Figures 2.11 through 2.14. The Q-7,10 flowrate is used as a basis for a low-flow comparison among the eastern Pennsylvania creeks. The normalized Q-7,10 for Jordan Creek is significantly lower than the other eastern Pennsylvania creeks. The normalized Q-7,10 for Little Lehigh Creek is greater than the other three values. The Monocacy and Aquashicola Creeks have a similar normalized Q-7,10 flowrate despite the differences in watershed geology. Table 2.4 shows a comparison of normalized Q-7,10 between the creeks analyzed and lists the actual Q-7,10 values for each watershed according to data obtained from Page and Shaw (1977).

Creek	**Q-7,10 per Area (cfs/mi^2)**	**Actual Q-7,10 (cfs)**
Monocacy	0.20	9
Jordan	0.02	1.5
Little Lehigh	0.32	26
Aquashicola	0.19	15

Table 2.4 Comparison of Q-7,10

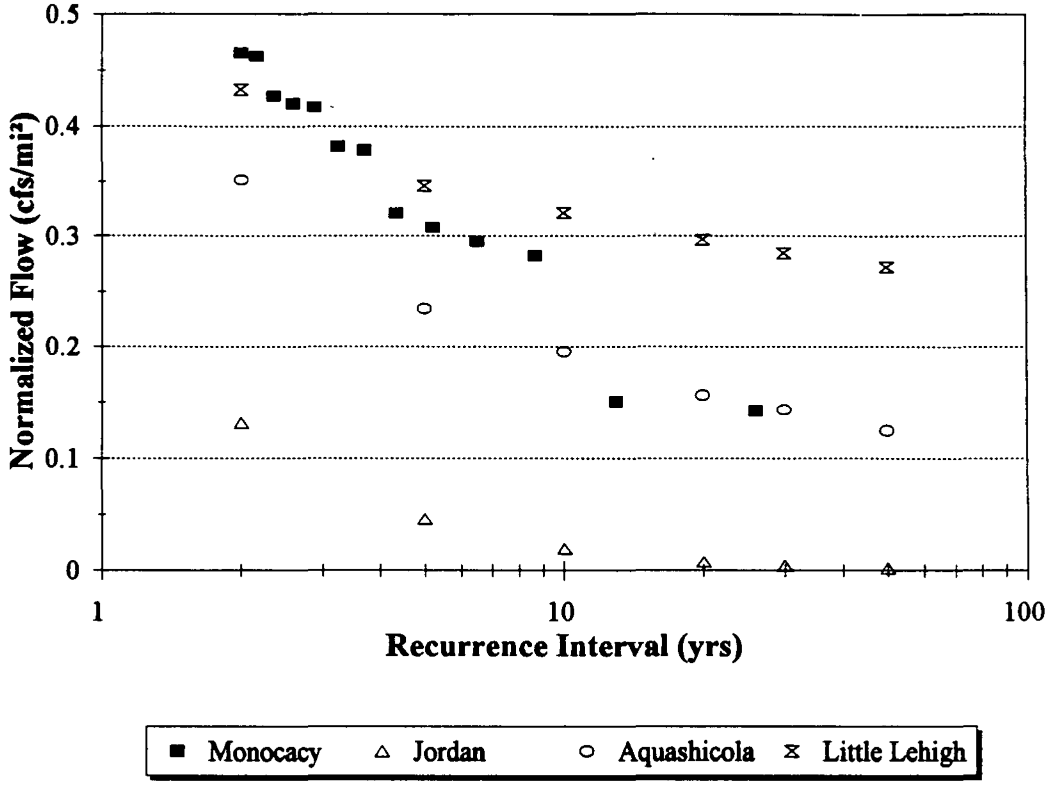


Figure 2.11 Comparing Eastern Pennsylvania Creeks; Q-7

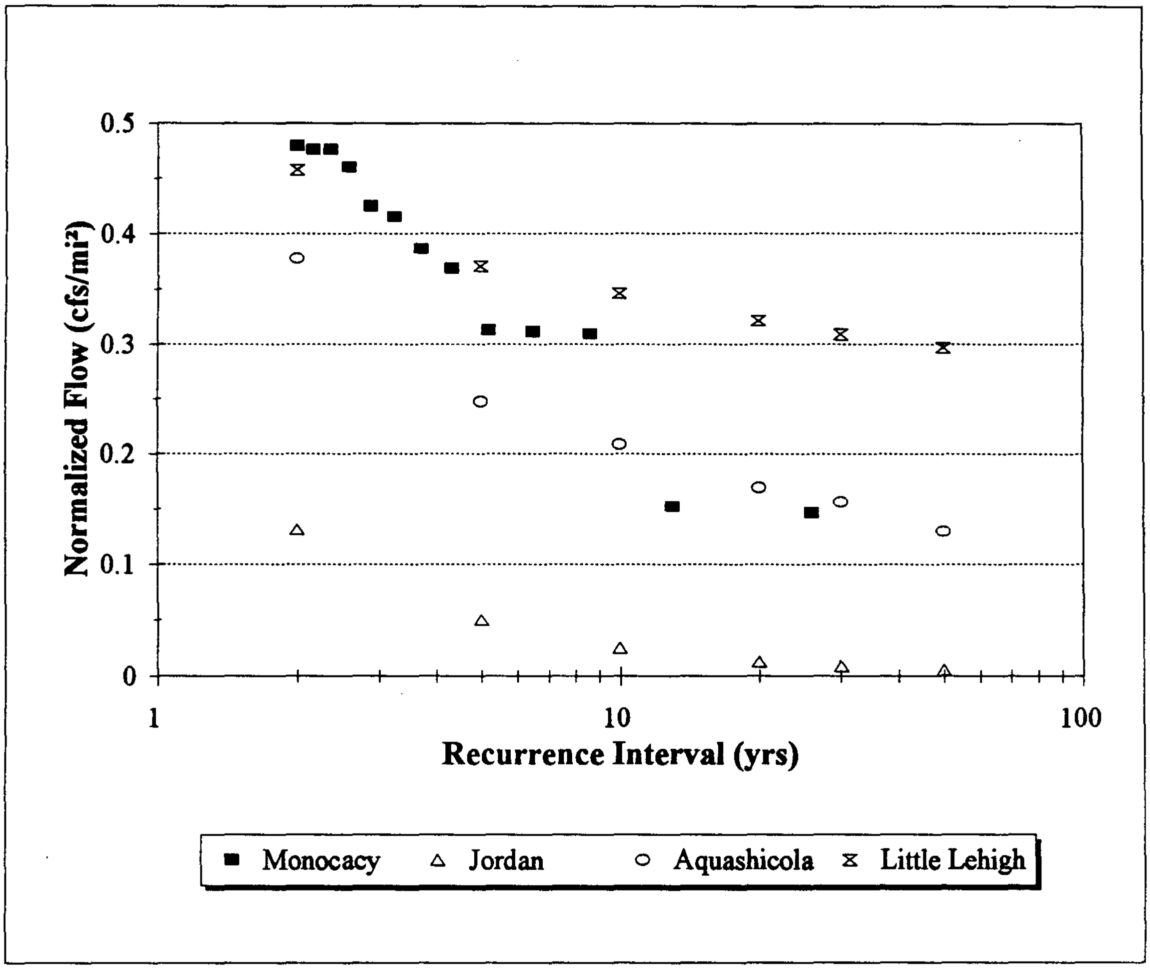


Figure 2.12 Comparing Eastern Pennsylvania Creeks; Q-14

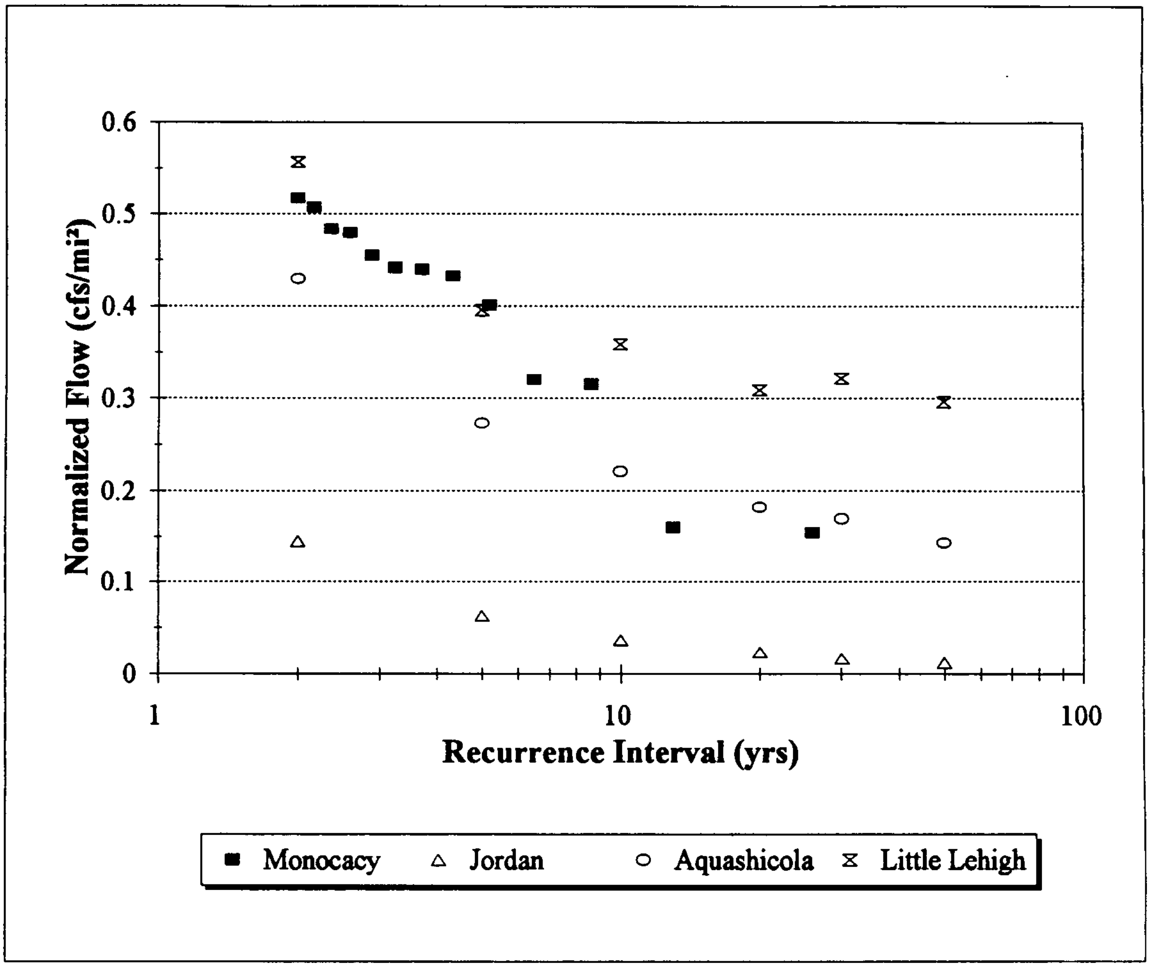


Figure 2.13 Comparing Eastern Pennsylvania Creeks; Q-30

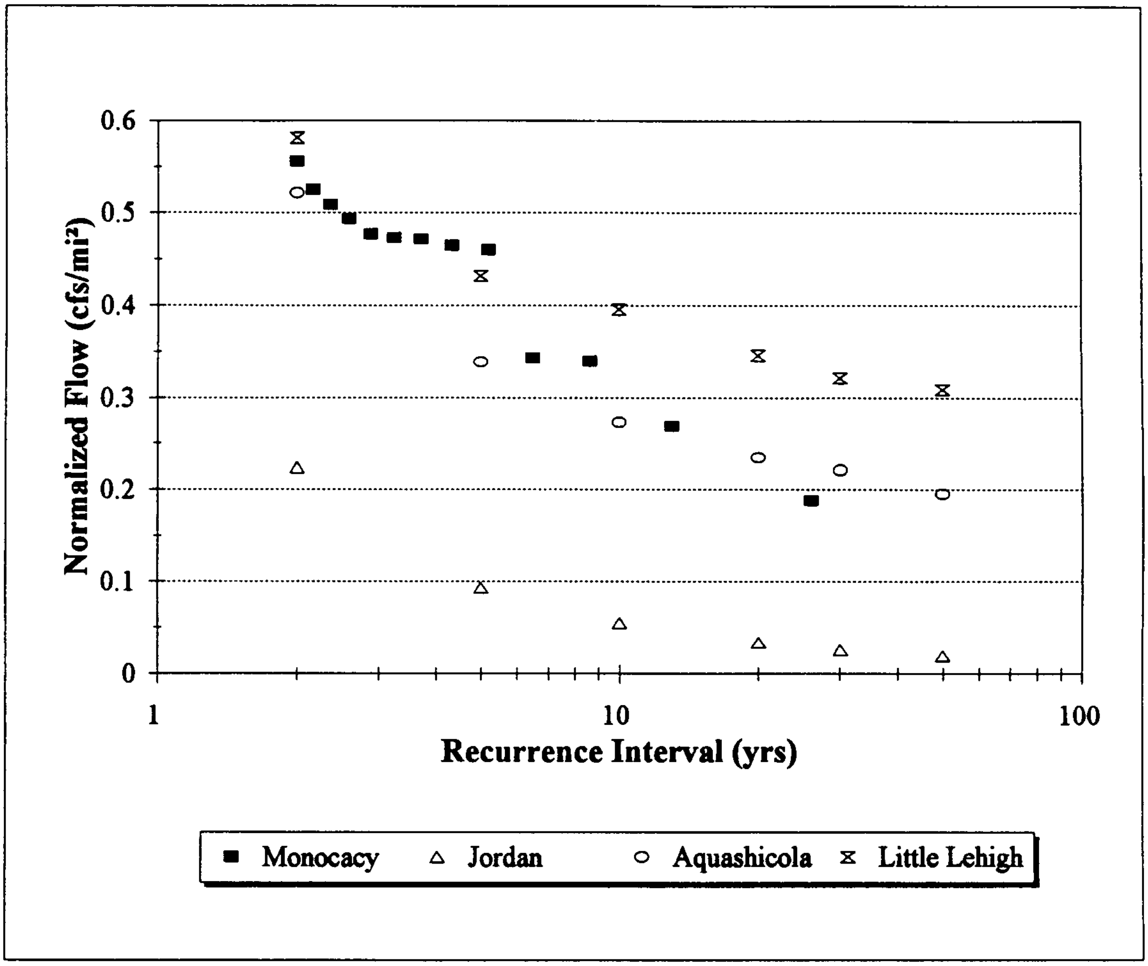


Figure 2.14 Comparing Eastern Pennsylvania Creeks; Q-60

