3-1996

Flash-Flood Monitoring and Modeling in Kentucky

Digital Object Identifier: https://doi.org/10.13023/kwrri.rr.195

Mark French
University of Kentucky

Nageshwar Bhaskar
University of Kentucky

George K. A. Kyiamah
University of Kentucky

Research Report No. 195

Flash-Flood Monitoring and Modeling in Kentucky

by

Mark French
Co-Principal Investigator

Nageshwar Bhaskar
Co-Principal Investigator

George K. A. Kyiamah
Graduate Research Assistant

Project Number: 94-09 (A-128)
Agreement No.: 14-08-0001-G2021
Period of Project: July 1994 to December 1995

University of Kentucky
Kentucky Water Resources Research Institute
Lexington, KY 40506-0225

The work on which this report is based was supported in part by the Department of the Interior, Washington, D.C. as authorized by the Water Resources Research Act of P.L. 101-397

March 1996

Disclaimer

Abstract

This research project focused on the evaluation of hydrologic issue of flash-flooding in the state of Kentucky. The primary objectives of this project were the following:

(1) to initiate the establishment of a hydrologic database archive necessary for characterizing rainfall and runoff associated with flash-flooding;

(2) identification of appropriate modeling approaches for evaluating site-specific flash-flood runoff behavior.

Specific tasks accomplished to meet the objectives include the following:

(1) development of a rainfall and streamflow data archive using existing measurement gages and identification of the rain gage data from two sources for preliminary quality control;

(2) identification of the spatial and temporal characteristics of rainfall at daily, seasonal, and annual time scales;

(4) definition of the characteristics of runoff associated with flash-flooding; and

(5) initiation of a review of flash-flood runoff modeling approaches for small watersheds.

Flash-flooding is one of the most costly natural hazards nationally each year. In 1990, it resulted in 109 deaths and damages of $625 million (Kentucky Engineer, 1992) in the United States. In 1992, a single flash-flood event in Bar-Creek, Kentucky resulted in four deaths and displaced approximately 54 families (National Weather Service, 1992). Due to the short response time associated with the watersheds prone to flash flooding, rainfall data must be collected rapidly in real-time and flood estimates computed accurately in order that adequate and timely warnings may be issued. Accurate estimates of flash-flood water levels require site-specific information describing the hydrometeorologic conditions and physiographic characteristics of the watershed for use of high resolution runoff modeling approaches. Monitoring rainfall events that lead to or cause flash-flooding is necessary to identify the rainfall characteristics associated with flooding and flash-flooding. The ultimate objective in a flash-flood warning system is to provide increased warning time to residents to allow them to escape the rapidly rising water. National-level agencies are only beginning to address the issue of real time, high resolution flood forecasts meeting the needs of state agencies and local-area residents. Other issues, beyond the scope of this work, must be addressed and resolved before such a system can be significantly mitigate flash-flood losses. This project addresses the initial step toward establishing such a system by compiling a flash-flood precipitation and runoff database for Kentucky from existing gage networks, and quantitatively defining the behavior of precipitation and runoff.

FOCUS CATEGORIES: FL, CP, HYDROL

KEYWORDS: **Flood Control, Geomorphology, Hydrologic Models, Rainfall, Rainfall-Runoff Models, Rainfall-Runoff Processes, Rainfall Data Collection, Rainfall Forecasting, Runoff, Streams, Watershed Management**

Acknowledgement

The Principal Investigators would like to thank the following individuals and the agencies for providing assistance with the tasks of acquisition of the components of hydrologic data associated with this project. This project was made possible through the support of the Kentucky Water Resources Research Institute at the University of Kentucky. The successful completion of this work was made possible through the cooperation of the following persons at the National Weather Service (NWS) Louisville, Kentucky, Weather Forecast Office (WFO): Marvin Maddox, Mike Callahan, and Bill Wilson. Additionally, Kevin Ruhl at the United States Geological Survey (USGS) Office Louisville, Kentucky provided access to a portion of the streamflow data incorporated in this study.

Table of Contents

Chapter 1 - Introduction . . . 1
Related Literature on Flash Flooding . . . 3
A Climatological Perspective on Flash Flooding . . . 3
A Geomorphological Perspective on Flash Flooding . . . 7

Chapter II - Research Procedures . . . 10
Development of a Flash Flood Monitoring System for Eastern Kentucky . . . 10
Description of study area . . . 11
Hydrological Components Required for a Flash Flood Monitoring System . . . 13
Existing Hydrologic Components in Study Area . . . 14
Rain Gage Network . . . 14
Adequacy of Existing Rainfall Data Sources . . . 15
Additional Rainfall Data Sources . . . 16
Integrated Flood Observing and Warning System (IFLOWS) . . . 18
Rain Gage Network Size for Automated Flood Warning System . . . 21
IFLOWS Rainfall Data . . . 21
Existing Streamflow Gage Network in the Study Area . . . 22
A Review of Physically-Based Flash Flood Modeling Approaches Appropriate for eastern Kentucky . . . 23
Selection of Events for Flash Flood Characterization . . . 26
Selection of Gaged Watersheds without Streamflow Regulation . . . 27
Rain gage selection . . . 27
Summary of Streamflow and Watershed Characteristics . . . 28
Selection of Flood Events for Hydrograph Analysis . . . 29

Chapter III - Data and Results . . . 31
Characteristics of Rainfall Associated with Flash Flooding . . . 31
Analysis of IFLOWS Rainfall Data . . . 34
Analysis of Selected Flood Events . . . 35
Precipitation Characteristics of Selected Flood Events . . . 36
Development of Flash Flood Index (R_F) . . . 37

Chapter IV - Discussion of Results . . . 47
Precipitation . . . 47
Flash Flood Characterization . . . 62
Conclusion . . . 70
Ongoing Research . . . 71

References . . . 72

APPENDICES . . . 77

APPENDIX A 78
TABLE A1: Station Index for IFLOWS Rain Gages 79
TABLE A2: Streamflow Characteristics for Continuous - Recording Gaging Stations in Eastern Kentucky 81
APPENDIX B 82
FIGURE B1: Streamflow Discharge and corresponding Rainfall for Selected Flood Events. 83

Illustrations

FIG. 1. Causes of Floods and Flood Intensifying Conditions. 4

FIG. 2. Kentucky Counties Participating in the IFLOWS Program 20

FIG. 3. Time Series of Daily Averaged Rainfall Depth (inches) for the Year, July 1, 1994 through June 30, 1995 51

FIG. 4. Time Series of Daily Averaged Rainfall Depth and Maximum Daily Rainfall Depth recorded at any Gage in the Network (inches) for the Year, July 1, 1994 through June 30, 1995 52

FIG. 5. Time Series of Daily Averaged Rainfall Depth (inches) for the, July 1, 1994 through June 30, 1995. The lower portion of Figure 6 shows the Temporal Autocorrelation of the Averaged Daily Rainfall Depth. 53

FIG. 6. Time Series of the Monthly-averaged, Minimum and Maximum Rainfall Depths for each Month. 54

FIG. 7. Spatial Autocorrelation Function of the Annual Total Rainfall Depths at all 161 IFLOWS Gages. 55

FIG. 8. Spatial Autocorrelation Function of the Summer Season (June 1995, July 1994, and August 1994) Total Rainfall Depths at all 161 IFLOWS Gages. 58

FIG. 9. Spatial Autocorrelation Function of the Fall Season (September 1994, October 1994, November 1994) Total Rainfall Depths at all 161 IFLOWS Gages. 59

FIG. 10. Spatial Autocorrelation Function of the Winter season (December 1994, January 1995, February 1995) Total Rainfall Depths at all 161 IFLOWS gages. 60

FIG. 11. Spatial Autocorrelation Function of the Spring Season (March 1995, April 1995, May 1995) Total Rainfall Depths at all 161 IFLOWS gages. 61

FIG. 12. Streamflow Discharge and Corresponding Rainfall for Reported Flash Flood Events . . 65

FIG. 13. Relationship between Flash Flood Index and Rising Curve Gradient. 66

FIG. 14. Relationship between Flash Flood Index and Flood Magnitude Ratio. 66

FIG. 15. Relationship between Flash Flood Index and Flash Flood Response Time. 66

FIG. 16. Relationship between Flash Flood Index and 24-hr Antecedent Precipitation. 67

FIG. 17. Relationship between Flash Flood Index and 48-hr Antecedent Precipitation. 67

FIG. 18. Relationship between Flash Flood Index and 5-day Antecedent Precipitation. 67

FIG. 19. Relationship between Flash Flood Index and Maximum Rainfall Intensity. 68

FIG. 20. Relationship between Flash Flood index and Average Rainfall Intensity. 68

FIG. 21. Relationship between Flash Flood Index and Storm Advancement Ratio. 68

FIG. 22. Relationship between Flash Flood Index and Storm Intensity Ratio. 69

Tables

TABLE 1. National Weather Service Continuous Recording Gages. 15

TABLE 2. National Weather Service Daily Total Precipitation Gages in Eastern Kentucky 17

TABLE 3. Kentucky Counties with IFLOWS Equipment U.S. Dept. Of Commerce, 1993) 21

TABLE 4. Watershed Characteristics 28

TABLE 5. Streamflow Characteristics 29

TABLE 6. A list of Selected Flood Events With Corresponding Watershed and Streamflow Gage Number. 30

TABLE 7. A Summary of Rainfall Characteristics 36

TABLE 8. Class Intervals for Rising Curve Index, k, and the corresponding Relative Severity Factors, R_K 38

TABLE 9. Class Intervals for Flood Magnitude Ratio, M, and corresponding Relative Severity Factors, R_M 39

TABLE 10.Class Intervals for Flash Flood Response Time, T_P, and corresponding Relative Severity Factors, R_T 41

TABLE 11. Summary of Flash Flood Indexing Parameters. 41

TABLE 12. A Summary of Relative Severity Index Assigned to Each of the Flash Flood Indexing Parameters. 42

TABLE 13. Flash Flood Index Arranged in Decreasing Order of Magnitude 43

TABLE 14. A Summary of Flash flood Index and Precipitation Characteristics for Select Flood Events 44

TABLE 15. Summary of Hydrograph Characteristics for Select Flood Events 44

TABLE 16. Flash flood Index and Corresponding Hydrograph Characteristics for Select Flood Events. 45

TABLE 17. Indexing Parameters (T_P, M and k) for reported Flash Floods. 62

TABLE 18. Storm Characteristics Identified with reported Flash Floods 62

Chapter 1 - Introduction

Floods are one of the most dramatic hydrologic interactions between water and the environment, emphasizing both the sheer force of natural events and efforts to understand them. Floods are always news, from a small stream washing out a road, to the flash flood of Shadyside, Ohio (NWS, 1991). Although man has been responding to floods for a long time, programs of intensive and organized data collection are more recent in development. In the United States, for example, it dates back only to the mid-nineteenth century when the federal government first vigorously participated in flood protection and organized surveys. In recent years there have been major attempts in many countries including the United States to improve the knowledge of flood hazard and the possible responses to it. There is the need to understand the natural and man-induced causes of flooding; the need for adequate prediction and forecasting of flood occurrence and magnitude; the need to evaluate man's awareness of the flood hazard; and lastly, the need to develop sound economic responses to flood situations through properly planned programs of adjustment, abatement and protection. One such program which is designed for the prediction and real-time forecasting of flood occurrence and magnitude is the Integrated Flood Observing and Warning System (IFLOWS, 1993) in eastern Kentucky. The IFLOWS program will be discussed later in the report.

Defining a flood is challenging, partly because floods are a complex phenomena and are viewed differently according to the physiographic and societal impact they impose. Floods occur in many ways, usually in valley bottoms and coastal areas, and produced by a number of influencing conditions such as rainfall intensity, antecedent moisture conditions, and watershed topography. Their locations and magnitudes vary considerably, and as a result, they have markedly different

effects upon the environment. For most practical purposes and popular usage a meaningful flood definition incorporates the concept of damage and inundation. A more general form of flood definition is as follows (Ward, 1978): a flood is a body of water which rises to overflow land which is normally unsubmerged. In this example inundation is explicit and damage is implied only in developed areas in the definition. There are markedly different types of floods, related to different causal factors such as excessively heavy rainfall, coastal storm surges, earthquakes and dam failures. One kind of flood frequently experienced in the Appalachian region of eastern Kentucky is referred to as flash flooding and is primarily caused by excessively heavy rainfall. This study specifically focuses on flash floods in eastern Kentucky, since it is the single most destructive weather related phenomenon in the region.

The primary aim of this study is to develop a database for flash-flood monitoring and modeling. In addition to this, an effort is made to characterize the temporal and spatial aspects of flash-flood rainfall-runoff events as observed in select watersheds in eastern Kentucky. In order to achieve these objectives, this study focused on the following specific tasks: 1) to develop a flash-flood precipitation database for eastern Kentucky; 2) to evaluate and quantify the spatial and temporal rainfall/runoff characteristics associated with flash-floods in eastern Kentucky; and 3) review of physically-based flash-flooding modeling approaches appropriate for eastern Kentucky watersheds. This proposed flash-flood monitoring system is a first step at establishing a systematic approach for understanding the problems associated with flash floods in eastern Kentucky.

Related Literature on Flash Flooding

In view of the markedly varying flood response to different rainfall conditions, many attempts have been made to classify floods on the basis of the rainfall event. There are a number of flood types associated with different causal factors. In eastern Kentucky flash flooding occurs frequently. Figure 1 illustrates the primary causes of floods and the watershed geomorphological effects that lead to flood intensification. A comprehensive review of floods and flash floods is given by (Ward, 1978). Portions of the following text follows closely from that work.

A Climatological Perspective on Flash Flooding:

Flash floods are often caused by intense, convective storms that tend to be of short duration, often measured in minutes rather than hours. These storms normally have a small areal extent and lead to floods on either small headwater streams, minor tributaries or in urban areas. Due to the sudden influx of runoff from a relatively small watershed, flash floods exhibit sharp peaks with floodwater rising and falling rapidly. Flash floods also result from other types of intense rainfall. For example, the headwater streams of the Appalachians experience flooding as remnants of hurricanes move through the region.

Flash floods occur almost everywhere in the world due to the global distribution of convective rainfall. In the British Isles, one of the most dramatic of these resulted from the cloudbursts of June 18, 1930, which fell on part of Stainmore Forest in the Pennines.

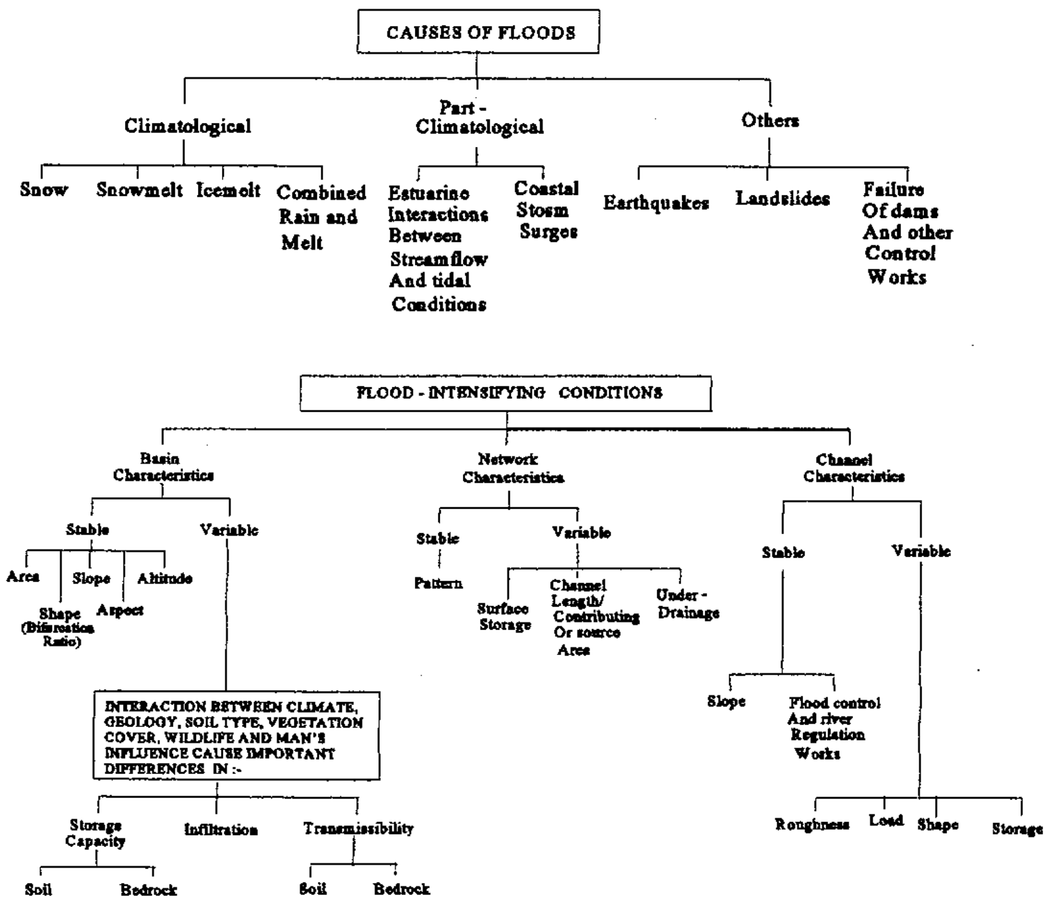


FIG 1. Causes of Floods and Flood Intensifying Conditions (adapted from Ward 1978).

A series of intense convection cells yielded 60 mm of rainfall in an hour at one gage located about 1 km from the storm center and resulted in a series of short-lived flood peaks that swept away bridges and field walls (Ward, 1978). Thunderstorms are particularly frequent in continental interiors during the summer, and hundreds of flash floods resulting from them are recorded each year in the United States.

Flash floods are floods that occur suddenly, within six hours of the rain event (heavy rainfall) and are usually recognized as the deadliest type of flooding. The sudden rise of water limits the time allowed for forecasters to warn of the event, and for endangered individuals to take protective action. The convective origin of rains leading to flash floods are characterized by an unstable air mass, with abundant moisture throughout a deep tropospheric layer, and weak to moderate wind shear. Rainfall efficiency is enhanced as a result of this moisture distribution due to a reduction in the negative effects of evaporation and sublimation in entrained air. Surface fluxes and advection can moisten the lower troposphere, while horizontal and vertical advection can moisten the middle and upper troposphere (LaPenta et al. 1995).

Orographic effects provided by the Appalachian Mountains tend to complicate the forecasting of heavy precipitation in the National Weather Service (NWS) eastern region. Upslope flow of moisture regularly helps to enhance the occurrence of heavy convective rainfall by forcing the upward movement of unstable air mass over higher terrain. Furthermore, the Appalachian region is characterized by small river and stream basins with steep slopes and narrow valleys, offering prime conditions for generating runoff during rain events and contributing to flash flooding. Differential heating caused by marked changes in mountain slopes can also result in upward motion and the development of convection during daylight hours (LaPenta et al, 1995).

The mountainous terrain of the NWS eastern region contributes to the formation of mesoscale boundaries that can initiate or enhance convection. For example, a lee trough occasionally forms on the east side of the Appalachians. Additionally, extensive coastlines along the Atlantic Ocean and Lakes Erie and Ontario are conducive to sea-lake breeze fronts, especially during the warm season. Given a moist, unstable air mass, geographically induced boundaries can enhance convergence and provide subsequent lift necessary for convective development and heavy rainfall.

The following is a discussion of two examples of flash flooding resulting from mesoscale systems. One of the more significant flash floods within the NWS eastern region occurred on July, 19-20 1977 in an area centered around Johnstown, Pennsylvania. A squall line that moved across Pennsylvania during the afternoon of July 19, 1977 left an outflow boundary over western Pennsylvania. The boundary remained quasi-stationary as moist low-level inflow from the Ohio Valley was directed nearly perpendicular to the boundary resulting in the formation of a series of thunderstorms that moved repeatedly over the same area during the evening and night time hours of July 19. Also, the storms moved nearly perpendicular to the western slopes of the Appalachians. Orographic lift probably enhanced storm intensities and helped concentrate the heavy rains in the hills north and east of Johnstown (LaPenta et al 1995). Twenty to thirty centimeters of rain fell over 9 hours in parts of the Conemaugh River Basin causing major flash floods on many streams and seven dam failures, which exacerbated the flooding. Seventy-six individuals died, over 2500 were injured, and property damage was estimated at over $200 million (National Oceanic and Atmospheric Administration 1977).

A second flash flood example occurred on the evening of June 14, 1990. Convective storms produced 12.7 cm of rain and major flash flooding near the town Shadyside, Ohio. The majority of the rain fell in just 1 hour (National Weather Service (NWS), 1991). The thunderstorms developed from a Mesoscale Convective System (MCS) that formed in a moist air mass which had been part of a tropical water vapor plume. Outflow boundaries from an MCS that formed over the Midwest the previous night played a critical role in focusing convection near Shadyside. Thunderstorms initially developed in western Pennsylvania along the east-west outflow boundary, then slowly developed southwestward over southeastern Ohio. Meanwhile, other storms that had formed earlier along an outflow boundary in western Ohio moved across the state and merged with the convection already in the Shadyside area. In addition, low-level upslope flow was prevalent in the area, which may have further enhanced the storms. The thunderstorms remained nearly stationary for approximately 90 minutes; flooding started about 45 minutes after the heavy rain began. A wall of water, which was estimated to be 3 to 9 m in depth, rapidly moved down the Wegee and Pipe Creek Basins and caused 26 deaths, with over 300 residences either damaged or destroyed (NWS 1991).

A Geomorphological Perspective on Flash Flooding

Although it is known that climatological factors contribute to the occurrence of flash floods, it is relevant to mention that other conditions, such as watershed physical characteristics, intensify flash flooding (for example those shown in Figure 1). This section specifically discusses some of these conditions that relate to characteristics associated with eastern Kentucky watersheds.

Flood intensifying conditions associated with climatological factors may cause a different flood response on the same catchment, although the flood generating mechanisms might be similar. The dominant flood intensifying conditions may be grouped into basin, network, and channel characteristics, each group having characteristics which are relatively stable and others that exhibit variability. Watershed is considered to be the most important stable characteristic, because it influences both the time of concentration and the total volume of streamflow generated. In association with the configuration of channel network within a basin, the shape of a basin is particularly important. A high watershed shape factor (ratio of length to average width of the watershed) usually associated with a long narrow basin, produces flood peaks which are low and attenuated, whereas a low shape factor normally associated with a comparatively rounded basin, produces flood peaks that tend to be both higher and sharper. Steep slopes tend to increase the movement of water within the watershed, while aspect and altitude affect the amount of precipitation intercepted by the watershed.

The effects on flood hydrology of the many variable basin characteristics are complicated. There are several important secondary characteristics that result from the complex interaction between factors such as climate, geology, soil type, vegetation cover and the effects of wildfire, landuse and urbanization. The capacity of water storage of both soil and deeper subsurface layers may affect both the timing and magnitude of flood response to rainfall. A low storage potential often results in rapid and intensified flooding. High soil infiltration rates allow the bulk of precipitation to be absorbed by the soil surface reducing the potential for flooding, while low infiltration capacities encourage faster over-the-surface movement of water associated with rapid increases in channel flow. In cases where most precipitation infiltrates into the soil surfaces, flood response may be greatly modified by sub-surface transmissibility (Ward, 1978).

The channel network characteristics are often important in modifying the flood response of a catchment to precipitation. Large volumes of unconnected surface or depression storage areas can act as a storm reservoir system and can contribute to direct streamflow only when the necessary interconnections have been made by continued precipitation or by the creation of channel links. One of the most important of all flood-producing conditions is the percentage of the watershed that contributes to runoff and saturated surfaces within the catchment where the effective infiltration capacity is zero causing all falling precipitation to contribute directly to streamflow. During the early stage of precipitation, or at the end of a prolonged drought, these contributing or source areas may be restricted to the water surface of the channel network, but as precipitation continues the contributing area expands with consequent major increases in the volume of rapid runoff entering stream channels. Artificial drainage, such as furrowing often linked with deforestation or the under drainage of arable farmland, speeds the movement of water towards stream channels (Ward, 1978).

It is apparent that the passage of a floodwave down a channel will be faster in steep channels and slower in relatively flat channels, however variable channel characteristics, particularly channel roughness, greatly affects down stream velocity and magnitude of a floodwave. The channel roughness depends on factors such as bed and bank material, as well as channel shape and storage properties (Ward, 1978).

Chapter II - Research Procedures

The Integrated Flood Observation System (IFLOWS) is a network of raingages in the Appalachian region of the United States that are primarily utilized for monitoring heavy rainfall in real-time (IFLOWS 1993; Larson et al. 1995). A subset of this gage network covers a region of eastern Kentucky and this project initiated establishment of an archive of the complete set of rain gage data from the IFLOWS network for Kentucky. The primary objectives of the IFLOWS program does not focus on the utilization of the observed rainfall data for quantitative rainfall analysis. Due to this factor, regular archiving of the data by agencies is limited. Additionally, one of the primary goals of the IFLOWS program is the detection of heavy rainfall periods in real-time rather than the explicit definition of rainfall accumulations. The relatively high density of the gages and the geomorphic characteristics of the area provide both an opportunity and challenge for runoff estimation research. The region contains many small, steep-sloped watersheds that are inherently prone to flash-flooding and typically present a challenge when making runoff estimations. These two issues highlight the need for evaluation of the characteristics of heavy rainfall and evaluation of the potential for runoff and flood estimation using this data. Prior to utilization of IFLOWS data for such purposes, the data must be evaluated to determine the quality of the derived rainfall characteristics.

Development of a Flash-Flood Monitoring System for Eastern Kentucky

In the development of a flash-flood monitoring system for a given watershed or region, knowledge of the area and the available hydrological information relevant to flash flooding is necessary. In order to address this, the following information was either identified or collected:

1. description of study area including description of landforms, geology, soils, and landuse;

2. required components for a flash flood monitoring system; and 3. existing hydrological data components such rainfall and streamflow gage observations. A more detailed discussion of the above items follows. Portions of the following text follow closely from United States Geological Survey reports (USGS, 1982,1983).

Description of study area

Land Forms of Eastern Kentucky: Most of eastern Kentucky lies within the Appalachian physiographic province, which is divided into the Kanawha and Cumberland Plateau sections. A small fraction of eastern Kentucky lies within the Interior Low plateau and its known as the Knobs section. Most of eastern Kentucky can be characterized as a dissected plateau with narrow, crooked valleys and narrow irregular steep sided ridges primarily underlain by sandstones, siltstones, shales, and coals. The Knobs section of the Interior Low Plateau is characterized by conical hills that are separated by wide valleys or lowlands and are erosional remnants of the Cumberland Plateau section.

Geology: Five major rock units underlie eastern Kentucky. These rock units are subdivided into the Conemaugh, Breathitt, and Lee Formations of Pennsylvania age. Older rocks of Mississippian to Devonian age underlie these rocks. The youngest coal bearing rocks, which are of Pennsylvanian age, occur mainly in the northern part of eastern Kentucky. The Conemaugh Formation is about 500 feet in thickness and consists mostly of shale, siltstone, and sandstone. The shale and siltstone, of various shades of red, green, and gray, are commonly calcareous, and may contain thin beds of limestone. A few thin and discontinuous coal beds occur in the lower part of the Conemaugh

Formation.

The Breathitt Formation crops out extensively in eastern Kentucky. Its maximum thickness is about 3,500 feet and consists of sandstones, siltstone, shale, coal, ironstone, and some limestone. Individual sandstone beds range from 30 to 120 feet in thickness and commonly show rapid lateral changes in lithology. Many coal beds or coal zones are present in the formation with wide lateral extent, and range in thickness from less than 6 inches to as much as 19 feet. The coal beds are irregular in shape. Limestone is present as thin, discontinuous beds or as concretions, which commonly occur above coal beds.

The Lee Formation is generally overlain by the Breathitt Formation. The Lee Formation is, however, exposed in areas with larger and more deeply eroded valleys and in some of the areas of structural highs. The formation consists of conglomerate, sandstone, siltstone, calcareous shale, underclay, and coal and is characterized by massive beds of orthoquartzite that locally contains conglomerate lenses. In places, sandstones make up more than 80 percent of the formation. Pre-Pennsylvania rocks of Mississippian and Devonian age consist of shale, siltstone, limestone, and sandstone. These strata range in thickness from about 2,400 to 3,100 feet.

Land Use: Most of the land in eastern Kentucky is classified as deciduous forest and occupies about 82% of the area. The steep, hilly landscape is generally not suited for agriculture, industrial, or urban development. Land suitable for agriculture occurs in relatively small areas in narrow valleys or on narrow ridgetops. These areas are generally not suited for extensive cropping and the narrow valleys are often subjected to flash flooding. Barren land, which includes both active and orphaned mined areas, is about 2-4% of the area. An exception is Perry County, a principal coal producing county, where contour strip mines account for about 14% of the acreage. Pastures comprise about 5-7% of the land use.

Soils: Most of the soils in eastern Kentucky are deep, well-drained, acidic soils of the Jefferson-Shelocta, Lathan-Shelocta and Shelocta-Gilpin associations. These soils occupy steep slopes, narrow ridge tops, and flood plains. They are formed from residuum (weathering rock products) of sandstone, siltstone, and shale on slopes varying from 20 to 60 percent.

Hydrological Components Required for a Flash-Flood Monitoring System

Due to the adverse impacts caused by flash floods, there is an interest to develop reliable, real-time flood-monitoring systems that provide timely and accurate forecasts of flood events. An effective monitoring system involves the development of an integrated network of flood data acquisition elements and computer models. This will expedite the forecasting of basin-wide flood flows during a flood event (Lovell et al, 1993). The primary requirements of a flash-flood monitoring system are described in this section.

The complicated and diverse topography as well as the numerous land uses found in eastern Kentucky watersheds are often linked with different types of runoff responses due to heavy rainfall. Due to the spatial variability of rainfall and watershed geomorphological characteristics in eastern Kentucky, runoff models used in real-time flash-flood forecasting, must be calibrated using a system that captures this diversity (Okamoto, 1993).

A weather radar system complimented with a network of gages capable of estimating the spatial and temporal variation in rainfall is critical in determining the performance of a flash-flood monitoring system. A network of gages alone is a compromise between efficiency and economics because it is not practical to maintain a sufficient number of gages to provide a detailed description of the rainfall distribution (Curtis and Dotson, 1993).

Streamflow data can be used as real-time independent information to evaluate model performance. An effective network of streamflow gages allows monitoring of the changing relationship between streamflow magnitude and time within the watershed.

Landuse and soils distribution data must be readily available. This information is used in the selection of infiltration and runoff parameters for hydrologic modeling. Forecasting of flood events also depends on the understanding of antecedent soil conditions, hydrologic and hydraulic characteristics of streamflow channels as well as information on groundwater movement or baseflow.

Existing Hydrologic Components in Study Area

In the development of a flood monitoring system, the identification of existing hydrological components and knowledge of their performance is useful in the design of the system. The following section discusses existing rain and streamflow gages found in eastern Kentucky watersheds.

Rain Gage Network

Data from the National Weather Service (NWS) and the Soil Conservation Service (SCS) are the main source of precipitation information for engineering and hydrologic applications in most parts of the country, with eastern Kentucky being no exception. Currently, the National Weather service operates a network of fifteen recording raingages and fifty-one total depth gages in eastern Kentucky. Tables 1 and 2 below give the station index and other information for NWS recording and total depth gages respectively.

Most NWS gages have commonly been located near populated low elevation areas. As a result, precipitation data for the mountainous areas of eastern Kentucky is limited. Some engineering applications are not limited by this gage configuration since projects are often near populated areas (Redmond and Doesken, 1993).

Adequacy of Existing Rainfall Data Sources: The National Weather Service (NWS) continues to be the most important source of precipitation data for eastern Kentucky, because they provide long and readily available records.

TABLE 1. National Weather Service Continuous Recording Gages.