2.4 Base-Flow Recession Analysis

2.4.1 Introduction

A base-flow recession curve is the lower part of the falling limb of a hydrograph and describes a relationship between base flow and time. Many names have been used to describe base flow such as groundwater flow, low flow, percolation flow, under-run, seepage flow, and sustained flow as described in Hall (1968). Base flow, as defined in a historical perspective of base-flow recessions by Hall (1968), is the portion of flow that comes from groundwater storage or other delayed sources. When groundwater is the main source of flow in a stream, water storage within a catchment is decreasing. Pochet (1905) states that if base flow is supplied by groundwater, then a relationship should exist between stream discharge and groundwater levels. Hall (1968) also explained that base-flow discharge diminishes as the stored water in a catchment is depleted and a characteristic base-flow recession is a hydrological property of a catchment. The recession of a streamflow hydrograph, according to Singh (1971), reflects the total effect of the various physical watershed factors affecting runoff.

According to Hall (1968), base-flow recessions have been widely used to forecast low flows. Hall further explains that an analysis of base-flow recessions could, ideally, yield a groundwater depletion curve for a drainage basin. Another application of base-flow recessions has been an attempt to determine the relations between hydrologic and geologic parameters in a drainage basin.

2.4.2 Theory and Methodology

Several curves have been suggested as representing base-flow recession. According to Toebes (1969) the most important of these are: simple exponential, double exponential, and hyperbolic. When choosing recession periods, Toebes (1969) cautions to allow sufficient time between the time chosen for the beginning of the period and the time of the last recorded rainfall so that resulting surface flow will have passed the gauging station. Toebes also suggests that chosen recessions should persist for periods of at least seven days.

The use of various base-flow equations involves the implicit assumption that the storage/flow ratio or response time is a constant property of the drainage basin. According to Amorocho (1967), this assumption has been challenged on the grounds that response time depends on various hydrologic, geologic and meteorologic factors which are not constant.