STATION	INDEX NO.	COUNTY	LATITUDE	LONGITUDE	ELEVATION (FT)
BARBOURVILLE	0381	KNOX	36 52	83 53	980
BAXTER	0450	HARLAN	36 51	83 20	1164
BEREA COLLEGE	0619	MADISON	37 34	84 18	1070
BUCKHORN LAKE	1080	PERRY	37 21	83 23	936
BURDINE 2 NE	1120	PIKE	37 13	82 35	1600
DAVELLA 1 SSW	2053	MARTIN	37 47	82 36	725
EASTERN KENTUCKY UNIVERSITY	2409	MADISON	37 45	84 20	1000
JACKSON WSO	4202	BREATHITT	37 36	83 19	1365
LOUISA 2 S	4946	LAWRENCE	38 06	82 36	650
META 4 SE	5370	PIKE	37 32	82 23	880
MOREHEAD 3 NW	5555	ROWAN	38 13	83 29	830
OLIVE HILL	6012	CARTER	38 18	83 11	880
SALYERSVILLE 1 W	7129	MAGOFFIN	37 45	83 05	910
SOMERSET 2 NE	7508	PULASKI	37 07	84 36	955
STAFFORDSVILLE 2 NW	7622	JOHNSON	37 51	82 52	760

Most NWS cooperative sites use unshielded gages and this, in general, results in under measurement of precipitation which varies with windspeed (Redmond and Doesken, 1993). While most data are 24-hour totals, not all time periods are consistent, and observation periods are either longer or shorter. In some cases, accumulated gage readings over several days are reported on a single day and may not be readily identified as such. This situation can lead to lower quality estimates of daily storm totals. Improper placement of decimal points has also occurred in some reports leading to similar adverse effects. One of the major issues related to any raingage network typically is the sparsity in space, and such is often the case in mountainous regions of eastern Kentucky. It is pertinent to note that the overall station density in mountainous areas is comparable to plain and plateau regions, but density in relation to precipitation gradient is extremely low. In other words, recorded rainfall data exhibit high spatial variability due to orographic factors, which is not adequately captured due to the sparsity of rainfall gages. This situation is addressed somewhat by the availability of hourly and finer resolution data from about one-third of NWS sites equipped with recording gages. Standard rain gages, which provide data on daily and monthly totals are more widely distributed but cannot be used for direct estimation of rainfall intensities at short time periods. Quite a number of users of precipitation information are usually interested in data at specific locations or at very small scales. In order to develop methods to interpolate or extrapolate to these locations, long-term consistent measurements from a spatially dense network such as the IFLOWS rain gage network, are needed to establish precipitation-elevation-aspect relations, especially where steep ground slopes exists (Redmond and Doesken, 1993).

Additional Rainfall Data Sources: The existing NWS rain gage networks in eastern Kentucky meets the needs of many users. Additionally, special operational and research needs have led to the establishment of a number of dense networks. These are for such purposes as municipal watershed management, irrigation scheduling, utilities, basic studies in hydrology and flood warning systems. One such program is the Integrated Flood Observing and Warning System (IFLOWS), which will be discussed in the following section. IFLOWS precipitation data compliments NWS data by

TABLE 2. National Weather Service Daily Total Precipitation Gages in Eastern Kentucky

STATION	INDEX NO.	COUNTY	LATITUDE*	LONGITUDE*	ELEVATION (ft)
ASHLAND	0254	BOYD	38 27	82 37	560
ASHLAND STATE POLICE	0268	BOYD	38 26	82 41	740
BARBOURVILLE	0381	KNOX	36 52	83 53	980
BAXTER	0450	HARLAN	36 51	83 20	1164
BIG CREEK	0687	CLAY	37 10	83 34	980
BLACKMONT	0700	BELL	36 47	83 31	1140
BUCKHORN LAKE	1080	PERRY	37 21	83 23	936
BURDINE 2 NE	1120	PIKE	37 13	82 35	1160
CLAY CITY 1 WNW	1576	POWELL	37 52	83 56	630
CLOSPLINT 4 ESE	1640	HARLAN	36 53	83 01	1800
CUMBERLAND 2	1965	HARLAN	36 58	82 59	1435
FEDSCREEK 1 SE	2812	PIKE	37 24	82 14	850
FISHTRAP LAKE	2825	PIKE	37 26	82 25	718
FRENCHBURG 2 W	3052	MENIFEE	37 57	83 40	920
GREY HAWK	3382	JACKSON	37 24	83 57	1250
GRAYSON 3 SW	3391	CARTER	38 17	82 58	700
GRAYSON LAKE	398	CARTER	38 14	82 59	715
HARLAN KSP POST 10	3629	HARLAN	36 49	83 19	1200
HAZARD STATE POLICE	3712	PERRY	37 16	83 12	960
HAZARD WATERWORKS	3714	PERRY	37 15	83 11	880
HAZEL GREEN 2 SW	3716	WOLFE	37 47	83 27	1010
HEIDELBERG	3741	LEE	37 33	83 46	665
HYDEN	4093	LESLIE	37 09	83 22	970
IVEL	4180	FLOYD	37 34	82 40	656
JACKSON WSO	4202	BREATHITT	37 36	83 19	1365
JEREMIAH 1 S	4255	LETCHER	37 09	82 56	1100
LLOYD GREENUP DAM	4848	GREENUP	38 39	82 52	537
LONDON FAA AIRPORT	4898	LAUREL	37 05	84 04	1188
LONDON STATE POLICE	4905	LAUREL	37 08	84 06	1215
LOUISA 2 S	4946	LAWRENCE	38 06	82 36	650
MANCHESTER 4 W	5111	CLAY	37 09	83 49	870
MARTIN 1 S	5175	FLOYD	37 33	82 46	630
META 4 SE	5370	PIKE	37 32	82 23	880
MENDACIOUSLY 3 NE	5524	WAYNE	36 52	84 50	979
MOREHEAD STATE POLICE	5559	ROWAN	38 11	83 28	760
MOUNT VERNON	5648	ROCKCASTLE	37 21	84 20	1160
NATURAL BRIDGE ST PK	5714	POWELL	37 47	83 41	950
ONEIDA	6028	CLAY	37 16	83 39	760
PAINTSVILLE 1 E	6136	JOHNSON	37 49	82 47	630
PHELPS 3 S	6216	PIKE	37 29	82 09	1135
PIKEVILLE NO 2	6355	PIKE	37 29	82 31	1060
PIKEVILLE KSP POST 9	6360	PIKE	37 32	82 35	670
PINE MOUNTAIN 3 NW	6379	HARLAN	36 59	83 13	1350
QUICKSAND	6624	BREATHITT	37 32	83 22	840
SALYERSVILLE NO 2	7134	MAGOFFIN	37 45	83 04	855
SKYLINE 1 SE	7431	LETCHER	37 04	82 58	1200
SLADE	7441	POWELL	37 51	83 41	707
SOMERSET 2 NE	7508	PULASKI	37 07	84 36	955
STEARNS 2 S	7677	MCCREARY	36 40	84 29	1220
VIRGIE	8348	PIKE	37 20	82 35	920
WEST LIBERTY	8551	MORGAN	37 55	83 16	830
WHEELERSBURG	8610	MAGOFFIN	37 49	83 01	880
WILLIAMSTOWN 3 NW	8824	GRANT	37 11	86 38	465

*Units in degrees and minutes

providing finer time resolution precipitation data and also by representing high elevation regions with more dense spatial coverage. When used in combination with NWS data, it is possible to map average seasonal and annual precipitation over most of the mountainous region of eastern Kentucky.

There is a growing interest in the use of models and modeling in recent years and this has led to an increased demand for accurate and timely precipitation data. Data from NWS networks continues to be a reliable source of long-term consistent precipitation data. Although specialized local data sources such as IFLOWS rainfall data offer potential to provide the types of detailed local information often required, data quality and continuity from these sources remains an issue. Remote sensing techniques that can adequately provide precipitation observations in mountainous regions such as eastern Kentucky holds promise for providing an improvement to the estimation of space time precipitation characteristics in this region. An attempt to improve the availability of data resources is to link together the many separate sources, as well as, raising and maintaining the level of performance and quality assurance of independent networks to meet engineering requirements.

Integrated Flood Observing and Warning System (IFLOWS)

The concept of the IFLOWS has developed extensively since the creation of the National Flash Flood Program Development Plan in 1978 by the National Weather Service (U.S. Department of Commerce, 1993). The aims of the IFLOWS program are to substantially reduce the annual loss of life from flash floods, reduce property damage, and reduce disruption of commerce and human activities. To develop IFLOWS, the National Weather Service (NWS) in conjunction with select states in Appalachia began a joint effort to improve flood warning capabilities in that region. To achieve the desired results in a timely manner, this program recognized the need to bring together essential state and county resources.

The NWS first began the development of a prototype IFLOWS system to use as a model for expansion into other areas. A 3-state, 12-county area along the borders of Virginia (VA), West Virginia (WV) and Kentucky (KY) was selected as a prototype due to the regional susceptibility to flooding, lack of existing flood warning system, and available communication circuits to tie this area together. The involvement of the three state governments also served to promote familiarity with new flood warning techniques and to encourage local coordination among the separate political jurisdictions.

The scope of the IFLOWS Program is geographically delineated by the cooperating states and participating counties within each state. The program is further defined by the equipment (sensors, telecommunication, computers, etc.), which constitutes each state network, and the Weather Service Offices, which are an integral part of the IFLOWS networks.

The Kentucky Program encompasses 38 counties (see Figure 2), 5 Weather Service Offices (located at Louisville, Lexington, Jackson, Covington and Paducah), a river forecasting center (RFC) in Cincinnati, Ohio, 37 county emergency operations centers, the state's Central Emergency Services Center, and 4 area operations centers. The Ohio Forecast Operations Center, located in Cincinnati, Ohio, supports the eastern Kentucky area. There are 161 radio reporting rain gages (RRRG) (see Table A1, Appendix A for a station index of these gages) and 34 terminals or microprocessor sites (30 state/county and 4 NWS). Table 3 lists the Kentucky counties with IFLOWS equipment maintained by the state.

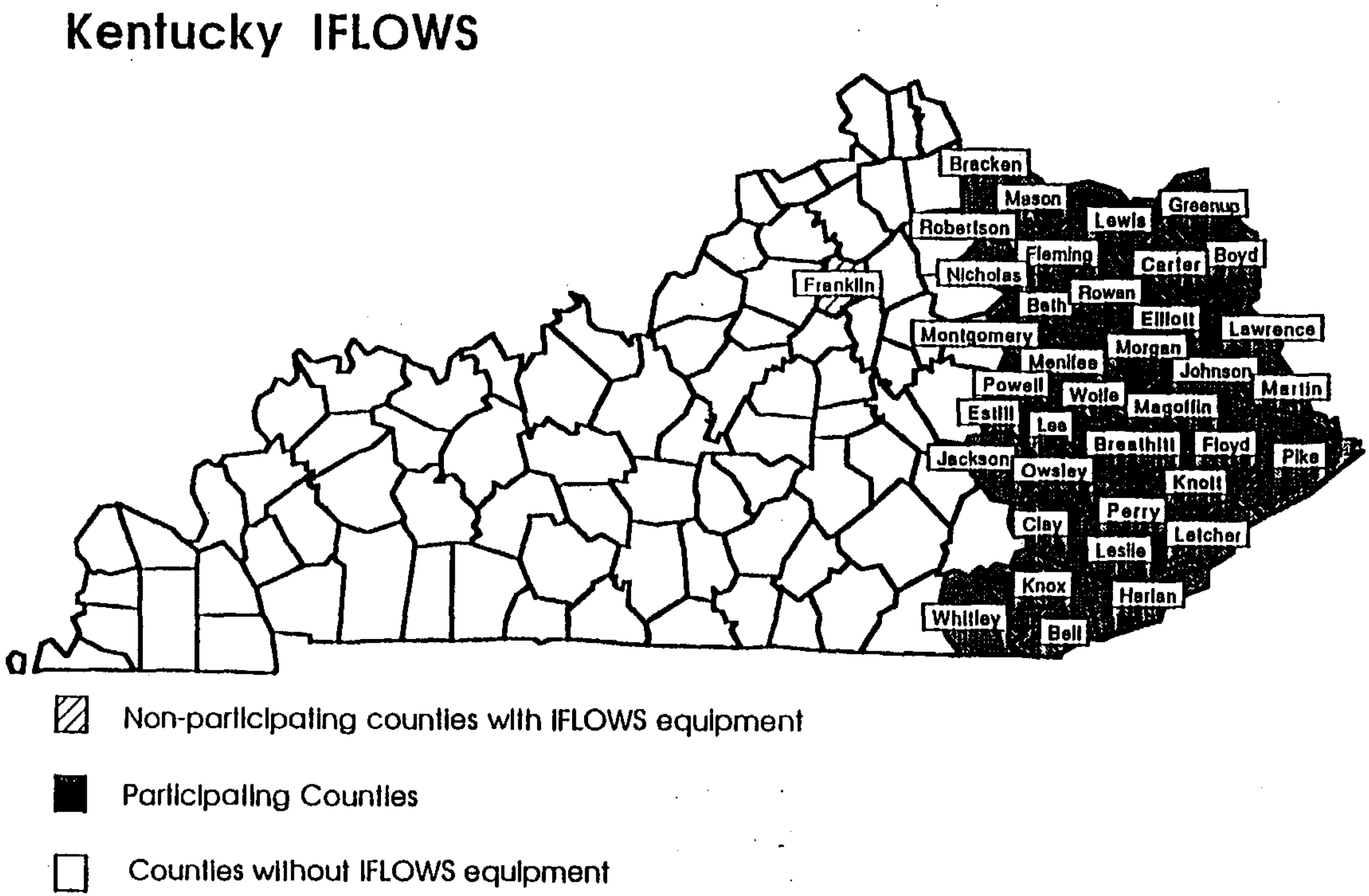


FIG. 2. Kentucky Counties Participating in the IFLOWS Program

TABLE 3. Kentucky Counties with IFLOWS Equipment

Harlan	Menifee	Montgomery
Bell	Jackson	Morgan
Boyd	Johnson	Nicholas
Bracken	Knott	Owsley
Breathitt	Knox	Perry
Carter	Lawrence	Pike
Clay	Lee	Powell
Elliot	Leslie	Robertson
Estill	Letcher	Rowan
Fleming	Lewis	Whitley
Floyd	Magoffin	Wolf
Franklin	Martin	

Rain Gage Network Size for Automated Flood Warning System: The performance of an automated flash-flood warning system such as IFLOWS is heavily dependent upon the system's ability to detect and measure rainfall. Accurate measurement of rainfall translates to better flood forecasts, leading to possible improvements in flood damage mitigation.

Typically a network of raingages is used to estimate the volumetric inflow of water into a basin in terms of mean areal rainfall. The estimate of mean areal rainfall generally improves with a larger number of gages in the network. However, the design of a network is usually a compromise between performance and economics (Curtis and Dotson, 1993).

IFLOWS Rainfall Data: Until recently (July 1994), a limited amount of rainfall under the IFLOWS program was archived. Part of the effort of this study is directed towards archiving and maintaining this rainfall database. Primarily, this data was not actively archived in the past because NWS networks such as IFLOWS assign a much lower value to data older than a few hours or a few days old.

Recent studies in hydrology have brought about an increased utilization of computer-based models for engineering systems and also the estimation of quantities, intensities, distributions and timing of precipitation. The development of such models, however, continues to depend on reliable precipitation data. In view of the above reasons, the program of archiving and evaluating IFLOWS rain data for quantitative runoff modeling is of interest, since it holds the potential of providing detailed spatial rainfall information as a compliment to existing NWS rainfall data. The raw IFLOWS rain data used in this work was received from the Louisville Office of the National Weather Service.