The base-flow recession curves generated in this report were formulated using the following simple exponential equation as presented in Singh (1971):

$$Q_t = Q_o \, k^t \tag{7}$$

where Q_t is the discharge at time t, Q_o is the initial discharge, and k is a recession constant. Recession constants were calculated for the Monocacy Creek using five different recession periods, all greater than seven days and of appropriate starting times as previously described. The chosen recession periods occurred during different seasons of the year and were all during the drought of the 1960's.

2.4.3 Results

The recession curves are plotted as straight lines on semi-log paper as shown in Figure 2.15. The slopes of the recession curves are very similar despite the variations in season and duration of the chosen recession periods. The recession constants calculated for each recession period are shown in Table 2.5. An average value of 0.985 was calculated using the constants from each recession period.

Recession Period	Recession Constant, *k*	Length of Period (days)
01/11/65 - 01/28/65	0.983	17
07/13/65 - 07/20/65	0.988	7
09/13/65 - 09/22/65	0.985	8
01/02/63 - 01/09/63	0.977	7
02/22/63 - 03/03/63	0.992	9

Table 2.5 Recession Constants of the Monocacy Creek

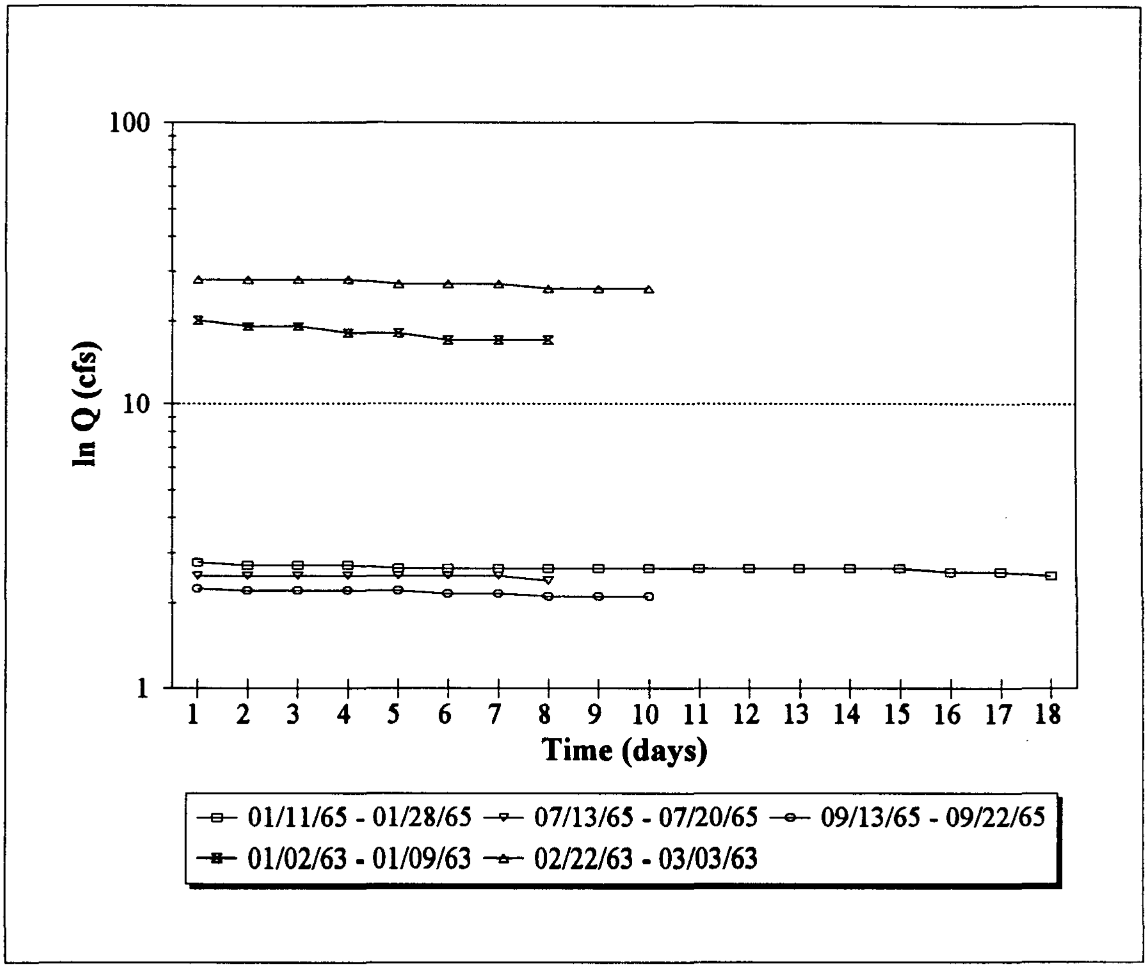


Figure 2.15 Base-flow Recession Curves

Chapter Three: SEDIMENT CHARACTERISTICS of the JOHNSTON REACH

3.1 Introduction

In some reaches of the Monocacy Creek sediment has restricted natural trout food supplies and covered valuable egg-laying habitat, thus threatening the quality of this waterway. Land disturbance due to construction and farming is the greatest single water pollution problem in the Monocacy Creek according to Horner (1981). Sediment in the Monocacy Creek watershed mainly originates as urban and agricultural runoff but has also come from road, bridge and home construction. During a rainfall event, sediment is transported by the creek through much of the upper reaches and a large amount of sediment is deposited downstream in areas of slow moving water. Evidence of this phenomenon is particularly visible in the Johnston Reach where bottom scour is low, increasing the tendency of sediment to settle out of suspension. Very fine sediment has reached a depth of one to two feet over a layer of coarser-grained sediment throughout the Johnston Reach due to a low-head dam at the end of the reach. A sediment characterization study provides information which may be helpful in assessing the stability and geomorphology of the stream bed in the Johnston Reach.

3.2 Theory and Methodology

During a rainfall event, sediment in the upper portions of the watershed is transported to the creek by runoff and then channel flow to the lower reaches. In turbulent flow, shear stress is proportional to the square of velocity. The following equation shows the relationship between shear stress, τ, and velocity profile:

$$\tau = K\frac{dv}{dy} \tag{8}$$

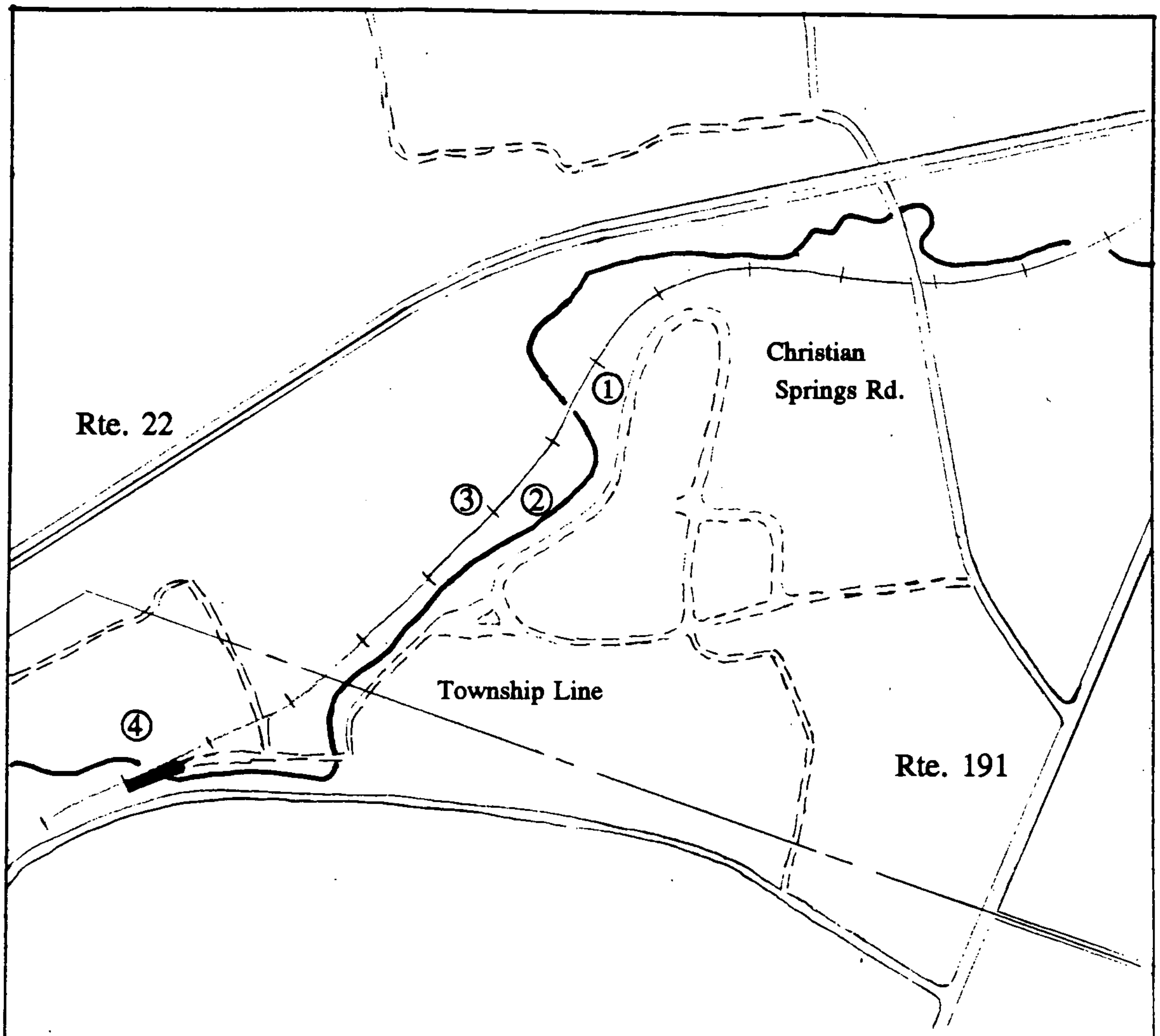
where K is a coefficient of molecular viscosity for viscous flow and a coefficient of eddy viscosity for turbulent flow, v is velocity, and y is depth. During periods of high flow, such as a flood, flow velocity increases and, subsequently, shear stress on the channel bed increases. As a result, the channel bed scours and sediment is transported during a flood. As shear decreases during the falling limb of a flood hydrograph, suspended sediment settles to the channel bottom.

Scouring of the stream bed during a rainfall runoff event depends on the stability of the sediment composing the stream bed as well as the shear on the bed. One parameter which can be used to preliminarily assess the stability of a stream bed is bulk density. Bulk density provides an indication as to the degree of consolidation, packing or cohesiveness of the stream bed. The bed stability in the Johnston Reach was evaluated by analyzing three core samples taken at a cross section of the channel just upstream from a foot bridge as shown in Figure 3.1. Cores were taken on the west bank, east bank and in the center of the creek. A Multi-Sensor Core Logger was used to generate plots of bulk density versus depth for each sediment core sample.

Multi-Sensor Core Logger

The Multi Sensor Core Logger (MSCL) system enables a number of geophysical measurements to be made on sediment cores encased in PVC liners. The unsplit core is placed on the rails of a conveyor system and aligned to its start position. A core pusher moves incrementally along the length of the track pushing the core through a number of sensors. Measurements of core position, differential core diameter, P-wave travel time, P-wave amplitude, gamma counts, and magnetic susceptibility are recorded at each incremental movement of the core sample.