Existing Streamflow Gage Network in the Study Area

Streamflow-gaging stations in a network are often established primarily to provide information on current streamflow conditions at particular locations. This information is useful for water-management decisions concerning water supply or water-disposal monitoring. In a flash flood monitoring system streamflow data are used to evaluate the performance of rainfall/runoff models used in forecasting. For example, modeled hydrographs are compared to observed hydrographs during a flash flood event. Most watersheds, especially small ones (most likely to experience flash flooding), have only one streamflow gage located at the outlet. For flash flood monitoring purposes it is essential that more streamflow recording gages are located within the watershed to monitor the movement of runoff. Accurate measurement of streamflow magnitude is also essential for the calibration of hydrologic models and the design of engineering structures. Table A2 (Appendix A) shows a summary of streamflow recording gages and corresponding characteristics in eastern Kentucky (USGS, 1991).

A Review of Physically-Based Flash Flood Modeling Approaches Appropriate for Eastern Kentucky

The concerns raised by flash flooding have led to the development of a number of modeling approaches and other advanced technologies for monitoring and forecasting this hydrologic phenomenon. The ensuing text reviews some physically-based flash flood modeling approaches that could be investigated for future use in eastern Kentucky.

There are several broad classes of hydrologic modeling approaches. Two principal classes are physical or physics-based and conceptual models. Physical models "represent the system on a reduced scale" and the hydrologic processes within the system are represented mathematically using a "set of equations linking the input and output variables" (Chow et al, 1988). In contrast, conceptual models represent the hydrologic behavior of watersheds using an abstract representation of hydrologic response of watersheds to rainfall inputs. An example is the use of a cascade of linear reservoirs and channels to represent the rainfall-runoff process. Both these types of models can be either deterministic or stochastic depending on the randomness of the input and output. The use of physics-based models is often more appealing because of the direct mathematical representation of the primary processes involved in runoff production. However due to limited availability of high resolution spatial and temporal data to calibrate these models, conceptual models are often applied as an alternative.

It has been shown (Michaud and Sorooshian, 1994) that the scale used in modeling influences the quality of model results. The two principal modeling approaches mentioned above could either be used as a lumped or distributed model depending on the scale. The lumped approach spatially-averages watershed characteristics such as landuse, rainfall distribution, drainage etc. over relatively large areas, whiles the distributed approach identifies spatial variability in more detail. Studies remain inconclusive in defining an absolute quantitative link between the distributed modeling approach and improved flood forecasting results. Most flash-flood models use the latter approach, since the finer spatial scale implies an attempt to address the spatially distributed processes inherent in flash flood generation.

Another method that is becoming increasingly popular is the grid cell data bank that stores data generated by subdividing a watershed into a uniform grid. Watershed characteristics are included for each grid cell and coded into a data bank. One model that uses this approach is the two-dimensional watershed rainfall-runoff model, CASC2D (Julien and Sagafian, 1991). The grid approach is useful with Geographic Information System (GIS) environments and spatially distributed datasets. A description of several models used in flash flood forecasting are given below:

a) HEC1F Model: This is a modified version of the HEC-1 model (HEC, 1990) developed for use in real-time forecasting and flood control operations (U.S. Army Corps of Engineers, 1988). The HEC1F is a component of an on-line software system that includes capability for data acquisition and processing, precipitation analysis, streamflow forecasting analysis, and graphical display of data and simulation results (Pabst and Peters, 1983). HEC1F also has the capability to virtually model any network of elementary basins (Hydrologic Engineering Center, 1983).

b) HED71 Model: The rainfall-runoff simulation model, HED71, as described by Buer (1988), has been used extensively by the California Department of Water Resources (DWR) and the NWS River Forecast Center for headwater flood forecasting in northern California for decades. The model was designed to effectively model: 1) precipitation input - rain or snow, 2) losses due to evaporation, infiltration, detention, 3) effect of snow on the ground upon runoff, 4) surface runoff routing and, 5) groundwater flow. A unit hydrograph approach is used to convert surface runoff to streamflow. The input requirements for this model include, soil moisture antecedent index, initial baseflow, elevation-dependent specification of snowpack water equivalent, estimate of rain/snow level, and an estimate of mean basin precipitation in 6-hour increments to any reasonable time limit (Rhea and Hartzell, 1993).

c) Convective Storm/Precipitation Model (CPS) : This model is used to provide guidance for quantitative convection precipitation forecasts (QCPF) in the Denver Flash Flood Prediction Program (F2P2) which is funded by the Urban Drainage & Flash Flood Prediction Program (F2P2). Description of the model's application to QCPF in the F2P2 program have been reported (Henz and Kelly, 1988). The F2P2 is designed to provide a pre-storm (3 to 6 hour lead-time) estimate of potential time and space QCPF as it relates to local urban street and stream flooding for use in response and resource planning by local emergency response agencies. A flood detection network of over 136 automated rain gages, stream gages and weather stations are maintained to verify the occurrence of storm activity and assist in decision-making during flooding events. Once the thunderstorms form, basin specific estimates of storm-specific rainfall are issued to agencies which are affected by the storm (Henz, 1993).

d) Other Advanced Flash Flood Forecasting Techniques: There are also technological advances that aid in the identification and prediction of excessive rainfall that may lead to flash flooding. Two examples are the WSR-88D radar and atmospheric vertical wind profilers. The WSR-88D radar has the capabilities to keep forecasters up-to-date on current rainfall, projected rainfall totals, and areas likely to be flooded (LaPenta et al. 1995). The radar may overestimate precipitation in certain cases, however the advantages of this system far outweigh any limitations (Opitz et al, 1994). Willis et al. (1981) conducted a cost/benefit analysis study associated with the WSR-88D radar. The result of the study showed that the improved flash flood prediction and detection capabilities due to the implementation of this doppler radar network could prevent the loss of hundreds of lives as well as provide millions of dollars in savings resulting from the reduction in flood related damages.

Observing systems such as vertical wind profilers (Opitz et al, 1994) have proven to be useful in the analysis of mesoscale convective systems (MCSs), a weather system commonly associated with flash flood events. Vertical wind profilers will contribute to the understanding, detection, and prediction of excessive rainfall. In the future, profilers may provide clues for the prediction of the amount, type, and areal extent of precipitation.

Selection of Events for Flash Flood Characterization

Knowledge of past significant flooding events, recognition of the storm characteristics that led to these events, and careful analysis of observed data such as rainfall and streamflow discharge are important factors in understanding the flash flood characteristics. A part of this study attempts to characterize flash floods by an analysis of observed rainfall and runoff data. Selection of flood events for flash flood characterization involved the following: 1) selection of gaged watersheds without streamflow regulation; 2) selection of raingages; and 3) selection of flood events. Each of these components are described below.

Selection of Gaged Watersheds without Streamflow Regulation

Most gaged streams are affected to some extent by human activity, the most significant impacts are upstream reservoirs, upstream diversions for water use within the watershed, and interbasin transfer of water. The major task associated with this project was identification of stream gaging locations as free as possible from the effects of upstream diversions and storage in order that the streamflow data recorded at these sites represents natural flood conditions. An attempt was also made to select watersheds with an area less than 100 sq. miles. Such watersheds are usually drained by headwater streams and, therefore, are more likely to experience flash flooding due to steep slopes and minimum degree of storage capacity. Based on the above considerations, four watersheds were selected from eastern Kentucky, namely, (1) Johns Creek near Meta, (2) Tygarts Creek at Olive Hill, (3) North Fork Triplett Creek near Morehead, and (4) Cutshin Creek at Wooton.

Rain gage selection

To determine precipitation characteristics associated with the selected flood events, NWS recording and IFLOWS precipitation data are used, since the latter are available at a finer time resolution (which is desirable for the estimation of rainfall intensities associated with flash flooding). Daily total depth gages together with NWS recording gages can be used to define the spatial distribution of precipitation. For runoff modeling, IFLOWS precipitation data can provide an estimation of the spatial rainfall distribution while the hourly and daily recording gages provide the best quantitative rainfall estimates.

Summary of Streamflow and Watershed Characteristics

Tables 4 and 5 summarize the important characteristics of four watersheds and streams selected for the study and discussed in the previous section. The streamflow characteristics for the selected watersheds in Table 5 were extracted from Table A2 (Appendix A).

Discharge magnitude during flood events on natural streams in Kentucky varies over a large range. In eastern Kentucky, it is common for the discharge during the high flow periods (e.g. flash-flooding) to be a thousand times the discharge during low-flow periods. Although high flow periods occur only a few days in a year, the volume of runoff contributes to a major portion of the annual runoff.

TABLE 4. Watershed Characteristics

Station Number	Station Name	Main Channel Slope (ft/mi)	Shape factor	Sinuosity	Mean Discharge (cfs)	Main Channel Length (mi)	Percentage Forested (%)	Drainage Area (mi^2)
03210000	Johns Creek near Meta	24	3.095	1.629	54.067	21.5	82	56.3
03280700	Cutshin Creek at Hazel Green	45	2.800	1.405	84.500	18.4	93	61.3
03216800	Tygarts Creek at Olive Hill	19	1.386	1.320	87.543	12	56	59.6
03250100	North Fork Triplett Creek	16	1.644	1.568	72.445	18.5	83	84.7

TABLE 5. Streamflow Characteristics

Station Number	Station Name	Long-term mean streamflow discharge (ft^3/s)	Station Streamflow Recession index (days/log cycle)	Station Streamflow Variability index	7-day 2-year Low Flow (ft^3/s)	7-day 10-year Low Flow (ft^3/s)
03210000	Johns Creek near Meta	70.1	19	0.720	0.68	0
03280700	Cutshin Creek at Hazel Green	95.1	21	0.698	0.86	0.10
03216800	Tygarts Creek at Hazel Green	88.0	22	0.829	0.34	0.02
03250100	North Fork Triplett Creek	133.0	19	0.913	0.28	0

The following are definitions of the Watershed and Streamflow characteristics in Tables 5 and 6:

- Main-channel length, in feet per mile, is the length measured along the main stream channel from the gage to the basin divide, following the longest tributary.
- Main-channel slope, in feet per mile, is computed as the difference in elevation between points located at 10 and 85 percent of the main-channel length from the gage, divided by the stream length between these two points.
- Drainage area, in square miles, is the total drainage area excluding any parts characterized by internal drainage
- Forested area, is measured as a percentage of contributing drainage area.
- Streamflow recession index at a station is defined as the number of days it takes base streamflow to decrease one log cycle, or one order of magnitude, as determined graphically from hydrographs plots of daily mean streamflow during representative periods of streamflow recession.
- Stream flow variability index at a station is computed as the standard deviation of the logarithms of 19 discharges at 5-percent class intervals from 5 to 95 percent on the flow duration curve of daily mean streamflow for the entire period of record. Like the streamflow recession index, this streamflow index is a measure of basin capacity to sustain baseflow in a stream.
- 7-day 2-year low flow and 7-day 10-year low flow is commonly expressed as the minimum 7- day mean discharge with an average recurrence intervals of 2 and 10 years.

Selection of Flood Events for Hydrograph Analysis

The analysis of flood events prior to July 1994 was performed using only the rain gage data archived by the NWS exclusive of the IFLOWS precipitation gages. The National Weather Service provided the precipitation data from the IFLOWS network for select events that occurred after July 1994. The flood data were obtained from the USGS at a temporal resolution of either 30 minutes or 1 hour.

The following criteria were used in the selection of flood events:

1) Well-defined peak discharge, with hydrographs exhibiting a rapid rise in flood waters. A number of selected flood events had rising limbs with at least one vertical segment, indicating an instantaneous increase in discharge. Events with high peak streamflow discharges (> 2000 cfs) are

selected for the study. However, some moderate events are included for comparative purposes.

2) In order to evaluate the flood response of a watershed to precipitation inputs, it is desirable to have NWS or IFLOWS precipitation gages in the vicinity of the watershed outlet.

3) Flood events with at least one inch of precipitation recorded within 24 hours of the peak streamflow discharge are selected. Based on the above criteria, a total of thirty events were selected from the four watersheds. These events are shown in Table 6 given below.

TABLE 6. A list of Selected Flood Events With Corresponding Watershed and Streamflow Gage Number.

WATERSHED NAME	STREAMFLOW GAGE NUMBER	FLOOD DATE
Cutshin Creek at Wooton	03280700	12/23/90
Cutshin Creek at Wooton	03280700	03/23/93
Cutshin Creek at Wooton	03280700	12/28/90
Cutshin Creek at Wooton*	03280700	05/18/95
Johns Creek near Meta	03210000	12/02/91
Johns Creek near Meta	03210000	12/28/90
Johns Creek near Meta	03210000	12/23/92
Johns Creek near Meta	03210000	07/01/92
Johns Creek near Meta	03210000	03/04/93
Johns Creek near Meta	03210000	03/24/93
Johns Creek near Meta*	03210000	05/18/95
North Fork Triplett Creek near Morehead	03250100	04/26/93
North Fork Triplett Creek near Morehead	03250100	02/06/91
North Fork Triplett Creek near Morehead	03250100	02/14/91
North Fork Triplett Creek near Morehead	03250100	02/21/93
North Fork Triplett Creek near Morehead	03250100	01/21/93
North Fork Triplett Creek near Morehead	03250100	03/04/93
North Fork Triplett Creek near Morehead	03250100	03/17/93
North Fork Triplett Creek near Morehead	03250100	03/22/91
Tygarts Creek at Olive Hill	03216800	08/13/93
Tygarts Creek at Olive Hill	03216800	12/03/91
Tygarts Creek at Olive Hill	03216800	12/18/90
Tygarts Creek at Olive Hill	03216800	01/05/93
Tygarts Creek at Olive Hill	03216800	01/07/91
Tygarts Creek at Olive Hill	03216800	03/26/91
Tygarts Creek at Olive Hill	03216800	03/31/93
Tygarts Creek at Olive Hill	03216800	05/09/92
Tygarts Creek at Olive Hill*	03216800	05/18/95
Tygarts Creek at Olive Hill*	03216800	08/06/95
Tygarts Creek at Olive Hill*	03216800	06/12/95
*IFLOWS rainfall data available		

Chapter III - Data and Results

Characteristics of Rainfall Associated with Flash Flooding

Identification of the primary factors influencing heavy rainfall and flooding is one of the important issues concerning the National Weather Service (LaPenta et al. 1995). LaPenta et al. (1995) provide a series of direct statistics highlighting the need for knowledge concerning the character of flooding. This includes information such as the average number of persons killed each year by floods as 140, and the number forced from their homes as 300,000. Property damage from flooding averaged $3 billion per year in the early and mid 1980s (LaPenta et al. 1995). In general, states with more variable terrain experience more flooding. The reasons for this are associated with both the character of rainfall and the topography of the region. A series of guidelines provided by Lapenta et al. (1995) define the primary factors associated with flood and flash-flood producing rainfall in this region: (1) flood-producing events closely follow previous heavy rainfall; and (2) varied topography, typical of the Appalachian region, augments rainfall and the resulting runoff.

Three type of floods are outlined by LaPenta et al. (1995): (i) flash-floods, small stream and headwater floods; (ii) river floods; and (iii) coastal (or tidal) floods. This work focuses on the first type of floods, flash-floods, since these are the most common and devastating to the eastern Kentucky region. In order to understand and develop approaches for either mitigating or eliminating flood losses, a knowledge of the characteristics of significant rainfall events is important. This knowledge can indicate the time of occurrence of heavy rainfall over annual, seasonal, monthly, and daily time scales. Additionally, the spatial characteristics of rainfall provides a means of interpreting the spatial homogeneity of rain events and indirectly evaluating the potential for flash-flood producing rainfall. The information can then be used to develop or improve short-term forecasts and forecast models of heavy rainfall and runoff for flood prone regions. Additionally, the need for accurate and useful precipitation data is highlighted by ongoing improvements planned for the National Center for Environmental Prediction (NCEP) (McPherson 1994) and modernization efforts in the National Weather Service (NWS) River and Flood Program (Fread et al. 1995).

According to the American Meteorological Society (AMS) policy statement (AMS 1993) on flash floods there are several important issues that must be addressed in order to predict and mitigate loss of life and property damage due to flash-flooding. One element of the policy statement includes the need for defining the spatial distribution of soil moisture and development of predictive models for local rainfall. This work supports these issues by providing an investigation of the characteristics of local rainfall as derived from the IFLOWS rain gage network.