Gamma counts are used to generate a bulk density calibration curve which is a plot of the natural log of gamma counts versus bulk density. It is generated using a core sample containing segments of known bulk density. The natural log of gamma counts is equated to a bulk density for each incremental segment. A calibration curve is used to relate gamma ray attenuation in an unknown sediment core sample to bulk density. The calibration curve used for this study is shown in Figure 3.2. A detailed procedure for determining the bulk density of a sediment core sample using a MSCL is described in GEO-TEK (1993).



① Beginning of Johnston Reach just downstream of R.R. bridge

② Foot bridge to get to the largest spring in the Johnston Reach

③ Sediment Core Sample Location - Just upstream of foot bridge

④ Low-head dam at the end of the Johnston Reach

Figure 3.1 Archibald Johnston Conservation Area

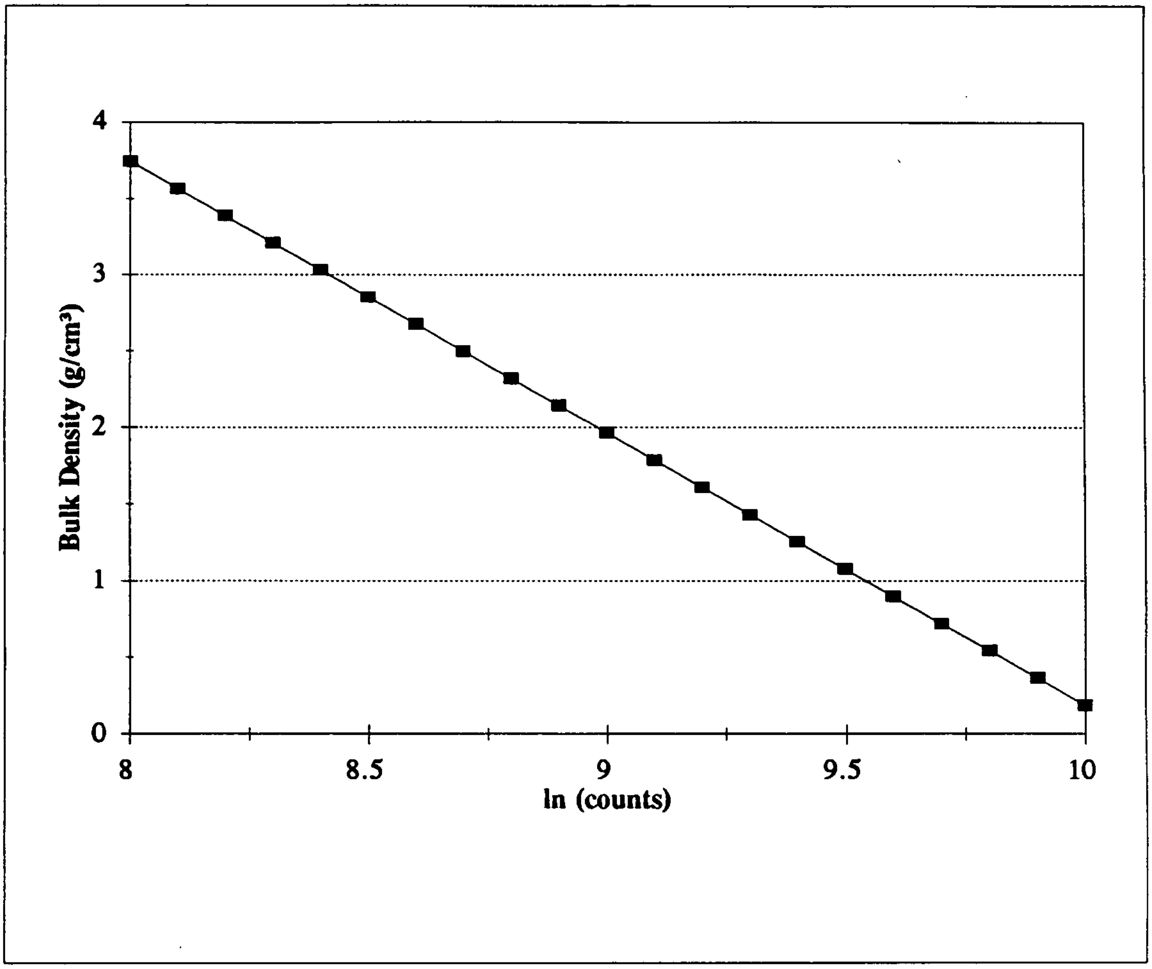


Figure 3.2 MSCL Calibration Curve

3.3 Results

Values of bulk density for different depths throughout each sediment core sample taken at the foot bridge are shown in Figure 3.3. Bulk density in the west bank core increases from approximately 1.5 g/cm^3 in the top ten inches to 1.8 g/cm^3 in the bottom nine inches. Since the grain size of the sediment in this core is fairly uniform throughout, the increase in bulk density implies that sediment in the lower nine inches of the core is more consolidated than the sediment in the top ten inches.

Bulk density increases at a fairly constant rate with depth for the east bank core from approximately 1.3 g/cm^3 at the top to approximately 1.5 g/cm^3 at the bottom. The bulk density values for the core taken at the east bank are similar to the values for the top ten inches of the west bank core. This implies that the sediment in the east bank core is relatively unconsolidated, as compared to the lower nine inches of sediment in the west bank core.

The values of bulk density for the center creek core are very inconsistent. Values range from approximately 1.3 g/cm^3 to 1.6 g/cm^3 through the top ten inches of the core. This implies that the sediment in the top ten inches of the center creek core is relatively unconsolidated, as compared to the lower nine inches of sediment in the west bank core. Bulk density decreased to 1.2 g/cm^3 at a depth of ten inches. This sharp decrease in bulk density can be attributed to a very unconsolidated layer of gravel at the base of the core. The core was not properly capped in the field and some of the gravel that should have been included in the bottom two inches was lost. This very low bulk density is therefore not correct.