Due to the complex structure and dynamics associated with local rainfall and the wide spectrum of spatial and temporal scales involved, one promising area of development for rainfall analysis is based on statistical-dynamical approaches. In response to the need for developing such analyses, it is necessary to understand and quantify the primary statistical characteristics of rainfall in the region of interest. Providing an initial evaluation of these characteristics is one goal of this study; and is completed through utilization of the existing IFLOWS gage network for defining the spatial and temporal statistical characteristics of intense rainfall in the region. To meet this goal, the IFLOWS rainfall data were archived, objectively evaluated and summarized, compared with other rainfall resource for validation, and utilized for identification of the primary statistical characteristics of rainfall.

The primary issues addressed in this study include an analysis of the temporal distribution of rainfall on daily and monthly time scales. While IFLOWS data are available at a time resolution of up to 15 minutes (Larson et al. 1995), a longer time scale was used in this work in an effort to make an initial quantitative evaluation of the observed rainfall characteristics. In general, rainfall characteristics are more homogeneous when larger time and space scales are considered. Additionally, accumulations over daily and monthly time scales provides a more compatible approach for comparing IFLOWS rain accumulations with the regularly archived rainfall records maintained by the National Weather Service. In applications, the findings of this study can be used to develop guidelines for defining quantitative information on characteristics such as interstorm variability, spatial distribution of heavy rainfall, seasonal variability of rainfall, and average and extreme rainfall characteristics. This is the type of information necessary for constructing storm models and runoff models for hydrologic applications (Huff 1967).

According to Changnon and Vogel (1981), intense and localized severe rainstorms are the most frequent type of flash flood-producing events in the United States. This study provides an initial effort toward understanding these characteristics for rainfall in eastern Kentucky. Typically rain events that lead to flash-flooding or extreme floods go unobserved due to the low spatial density of rain gages in most areas. Mitigation of flood related losses requires an understanding of the typical conditions associated with these events. Three criteria proposed by Changnon and Vogel (1981) for defining a heavy rain storm are: (1) rainfall period is less than 48 hours over the gage network; (2) the maximum rainfall amount at one or more gages exceeds the 25-year recurrence interval; and (3) maximum 12-hour point amount equals or exceeds the 10-yr recurrence interval. While these criteria were developed specifically for central and south Illinois a similar type of criteria could be developed from the IFLOWS data for eastern Kentucky.

Typically such a study must be derived from a data set covering many years of record; this study initiated a data archive and is limited to a description of the characteristics of the one-year study period.

The results of this work include: spatially-averaged rainfall accumulations over daily and monthly time scales; temporal autocorrelation of daily-averaged rainfall; spatial correlation functions for seasonal and annual rainfall accumulations. The analysis identifies the primary characteristics of rainfall in this region and later may be used for evaluation of the appropriateness of the use of this precipitation data in more quantitative hydrologic applications.

The next section describes the analysis procedure used to evaluate the rainfall data collected from the Kentucky IFLOWS system for the period of study, July 1994 through June 1995. This twelve-month period is the first complete archive of a set of IFLOWS data from this gage network. The interpretation of the analysis follows in a section devoted to results and discussion.

Analysis of IFLOWS Rainfall Data

The data base utilized in this analysis consists of one year of IFLOWS rain gage records, July 1994 through June 1995, for all the gages in the Kentucky system. The network contains 161 gages providing observations with a depth resolution of 1 mm (0.04 inch) and time resolution of 15 minutes. Using the methods described by Hevesi et al. (1992a, b) and the rain accumulations from the IFLOWS network, a study of the principal statistical character of rainfall was conducted.

Few existing studies quantitatively define the accuracy of rainfall accumulations associated with the tipping bucket-type rain gage utilized in the IFLOWS system. The accuracy of this type of raingage may be compromised periodically due to several issues such as blockage of the gage inlet, wind effects, malfunction of the transmission device, and rainfall rates exceeding the gage capacity. In an attempt to overcome these issues in a simple way, the analysis conducted in this work was limited to gages with daily total accumulations greater than 2.5 mm (0.1 inch). A similar constraint was applied to monthly-averaged data where gages with a total accumulation less than 2.5 mm (0.1 inch) per month were excluded from the study. This criteria is assumed to introduce a negligible positive bias since the focus is on significant runoff producing rainfalls. Additionally, due to the spatial characteristics of rainfall accumulations most rain gages in the region are likely to receive a measurable amount of rainfall when large rain systems move through the region. Additionally, this guideline is similar to the criteria proposed by Cooper (1967) for establishing the characteristics of rainfall in a mountainous region of southwestern Idaho. The next section describes details about the flood events selected for inclusion in this study.

Analysis of Selected Flood Events

Selected flood events are used in an effort to characterize flash floods. Primarily, this section attempts to develop a procedure for characterizing flash flood severity by defining an index to each flood event based on several parameters which describe the shape of the flood hydrograph. This index, referred to as the 'flash flood index', R_F is used in characterizing and identifying flash floods from other flood events. Relevant precipitation characteristics associated with these flood events are also determined for the following reasons: (1) to determine the quantity, intensity, and temporal distribution of precipitation associated with these flash floods; (2) to objectively evaluate the severity of the flash flood as defined by the flash flood index R_F. A discussion of precipitation characteristics and the development of flash flood index, R_F, is given in the following sections.

Precipitation Characteristics of Selected Flood Events

Knowledge of precipitation characteristics can be used to develop or improve forecasts and forecast models of heavy rainfall and runoff for areas prone to flooding. As described earlier in Chapter 1, floods are caused or intensified by a number of factors such as antecedent moisture conditions and temporal and spatial variability of rainfall. With this in mind, a number of precipitation characteristics are identified from rainfall data as shown in Table 7. Following the table are definitions of these characteristics.

TABLE 7. A Summary of Rainfall Characteristics

Streamflow Gage	Flood Date	R_N	Q_P	P_{24}	P_{48}	P_{120}	I_M	I_A	T_D	T_H	S_I	S_A
Cutshin Creek at Wooton	12/23/90	151080	1770	1.62	1.63	3.88	0..52	0.11	30.00	1.00	4.61	0.50
Cutshin Creek at Wooton	03/23/93	151080	2910	1.17	1.17	1.30	0.28	0.12	13.50	10.00	2.39	0.74
Cutshin Creek at Wooton	12/28/90	151080	2370	1.51	1.51	3.66	0.40	0.20	13.00	5.00	2.04	0.62
Cutshin Creek at Wooton*	05/18/95	13169	7470	1.80	2.04	3.80	1.12	0.50	7.50	1.50	2.26	0.20
Johns Creek near Meta	12/02/91	155370	2230	2.60	3.50	3.90	1.20	0.11	11.00	2.00	4.00	0.38
Johns Creek near Meta	12/28/90	155370	1730	1.50	1.50	2.20	0.40	0.14	11.00	1.50	2.80	0.62
Johns Creek near Meta	12/23/92	155370	789	1.10	1.10	1.80	0.40	0.10	10.00	2.00	4.00	0.56
Johns Creek near Meta	07/01/92	155370	1800	2.20	3.30	4.50	1.20	0.26	9.00	1.50	4.62	0.25
Johns Creek near Meta	03/04/93	155370	1580	1.00	1.50	1.60	0.40	0.10	18.00	0.50	4.00	1.00
Johns Creek near Meta	03/24/93	155370	2010	1.30	1.30	1.50	0.40	0.08	6.50	1.50	5.19	0.92
Johns Creek near Meta*	05/18/95	13125	2580	1.28	1.68	2.60	0.48	0.26	8.50	4.50	1.85	0.38
North Fork Triplett Creek	04/26/93	155555	1830	1.00	1.40	1.40	0.40	0.20	4.00	1.00	2.00	0.17
North Fork Triplett Creek	02/06/91	155555	1620	0.80	1.00	1.00	0.40	0.06	10.00	2.50	6.35	0.63
North Fork Triplett Creek	02/14/91	155555	2680	1.10	1.10	1.10	0.40	0.12	5.50	1.50	3.33	0.10
North Fork Triplett Creek	02/21/93	155555	7680	1.60	1.60	1.70	0.40	0.22	11.50	5.50	1.84	0.33
North Fork Triplett Creek	01/21/93	155555	1360	1.00	1.00	1.00	0.80	0.53	1.00	1.00	1.51	1.00
North Fork Triplett Creek	03/04/93	155555	3610	1.00	1.10	1.10	0.40	0.06	16.00	0.50	6.40	0.86
North Fork Triplett Creek	03/17/93	155555	2690	0.50	1.00	1.00	0.40	0.07	10.50	0.50	5.48	0.77
North Fork Triplett Creek	03/22/91	155555	5230	2.00	2.20	2.60	0.40	0.25	3.00	1.50	1.60	0.25
Tygarts Creek at Olive Hill	08/13/93	155555	2090	3.50	3.50	3.90	1.20	0.22	16.00	3.00	5.45	0.20
Tygarts Creek at Olive Hill	12/03/91	156012	6000	3.49	4.06	4.40	1.24	0.15	24.00	5.00	8.35	0.79
Tygarts Creek at Olive Hill	12/18/90	156012	4310	2.50	2.74	3.59	0.84	0.08	37.00	9.00	11.05	0.64
Tygarts Creek at Olive Hill	01/05/93	156012	1670	0.70	1.00	1.00	0.40	0.12	6.00	3.00	3.43	0.33
Tygarts Creek at Olive Hill	01/07/91	156012	1040	0.77	1.00	0.94	0.12	0.05	18.00	18.00	2.67	0.69
Tygarts Creek at Olive Hill	03/26/91	156012	2020	1.02	1.02	3.88	0.52	0.17	6.00	3.00	3.09	0.55
Tygarts Creek at Olive Hill	03/31/93	156012	1880	0.90	1.00	1.20	0.40	0.13	6.50	2.00	3.08	0.27
Tygarts Creek at Olive Hill	05/09/92	156012	1080	0.90	1.50	1.80	0.40	0.06	14.00	1.00	7.02	0.46
Tygarts Creek at Olive Hill*	05/18/95	13028	2490	1.94	1.94	2.34	1.56	0.20	10.00	2.00	7.72	0.31
Tygarts Creek at Olive Hill*	08/06/95	13033	3090	3.20	3.20	3.85	1.12	0.25	15.00	5.00	4.51	0.13
Tygarts Creek at Olive Hill*	06/12/95	13033	1720	1.91	2.31	2.90	1.40	0.19	10.00	5.00	7.33	0.03
* IFLOWS rainfall data available												

P_{24} = Total rainfall 24 hours prior to occurrence of peak discharge (inches)
P_{48} = Total rainfall 48 hours prior to occurrence of peak discharge (inches)
P_{120} = Total rainfall 120 hours (5 days) prior to occurrence of peak discharge (inches)
I_A = Average rainfall intensity (in/hr)
I_M = Maximum rainfall intensity (in/hr)
S_I = Storm intensity ratio (ratio of maximum rainfall intensity to average rainfall intensity)
S_A = Storm advancement ratio (ratio of duration between start of storm and maximum rainfall intensity to total storm duration)

Q_P = Peak streamflow discharge (cfs)
T_D = Rainfall duration (hrs)
T_H = Duration of high intensity rainfall (hrs)
R_N = National Weather Service (NWS) or IFLOWS recording gage number

Development of Flash Flood Index (R_F)

During flash flooding, certain portions of the flood hydrograph, such as the rising limb, time to hydrograph peak, and magnitude of the peak are more important than others. To recognize this, parameters such as the rising curve gradient, k, flood magnitude ratio, M, and flash flood response time, T_P, are used to characterize flash floods. A discussion of these parameters is given in the ensuing section:

1. The Rising Curve Gradient (k)

The rising curve of the hydrograph can be described by an exponential equation of the general form:

$$Q_t = Q_o e^{kt} \tag{1}$$

where

Q_o = specified initial discharge,
Q_t = discharge at a later time t,
k = rising curve gradient (day^{-1})

Equations of this form are often used in engineering to describe first-order processes. Basically, the rising curve gradient is a measure of the steepness of the rising limb of the flood hydrograph. From the above equation, an increase in the rising curve gradient parameter k depicts an increase in the slope of the rising limb. Flash floods would be associated with large values of parameter k. For all the flood events analyzed in this study, computed values for the rising curve gradient, k, varied from 4 to 67 as shown in column 5 of Table 11.

Values of rising curve gradient, k, are then grouped into the class intervals shown in Table 8. Based on these class intervals each value is assigned a relative severity factor, R_K, ranging from 1 to 7. Table 12 shows the values of the factor R_K, as assigned to each of the flood events examined in the study. A high value of R_K indicates a steep rising curve as would be the case with flash flood events.

TABLE 8. Class Intervals for Rising Curve Index, k, and the corresponding Relative Severity Factors, R_K

Class Interval for k (1/day)	0-10	10-20	20-30	30-40	40-50	50-60	60-70
Number of events	12	10	6	1	0	0	1
Relative severity factor, R_K	1	2	3	4	5	6	7

2. The flood magnitude ratio (M)

This parameter is an indication of the order of magnitude by which the peak discharge during a flood event exceeds the average long-term streamflow discharge. The flood magnitude ratio, M, is defined as follows,

$$M=\frac{Q_{max}}{Q_o} \qquad (2)$$

where: Q_{max} = peak discharge (cfs)
Q_o = long-term streamflow discharge (cfs)

On many natural streams in eastern Kentucky, it is common for discharge during high-flow periods, especially during flash flooding, to be several orders of magnitude higher than either the flow associated with low-flow periods or the long-term average streamflow discharge. The flood magnitude ratio, M (the larger the value the more severe the flood), captures this aspect of streamflow variability and, hence, has a direct bearing on the severity of a flash flood event.

Computed values for the flood magnitude ratio for the selected flood events varied from 10 to 79 as shown in column 4 of Table 11. Each flood event is assigned a relative severity factor, R_M, ranging from 1 to 8 depending on the class interval shown in Table 9. Table 12 shows the values of relative severity factor, R_M, assigned to each of the flood events examined in the study.

TABLE 9. Class Intervals for Flood Magnitude Ratio, M, and corresponding Relative Severity Factors, R_M

Class Interval for M	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80
Number of events	0	9	12	5	1	1	1	1
Relative severity factor R_M	1	2	3	4	5	6	7	8

3. The flash flood response time (Tp)

The flash flood response time is measured directly from the hydrograph. The flash-flood response time is defined as the duration from the start of flood event to the point when peak flow is attained. A low flash flood response time is caused by high runoff velocities typical of flash flooding. In view of this, low values of flash flood response time are assigned higher relative severity factor, R_T. Values for flash flood response time varied from 4 to 21 hours as shown in Table 11, and each flood event is assigned a relative severity factor, R_T, ranging from 1 to 6 as shown in Table 10. Table 12 summarizes the values of relative severity factors assigned to each of the flood events examined in the study. The flash flood index, R_F, shown in the last column of Table 12, was obtained by summing the relative severity factors for the three parameters, namely, the rising curve gradient, k, the flood magnitude ratio,M, and the flash flood response time, T_P.

Table 13 shows flash flood index for the select flood events arranged in decreasing order of magnitude. The information in this table was derived from the data presented in Table 12. The arranged set of values emphasize the flash flood index magnitude as the discriminating variable rather than the watershed location used in Table 12.

Both the flash flood index and the primary characteristics of the rain event are summarized in Table 14. Additionally, Table 15 provides a summary of the hydrograph characteristics for the select flood events. This information was used to compare the depth of runoff to the average precipitation depth for each event.

A review of Table 16 shows the total recorded precipitation and the computed runoff depth. Differences between the two values are attributed to such factors as infiltration losses, evaporation, and surface storage. Two flood events, show a total recorded precipitation depth less than the runoff depth. This is attributed to the following: 1) the total recorded precipitation is not a correct representation of precipitation that fell on the watershed; 2) malfunctioning raingages may result in erroneous precipitation data; and 3) human errors in data collection.

Excess rainfall was computed by dividing the total volume under the hydrograph after base flow separation by the area of the watershed. Base flow was estimated as the location on the recession limb where streamflow discharge was about 10% of peak streamflow discharge. Calculation of excess rainfall is based on the assumption that rainfall is uniformly distributed throughout the watershed, which is not necessarily the case, especially with flash flooding, which may be caused by mesoscale convective storms. This assumption of uniform rainfall distribution may cause exceptionally low values of excess rainfall as exhibited by a number of flood events.

TABLE 10. Class Intervals for Flash Flood Response Time, T_P, and corresponding Relative Severity Factors, R_T

Class Interval for T_p	0-5	5-10	10-15	15-20	20-25	25-30
Number of events	2	16	8	1	2	1
Relative severity factor R_T	6	5	4	3	2	1

TABLE 11. Summary of Flash Flood Indexing Parameters.

Streamflow Gage	Event Date	Flood response time T_P (hour)	Flood Magnitude ratio M	Rising curve gradient k (day^{-1})
Cutshin Creek at Wooton	12/23/90	7.6	18.6	9.6
Cutshin Creek at Wooton	03/23/93	9.0	30.6	8.3
Cutshin Creek at Wooton	12/28/90	8.0	24.9	9.5
Cutshin Creek at Wooton*	05/18/95	9.0	78.6	40.0
Johns Creek at Meta	12/02/91	10.2	32.3	9.6
Johns Creek at Meta	12/28/90	10.7	25.0	12.0
Johns Creek at Meta	12/23/92	12.3	11.4	7.4
Johns Creek at Meta	07/01/92	7.7	26.1	20.2
Johns Creek at Meta	03/04/93	25.4	22.9	3.2
Johns Creek at Meta	03/24/93	13.4	29.1	9.2
Johns Creek at Meta*	05/18/95	9.0	37.3	8.5
North Fork at Triplett Creek	04/26/93	12.0	13.8	19.4
North Fork at Triplett Creek	02/06/91	20.1	12.2	4.0
North Fork at Triplett Creek	02/14/91	10.6	20.2	12.0
North Fork at Triplett Creek	02/21/93	8.0	57.7	23.7
North Fork at Triplett Creek	01/21/93	9.8	10.2	17.2
North Fork at Triplett Creek	03/04/93	21.0	27.1	4.6
North Fork at Triplett Creek	03/17/93	13.4	20.2	6.1
North Fork at Triplett Creek	03/22/91	6.0	39.3	67.0
Tygarts Creek at Olive Hill	08/13/93	8.6	23.8	29.0
Tygarts Creek at Olive Hill	12/03/91	8.5	68.2	19.0
Tygarts Creek at Olive Hill	12/18/90	10.0	49.0	12.3
Tygarts Creek at Olive Hill	01/05/93	4.2	19.0	27.6
Tygarts Creek at Olive Hill	01/07/91	19.9	11.8	9.2
Tygarts Creek at Olive Hill	03/26/91	5.1	23.0	20.2
Tygarts Creek at Olive Hill	03/31/93	9.0	21.4	13.8
Tygarts Creek at Olive Hill	05/09/92	12.0	12.3	5.6
Tygarts Creek at Olive Hill*	05/18/95	8.0	28.3	11.1
Tygarts Creek at Olive Hill*	08/06/95	5.0	35.1	27.5
Tygarts Creek at Olive Hill*	06/12/95	6.0	19.0	13.2
* IFLOWS rainfall data available				

TABLE 12. **A Summary of Relative Severity Index Assigned to each of the Flash Flood Indexing Parameters.**

Recording Gage	Date	R_T	R_M	R_K	R_F
Cutshin Creek at Wooton	12/23/90	5	2	1	8
Cutshin Creek at Wooton	03/23/93	5	4	1	10
Cutshin Creek at Wooton	12/28/90	5	3	1	9
Cutshin Creek at Wooton*	05/18/95	5	8	4	17
Johns Creek at Meta	12/02/91	4	4	1	9
Johns Creek at Meta	12/28/90	4	3	2	9
Johns Creek at Meta	12/23/92	4	2	1	7
Johns Creek at Meta	07/01/92	5	3	3	11
Johns Creek at Meta	03/04/93	1	3	1	5
Johns Creek at Meta	03/24/93	4	3	1	8
Johns Creek at Meta*	05/18/95	5	4	2	11
North Fork at Triplett Creek	04/26/93	4	2	2	8
North Fork at Triplett Creek	02/06/91	2	2	1	5
North Fork at Triplett Creek	02/14/91	4	3	2	9
North Fork at Triplett Creek	02/21/93	5	6	3	14
North Fork at Triplett Creek	01/21/93	5	2	2	9
North Fork at Triplett Creek	03/04/93	2	3	1	6
North Fork at Triplett Creek	03/17/93	4	3	1	8
North Fork at Triplett Creek	03/22/91	5	4	7	16
Tygarts Creek at Olive Hill	08/13/93	5	3	3	11
Tygarts Creek at Olive Hill	12/03/91	5	7	2	14
Tygarts Creek at Olive Hill	12/18/90	5	5	2	12
Tygarts Creek at Olive Hill	01/05/93	6	2	3	11
Tygarts Creek at Olive Hill	01/07/91	3	2	1	6
Tygarts Creek at Olive Hill	03/26/91	5	3	3	11
Tygarts Creek at Olive Hill	03/31/93	5	3	2	10
Tygarts Creek at Olive Hill	05/09/92	4	2	1	7
Tygarts Creek at Olive Hill*	05/18/95	5	3	2	10
Tygarts Creek at Olive Hill*	08/06/95	6	4	3	13
Tygarts Creek at Olive Hill*	06/12/95	5	2	2	9
* IFLOWS rainfall data available					

R_M = Flood Magnitude ratio Relative Severity Factor.
R_K = Rising Curve Gradient Relative Severity Factor.
R_T = Flash Flood Response Time Relative Severity Factor.
R_F = Index ($R_F=R_M+R_K+R_T$)

TABLE 13. Flash Flood Index Arranged in Decreasing Order of Magnitude.

Recording Gage	Flood Date (Event)	Flash Flood Index (R_F)
Cutshin Creek at Hazel Green	05/18/95	17
North Fork at Triplett Creek	03/22/91	16
North Fork at Triplett Creek	02/21/93	14
Tygarts Creek at Olive Hill	12/03/91	14
Tygarts Creek at Olive Hill	08/06/95	13
Tygarts Creek at Olive Hill	12/18/90	12
Tygarts Creek at Olive Hill	08/13/93	11
Tygarts Creek at Olive Hill	01/05/93	11
Johns Creek near Meta	07/01/92	11
Tygarts Creek at Olive Hill	03/26/91	11
Johns Creek near Meta	05/18/95	11
Tygarts Creek at Olive Hill	05/18/95	10
Tygarts Creek at Olive Hill	03/31/93	10
Cutshin Creek at Hazel Green	03/23/93	10
North Fork at Triplett Creek	02/14/91	9
North Fork Triplett Creek	01/21/93	9
Tygarts Creek at Olive Hill	06/12/95	9
Johns Creek near Meta	12/02/91	9
Johns Creek near Meta	12/28/90	9
Cutshin Creek at Hazel Green	12/28/90	9
North Fork Triplett Creek	04/26/93	8
Cutshin Creek at Hazel Green	12/23/90	8
North Fork Triplett Creek	03/17/93	8
Johns Creek near Meta	03/24/93	8
Tygarts Creek at Olive Hill	05/09/92	7
Johns Creek near Meta	12/23/92	7
Tygarts Creek at Olive Hill	01/07/91	6
North Fork Triplett Creek	03/04/93	6
North Fork Triplett Creek	02/06/91	5
Johns Creek near Meta	03/04/93	5

TABLE 14. A Summary of Flash flood Index and Precipitation Characteristics for Select Flood Events

Recording Gage	Flood Date (Event)	Flash Flood Index (R_L)	P_{24}	P_{48}	P_{120}	I_M	I_A	T_M	T_D	T_H	S_I	S_A
Cutshin Creek at Hazel Green*	05/18/95	17	1.80	2.04	3.80	1.12	0.50	2.00	2.50	1.50	2.26	0.20
North Fork at Triplett Creek	03/22/91	16	2.00	2.20	2.60	0.40	0.25	5.00	3.00	1.50	1.60	0.25
North Fork at Triplett Creek	02/21/93	14	1.60	1.60	1.70	0.40	0.22	6.50	6.00	5.50	1.84	0.33
Tygarts Creek at Olive Hill	12/03/91	14	3.50	4.06	4.40	1.24	0.15	5.00	23.50	5.00	8.35	0.79
Tygarts Creek at Olive Hill	08/06/95	13	3.20	3.20	3.85	1.12	0.25	6.25	14.00	5.00	4.50	0.13
Tygarts Creek at Olive Hill	12/18/90	12	2.50	2.74	3.59	0.84	0.08	6.00	36.00	9.00	11.00	0.64
Tygarts Creek at Olive Hill	08/13/93	11	3.50	3.50	3.90	1.20	0.22	13.00	15.00	3.00	5.45	0.20
Tygarts Creek at Olive Hill	01/05/93	11	0.70	1.00	1.00	0.40	0.12	5.00	6.00	3.00	3.43	0.33
Johns Creek near Meta	07/01/92	11	2.20	3.30	4.50	1.20	0.26	3.50	9.00	1.50	4.62	0.25
Tygarts Creek at Olive Hill	03/26/91	11	1.02	1.02	3.88	0.52	0.17	3.25	5.00	3.00	3.09	0.55
Johns Creek near Meta*	05/18/95	11	1.28	1.68	2.60	0.48	0.26	5.50	8.00	4.50	1.85	0.38
Tygarts Creek at Olive Hill	03/31/93	10	0.90	1.00	1.20	0.40	0.13	5.00	6.50	2.00	3.08	0.27
Tygarts Creek at Olive Hill*	05/18/95	10	1.94	1.94	2.34	1.56	0.20	3.25	9.00	2.00	7.72	0.31
Cutshin Creek at Hazel Green	03/23/93	10	1.17	1.17	1.30	0.28	0.12	4.50	13.00	10.00	2.39	0.74
North Fork Triplett Creek	01/21/93	9	1.00	1.00	1.00	0.80	0.53	5.75	1.00	1.00	1.51	1.00
North Fork at Triplett Creek	02/14/91	9	1.10	1.10	1.10	0.40	0.22	6.50	5.00	1.50	1.84	0.33
Johns Creek near Meta	12/28/90	9	1.50	1.50	2.20	0.40	0.10	9.00	10.50	1.50	4.00	0.56
Tygarts Creek at Olive Hill	06/12/95	9	1.91	2.31	2.90	1.40	0.19	4.75	9.00	5.00	7.33	0.03
Johns Creek near Meta	12/02/91	9	2.60	3.50	3.90	1.20	0.11	8.50	8.50	2.00	4.00	0.38
Cutshin Creek at Hazel Green	12/28/90	9	1.51	1.51	3.66	0.40	0.20	4.75	12.50	5.00	2.04	0.62
Tygarts Creek at Olive Hill	05/09/92	7	0.90	1.50	1.80	0.40	0.06	7.00	13.00	1.00	7.02	0.46
North Fork Triplett Creek	04/26/93	8	1.00	1.40	1.40	0.40	0.20	1.75	3.50	1.00	2.00	0.17
Johns Creek near Meta	03/24/93	8	1.30	1.30	1.50	0.40	0.08	6.50	6.00	1.50	5.19	0.92
North Fork Triplett Creek	03/17/93	8	0.50	1.00	1.00	0.40	0.07	6.25	10.00	0.50	5.48	0.77
Cutshin Creek at Hazel Green	12/23/90	8	1.62	1.63	3.88	0.52	0.11	2.25	24.50	1.00	4.61	0.50
Johns Creek near Meta	12/23/92	7	1.10	1.10	1.80	0.40	0.10	9.00	9.00	2.00	4.00	0.56
Tygarts Creek at Olive Hill	01/07/91	6	0.77	1.00	0.94	0.12	0.05	20.00	17.00	18.00	2.67	0.69
North Fork Triplett Creek	03/04/93	6	1.00	1.10	1.10	0.40	0.06	4.25	16.00	0.50	6.40	0.86
Johns Creek near Meta	03/04/93	5	1.00	1.50	1.60	0.40	0.10	3.00	17.50	0.50	4.00	1.00
North Fork Triplett Creek	02/06/91	5	0.80	1.00	1.00	0.40	0.06	4.50	9.50	2.50	3.33	0.10

* Flash flood event

TABLE 15. Summary of Hydrograph Characteristics for Select Flood Events

Recording Gage	Date	Volume prior to peak discharge, V_P (ft^3)	Total Volume, V_T(ft^3)	Time base of Hydrograph (hr)	V_P/V_T
Cutshin Creek at Wooton	12/23/90	15,610,909.09	133,134,545.50	72	0.117
Cutshin Creek at Wooton	03/23/93	30,300,000.00	102,500,000.00	39	0.296
Cutshin Creek at Wooton	12/28/90	33,345,000.00	106,987,500.00	42	0.312
Cutshin Creek at Wooton*	05/18/95	63,874,285.00	200,571,428.60	45	0.318
Johns Creek at Meta	12/02/91	32,207,142.86	155,442,857.10	57	0.207
Johns Creek at Meta	12/28/90	28,963,636.36	106,232,727.30	54	0.273
Johns Creek at Meta	12/23/92	16,339,764.70	52,754,823.53	60	0.310
Johns Creek at Meta	07/01/92	32,150,769.23	91,218,461.54	48	0.352
Johns Creek at Meta	03/04/93	50,544,000.00	149,616,000.00	90	0.338
Johns Creek at Meta	03/24/93	34,020,000.00	139,455,000.00	75	0.244
Johns Creek at Meta*	05/18/95	58,959,183.67	146,240,816.30	60	0.403
North Fork at Triplett Creek	04/26/93	30,780,000.00	131,355,000.00	78	0.234
North Fork at Triplett Creek	02/06/91	42,768,000.00	155,952,000.00	123	0.274
North Fork at Triplett Creek	02/14/91	53,335,384.63	163,329,230.80	63	0.326
North Fork at Triplett Creek	02/21/93	116,168,067.20	415,663,865.50	72	0.280
North Fork at Triplett Creek	01/21/93	21,435,428.57	77,389,714.29	63	0.277
North Fork at Triplett Creek	03/04/93	78,141,176.47	209,488,235.30	60	0.373
North Fork at Triplett Creek	03/17/93	55,944,000.00	177,552,000.00	75	0.315
North Fork at Triplett Creek	03/22/91	122,194,285.70	449,691,428.60	66	0.272
Tygarts Creek at Olive Hill	08/13/93	28,512,000.00	82,368,000.00	66	0.362
Tygarts Creek at Olive Hill	12/03/91	86,940,000.00	186,570,000.00	36	0.466
Tygarts Creek at Olive Hill	12/18/90	78,975,000.00	263,250,000.00	54	0.300
Tygarts Creek at Olive Hill	01/05/93	9,720,000.00	61,965,000.00	51	0.157
Tygarts Creek at Olive Hill	01/07/91	32,227,200.00	73,958,400.00	81	0.436
Tygarts Creek at Olive Hill	03/26/91	9,553,846.15	44,134,615.38	30	0.216
Tygarts Creek at Olive Hill	03/31/93	15,255,000.00	103,815,000.00	93	0.147
Tygarts Creek at Olive Hill	05/09/92	18,596,521.43	41,307,428.57	78	0.450
Tygarts Creek at Olive Hill*	05/18/95	47,267,532.47	226,940,259.70	61	0.208
Tygarts Creek at Olive Hill*	08/06/95	30,621,176.47	95,548,235.29	33	0.320
Tygarts Creek at Olive Hill*	06/12/95	16,517,647.06	69,156,302.52	51	0.239
*IFLOWS rainfall data available					

TABLE 16. Flash flood Index and Corresponding Hydrograph Characteristics for Select Flood Events.