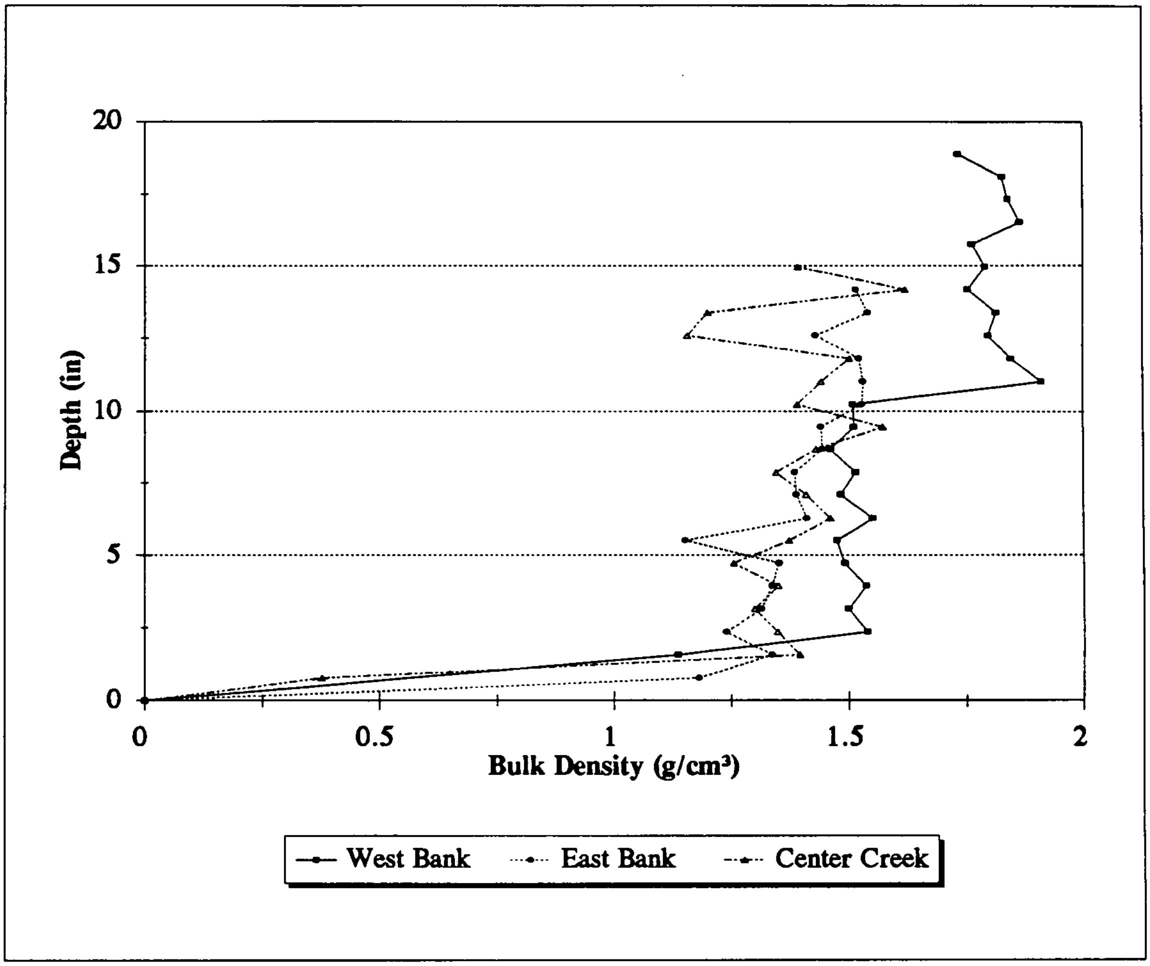


Figure 3.3 Vertical Bulk Density Profiles

The sediment in each of the three core samples ranged in color from a light olive to black. Most of the sediment in the top ten inches of each core had several air cavities and contained layers of leaves and sticks. The sediment in the lower nine inches of the west bank core varied in color and material composition but appeared to be more consolidated than the sediment in the upper ten inches. A description of the sediment core samples is shown in Table 3.1.

Figure 3.4 shows a plot of bulk density versus location along the cross section. The sediment at each incremental depth across the section has a greater bulk density on the west bank than the other two locations. This implies that the sediment on the west bank is more consolidated than the sediment on the east bank and in the center of the stream. The average bulk density calculated for the lowest two inches of the center creek core is incorrect for the same reason as stated above.

Depth (in)	Avg. Bulk Density (g/cm^3)	Color	Munsell Color Chart Code	Comments
East Bank Core				
0 - 2	1.25	Olive Gray	5Y 4/2	Air cavities & organics
2 - 4	1.30			
4 - 6	1.25			
6 - 8	1.40	Olive Gray & Olive	5Y 4/2 5Y 5/4	Fine stratification of Olive sediment
8 - 10	1.43			
10 - 12	1.52			
12 - 14	1.52	Dark Gray	5Y 3/1	High organic content
Center Creek Core				
0 - 2	1.00	Olive Gray	5Y 4/2	Air cavities & organics
2 - 4	1.32	Dark Gray	5Y 3/1	High organic content
4 - 6	1.32	Olive Gray	5Y 4/2	Air cavities & organics
6 - 8	1.40	Dark Gray	5Y 3/1	High organic content
8 - 10	1.50			
10 - 12	1.45	Dark Grayish Brown	2.5 Y 4/2	
12 - 14	1.20			Gravel
West Bank Core				
0 - 2	1.00	Dark Gray & Olive Gray	5Y 3/1	Air cavities & organics
2 - 4	1.52			
4 - 6	1.50			
6 - 8	1.50			
8 - 10	1.50			
10 - 12	1.70	Black	2.5Y 2/0	Anoxic organics
12 - 14	1.80	Olive	5Y 5/4	Light olive color
14 - 16	1.80			
16 - 19	1.82	Olive Gray	5Y 4/2	Fine sand

Table 3.1 Description of Sediment Core Samples

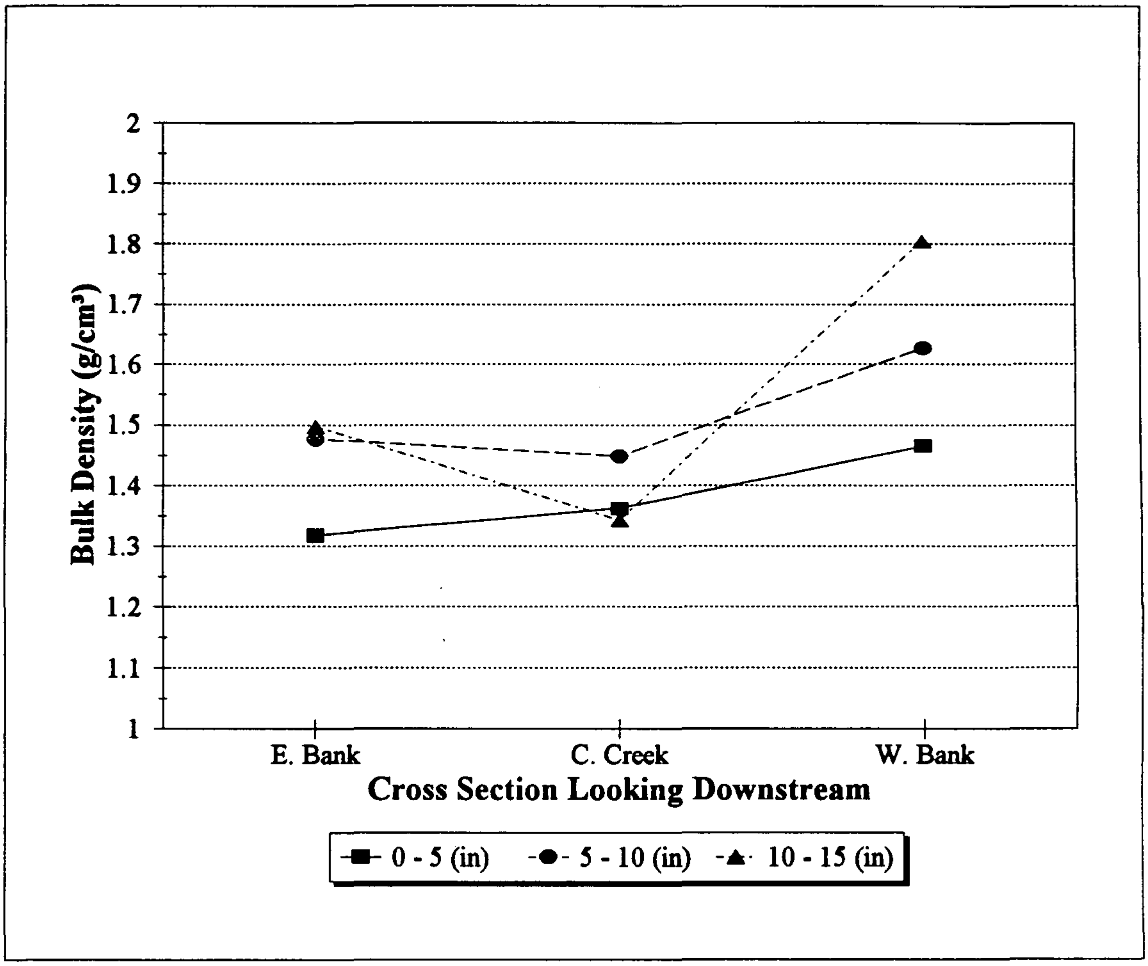


Figure 3.4 Horizontal Bulk Density Profiles

Chapter Four: CONCLUSIONS and SUGGESTIONS

Conclusions that can be drawn from this low-flow characterization study are as follows:

1. The drought of the 1960's is the primary cause for a lower duration curve from 1949 to 1972 compared to 1972 to 1993.

2. The drought of the 1960's is the primary cause for the spreading apart of the frequency curves.

3. The five recession constants are very similar, as shown in the results of the base-flow recession analysis. An average base-flow recession constant of 0.985 is a relatively constant hydrologic property of the Monocacy Creek.

4. Since little or no stream bank erosion occurs in the Johnston Reach, most of the sediment deposited there must originate upstream. The Johnston Reach is a depositional environment for fine sediment originating upstream.

5. Fine sediment has reached a depth of one to two feet above a coarser-grained material throughout most of the Johnston Reach. The top ten

inches of sediment is less stable than the sediment below ten inches.

6. The sediment on the east bank of the Johnston Reach (next to the man-made stone wall) is less stable than the sediment on the west bank at similar depth increments.

Additional research that could be done to help answer some of the questions raised in this thesis are as follows:

1. More accurately assess and then explain the differences among hydrologic properties of the compared eastern Pennsylvania creeks.

2. Use the low-flow characteristics generated in this thesis to do water quality modelling of the Monocacy Creek, in particular to assess the assimilative capacity of the creek with regard to various flowrate levels.

3. More accurately describe the sediment characteristics in the Johnston Reach in terms of particle size, material composition and transport susceptibility.

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