Recording Gage	Flood Date (Event)	Flash Flood Index (R_F)	T_P	T_B	T_P/T_B	V_P/V_T	r_d	P	Q_P/P
Cutshin Creek at Wooton*	05/18/95	17	9.0	45	0.20	0.32	1.41	2.12	5302.30
North Fork at Triplett Creek	03/22/91	16	6.0	66	0.09	0.27	2.29	2.20	2288.44
North Fork at Triplett Creek	02/21/93	14	8.0	72	0.11	0.28	2.11	2.00	3634.30
Tygarts Creek at Olive Hill	12/03/91	14	8.5	36	0.24	0.47	1.35	3.53	4451.70
Tygarts Creek at Olive Hill	08/06/95	13	5.0	33	0.15	0.32	0.69	3.48	4478.26
Tygarts Creek at Olive Hill	12/18/90	12	10.0	54	0.19	0.30	1.90	2.74	2266.04
Tygarts Creek at Olive Hill	08/13/93	11	8.6	66	0.13	0.36	0.60	3.50	3512.60
Tygarts Creek at Olive Hill	01/05/93	11	4.2	51	0.08	0.16	0.45	0.80	3731.01
Johns Creek near Meta	07/01/92	11	7.7	48	0.16	0.35	0.70	2.30	2586.21
Johns Creek near Meta*	05/18/95	11	9.0	60	0.15	0.40	1.12	1.68	2306.87
Tygarts Creek at Olive Hill	03/26/91	11	5.1	30	0.17	0.22	0.32	1.01	6335.47
Tygarts Creek at Olive Hill*	05/18/95	10	8.0	61	0.13	0.21	1.64	2.94	1519.03
Tygarts Creek at Olive Hill	03/31/93	10	9.0	93	0.10	0.15	0.75	1.00	2506.67
Cutshin Creek at Hazel Green	03/23/93	10	9.0	39	0.23	0.30	0.72	1.23	4041.67
North Fork at Triplett Creek	02/14/91	9	10.6	63	0.17	0.33	0.83	1.20	3236.71
North Fork Triplett Creek	01/21/93	9	9.8	63	0.15	0.28	0.39	1.00	3446.53
Cutshin Creek at Hazel Green	12/28/90	9	8.0	42	0.19	0.31	0.75	1.51	3154.95
Tygarts Creek at Olive Hill	06/12/95	9	6.0	51	0.12	0.24	0.50	2.63	3443.03
Johns Creek near Meta	12/02/91	9	10.2	57	0.18	0.21	1.19	4.10	1877.10
Johns Creek near Meta	12/28/90	9	10.7	54	0.20	0.27	0.81	1.50	2129.49
Cutshin Creek at Hazel Green	12/23/90	8	7.6	72	0.11	0.12	0.93	2.55	1893.45
North Fork Triplett Creek	04/26/93	8	12.0	78	0.15	0.23	0.67	1.50	2742.81
North Fork Triplett Creek	03/17/93	8	13.4	75	0.79	0.32	0.90	0.50	2971.72
Johns Creek near Meta	03/24/93	8	13.4	75	0.18	0.24	1.07	1.90	1886.90
Tygarts Creek at Olive Hill	05/09/92	7	12.0	78	0.15	0.45	0.30	1.60	3618.82
Johns Creek near Meta	12/23/92	7	12.3	60	0.21	0.31	0.40	1.10	1955.68
North Fork Triplett Creek	03/04/93	6	21.0	60	0.35	0.37	1.06	1.40	3391.58
Tygarts Creek at Olive Hill	01/07/91	6	19.9	81	0.25	0.44	0.53	0.94	1947.56
North Fork Triplett Creek	02/06/91	5	20.1	123	0.16	0.27	0.79	0.90	2045.45
Johns Creek near Meta	03/04/93	5	25.4	90	0.28	0.34	1.14	1.80	1380.88
* Flash flood event									

T_P = Duration from start of flood event to peak discharge (hr)
T_B = Time base of flood event (hr)
V_P = Volume to peak discharge (ft^3)
V_T = Total Volume under Hydrograph (ft^3)
r_d = Total Volume of runoff expressed in inches { V_T/(Area of watershed)}
P = Total rainfall recorded during flood event (inches)

Chapter IV - Discussion of Results

The first part of this chapter discusses the spatial and temporal characteristics of rainfall in eastern Kentucky as recorded by IFLOWS raingages for the period July 1994 to June 1995. Following the description of the rainfall analysis is a discussion of flash flood characterization and specific precipitation characteristics associated with the selected flood events. In addition, the relationship between the formulated Flash Flood Index, R_F, and the indexing parameters k, M, T_P, as well as the relationship between R_F, and precipitation characteristics as defined in the previous chapter are examined. Characterization of flash flooding in previous studies was done primarily by considering climatological factors. In this study, an attempt was made to characterize flash floods by studying the rate of change of streamflow discharge with time. To carry out this analysis, thirty flood events (flash floods) are selected from four watersheds in eastern Kentucky. Flood events are selected from unregulated watersheds, with the view that flow data recorded at these sites can be used for rainfall-runoff modeling. These watersheds are Cutshin Creek at Wooton, Johns Creek near Meta, North Forth Triplett Creek near Morehead, and Tygarts Creek at Olive Hill.

Precipitation

Figure 3 shows the initial time series of daily averaged rainfall depth (inches) for the year, July 1, 1994 through June 30, 1995. The day of the year is on the horizontal axis with day 1 corresponding to July 1, 1994 and day 365 corresponding to June 30, 1995. This figure shows a high variability in daily rainfall depths with a few trends evident. Greater daily rainfall depths are generally associated with the latter 6 months of record. The five largest daily accumulations occurred in this period. Additionally, note that there were fewer days with zero rainfall in the latter half of the record.

Figure 4 is a companion to Figure 3 and shows two characteristics of the IFLOWS gage data. The upper portion of Figure 4 repeats the data shown in Figure 3 and adds the maximum daily rainfall depth (inches) recorded at any gage in the network. This figure is useful for defining extreme rainfall periods associated with eastern Kentucky; the maximum daily rainfall accumulations correspond well with the average maximums, the highest magnitudes occur in the spring months of April, May, and June (days 270-365). The lower portion of Figure 4 shows the number of gages reporting rainfall depths exceeding the criteria stated earlier (>1 mm per day).

Figure 5 presents the daily-averaged rainfall depth for the year again for reference in the upper portion of the figure; the lower portion of Figure 5 is the temporal autocorrelation of average daily rainfall depth. This correlation is plotted versus the lag in days; a high temporal correlation would indicate a linear dependence of rainfall depth on any one day to the rainfall depth on one of the following days (the number of days following the initial day is equivalent to the lag magnitude). The lag-one (one-day) correlation of rainfall is shown to be equal to about 0.25, or which is less than the decorrelation magnitude typically defined as 1/e. This indicates that there is little linear dependence in the daily rainfall totals.

Figure 6 presents a time series of monthly-averaged rainfall depths in the upper portion of the figure, and includes three lines showing the average, minimum, and maximum depth for each month. This figure shows a peak season for rainfall in April and May 1995; and smaller peaks in July 1994, January and June 1995. In general, lower rainfall depths are associated with the fall and winter months. This trend agrees in general with the climatic character of rainfall distribution for this region. The lower portion of Figure 6 show the number of gages in each month that exceed the precipitation depth criteria described earlier.

The remaining results present with the spatial correlation function for rainfall depths averaged over both annual and seasonal time scales. The spatial correlation function is an indication of the homogeneity of the rainfall field in the spatial domain and can be used to assess rainfall variability across the region. In each case the correlation function was computed using three different range resolutions: 2 km, 4 km, and 8 km. This range resolution defines the incremental distance range between a particular gage and neighboring gages which are included in the estimation of the correlation coefficient. For example, with a range resolution of 4 km, the correlation coefficient between a particular gage and other gages located within 4 km increments from the gage is estimated. This implies a correlation coefficient for each 4 km distance increment from any particular gage. In figure 7 the annual total rainfall depths at all 161 IFLOWS gages were used in the estimation of the spatial correlation function. The results are shown in the upper portion of the figure, where the circle symbols mark the magnitude of the correlation using a 2 km spatial increment, the square symbols show the correlation using a 4 km resolution, and the diamond symbol indicates correlation based on an 8 km resolution. The results are relatively consistent with one another; the solid line is simply a smooth line drawn through the 8 km resolution correlation values. The solid line was added to provide a visualization of the trend in the computed values. The correlation function derived from the annual rainfall totals shows the expected decay with distance and a decorrelation distance of about 8 km. The correlation decreases to near zero for distances greater than about 14 km. The number of gages available for estimation of the correlation coefficient at any given distance is shown in the lower portion of Figure 7. In an effort to understand the seasonal spatial variability of rainfall, the spatial correlation function was derived for the summer, fall, winter, and spring seasons. The seasons are defined in the following manner: summer: June 1995, July, August 1994; fall: September, October, November 1994; winter: December 1994, January, February 1995; spring: March, April, May 1995. These results were derived in a manner similar to that described above for the annual rainfall spatial correlation function. Figures 8, 9, 10, and 11 present results following the same format used in Figure 7. The summer season results are presented in Figure 8 and are consistent with the annual spatial correlation function; the primary difference is a slightly greater rate of decrease in the correlation magnitude. The summer decorrelation distance is about 6 km, and tends to remain positive in magnitude up to a distance of about 45 km. This result is consistent with the typical summer season rainfall characteristics associated with a dominance of localized convective rainfall systems. There is also a slight increase in correlation detected at a distance of about 25-35 km. This increase may represent a qualitative measure of the mean distance between raincells imbedded in meso-scale rain storm systems in this region. The number of data values available for the computation of each correlation coefficient is shown in the lower portion of Figure 8.

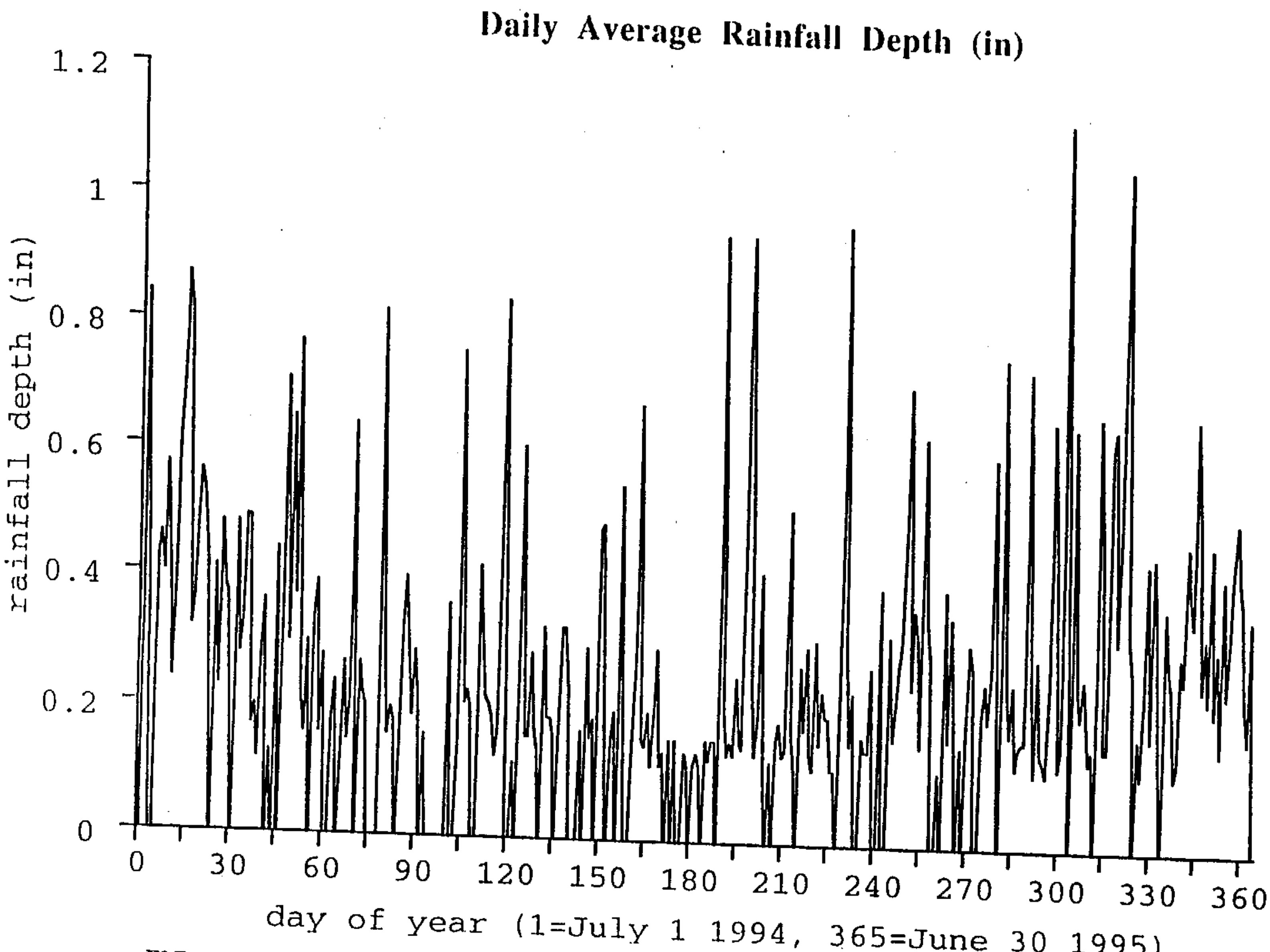
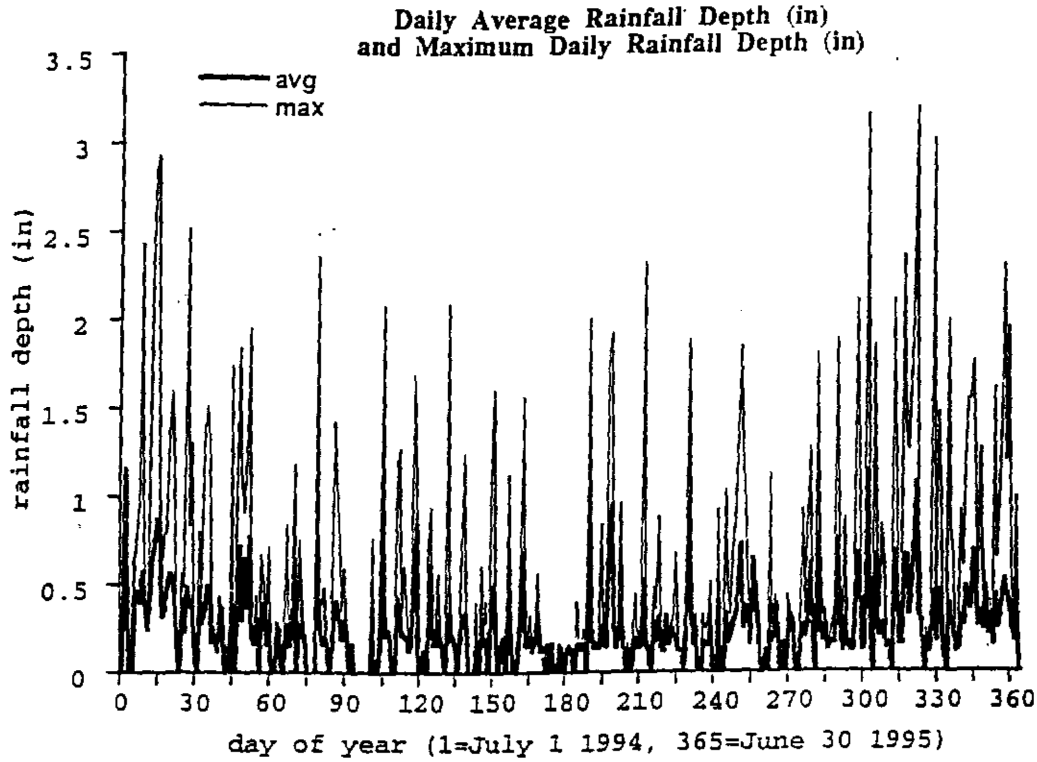


FIG. 3. Time Series of Daily Averaged Rainfall Depth (inches) for the Year, July 1, 1994 through June 30, 1995



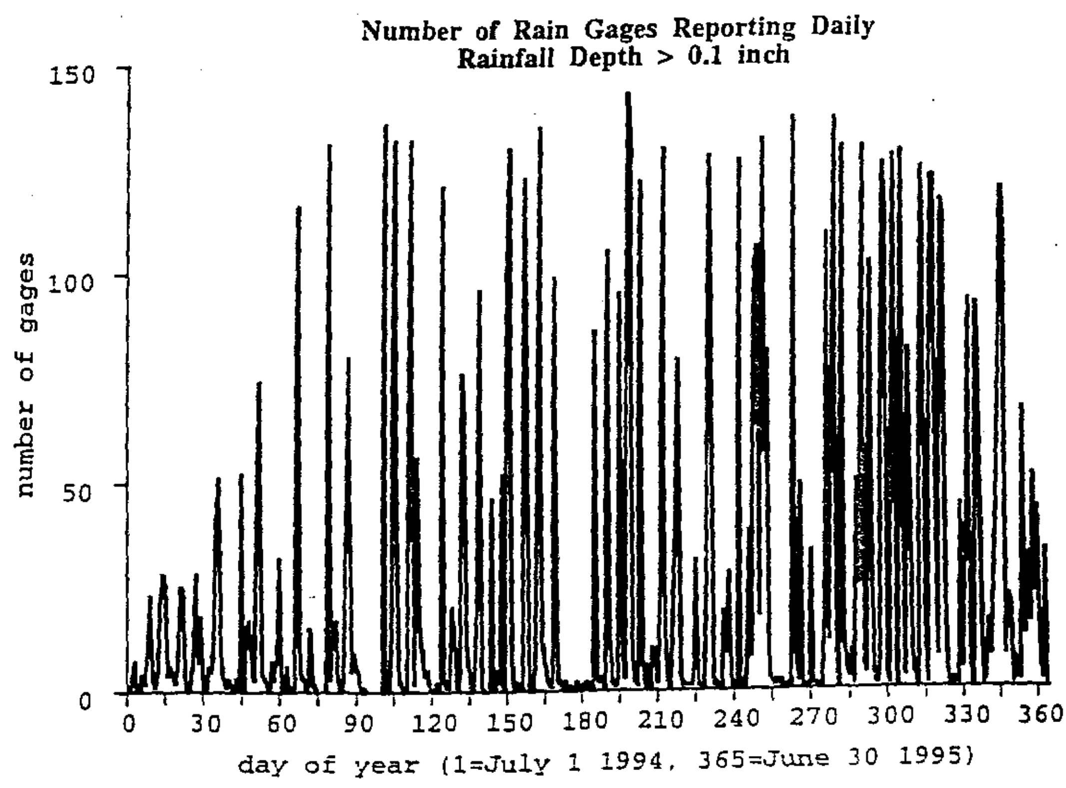


FIG. 4. Time Series of Daily Averaged Rainfall Depth and Maximum Daily Rainfall Depth recorded at any Gage in the Network (inches) for the Year, July 1, 1994 through June 30, 1995.

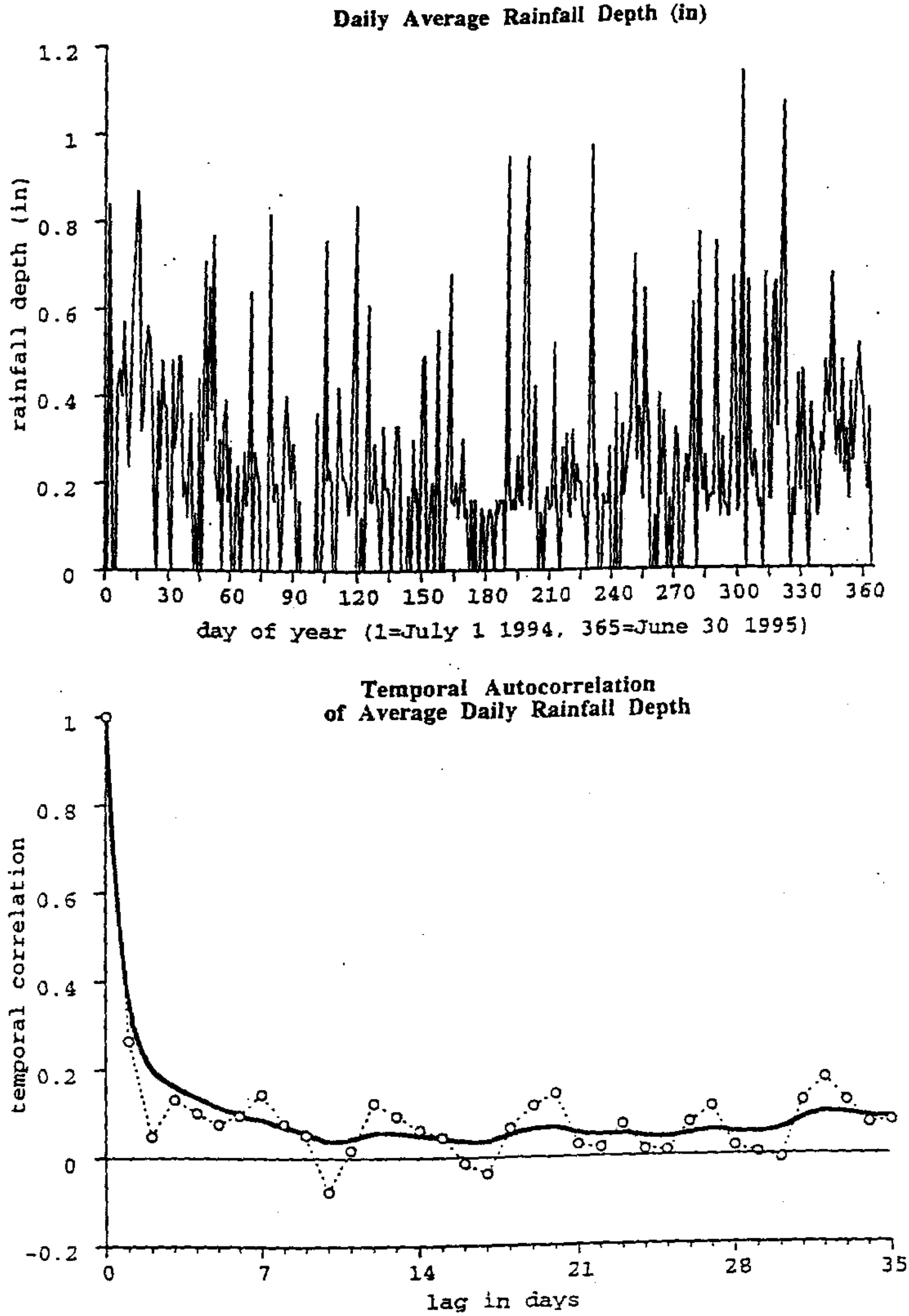


FIG. 5. Time Series of Daily Averaged Rainfall Depth (inches) for the, July 1, 1994 through June 30, 1995. The lower portion of Figure 6 shows the Temporal Autocorrelation of the Averaged Daily Rainfall Depth.

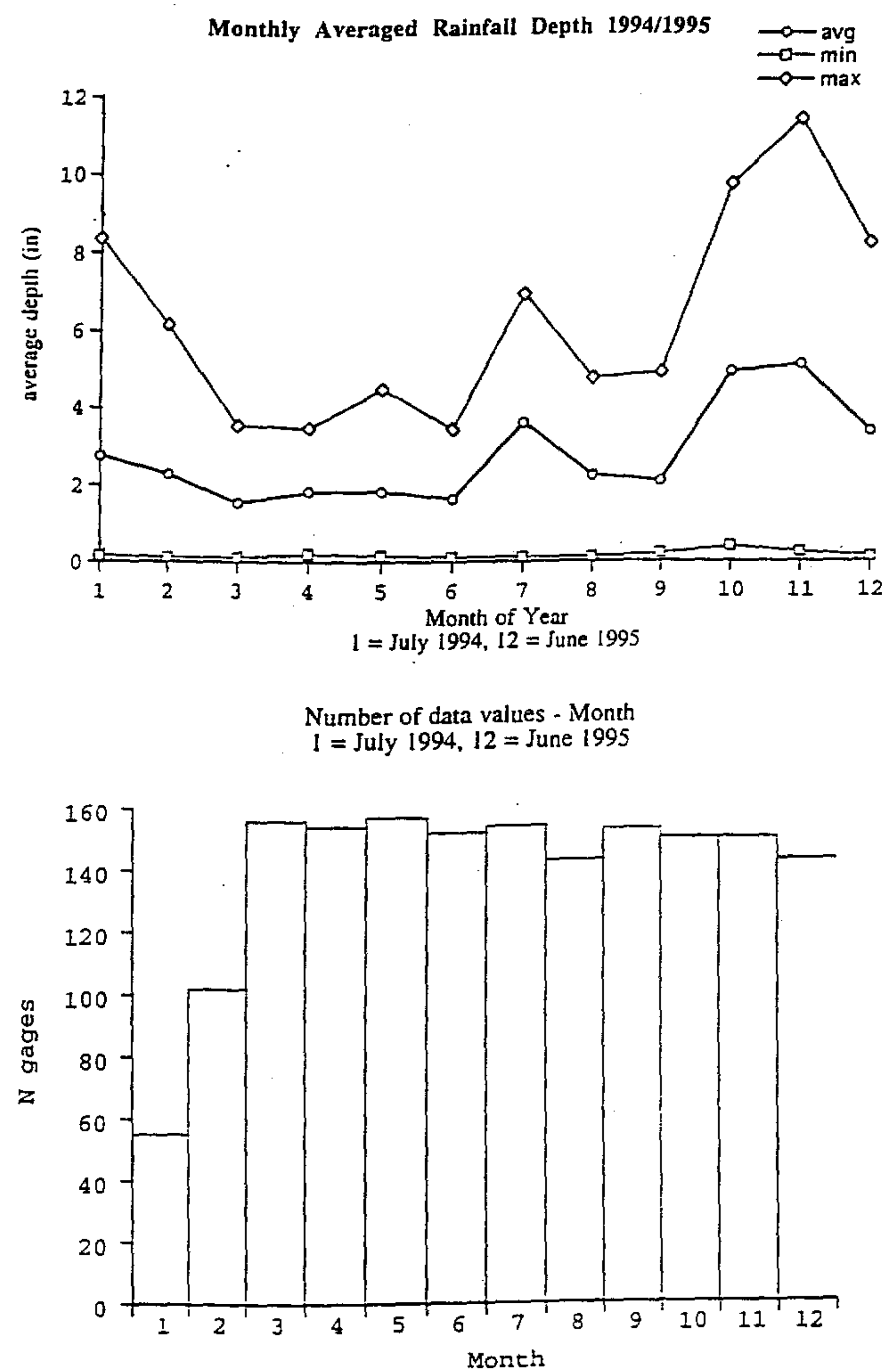


FIG. 6. Time Series of the Monthly-averaged, Minimum and Maximum Rainfall Depths for each month.

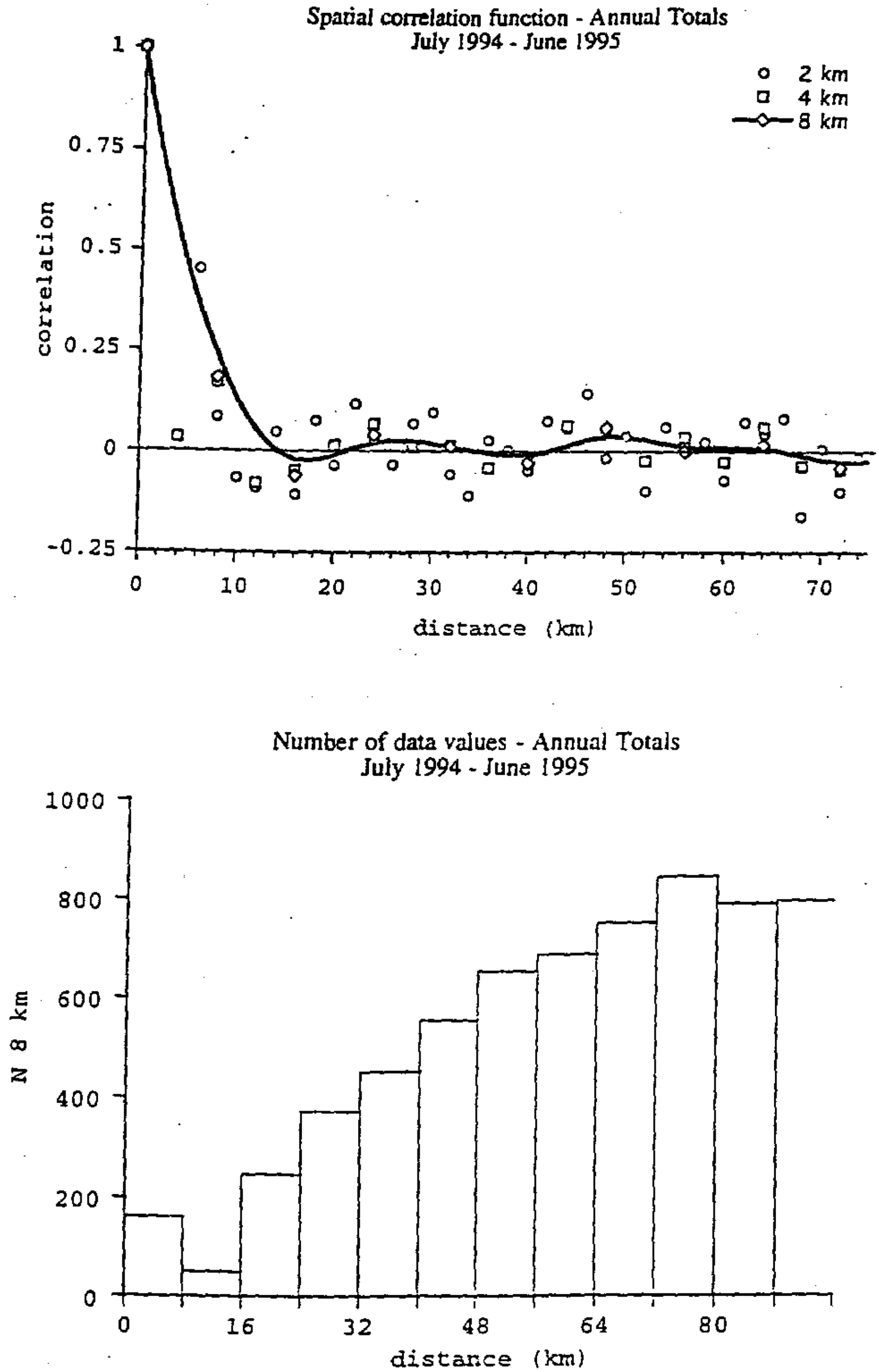


FIG. 7. Spatial Autocorrelation Function of the Annual Total Rainfall Depths at all 161 IFLOWS Gages.

The fall season spatial correlation function is shown in the upper portion of Figure 9, and the number of data values available for each correlation coefficient estimate is shown in the lower portion of the Figure. The shape of the fall season spatial correlation function is similar to the summer season spatial correlation. This can be interpreted to imply that the general characteristics of the spatial variability of rainfall during these two seasons, as interpreted from the IFLOWS rain gages, maintains a similar behavior. The correlation decreases to 1/e at approximately 6 km, and is slightly positive at distances up to about 45 km. A slight increase in the correlation function is observed at a range of 25 to 35 km as seen in the summer season.

The remaining two spatial correlation functions are for the winter and spring seasons. Figure 10 shows the winter season spatial correlation function. A comparison of Figure 10 with the previous spatial correlation function figures indicates that the decorrelation distance is slightly increased during the winter. This concept is further supported by the positive magnitude of the correlation coefficient at distances greater than 10 km. The previous two seasons showed a spatial correlation decreasing to a near zero magnitude at about 8 km followed by low positive magnitudes up to a distance of about 45 km. The winter season spatial correlation remains positive in magnitude throughout the range of distance from 0 to 50 km, and then decreases to near zero for distances greater than 50 km. This result appears intuitively correct, since winter rain storm systems moving over this region are typically more homogeneous in space than in the summer and fall season.

The spring season spatial correlation coefficient function is presented in the upper portion of Figure 11; the lower portion of the figure shows the number of data values used in the estimation of each correlation coefficient. The shape of the spatial correlation function is characterized by a somewhat lower decay rate in correlation with the decorrelation distance of about 7 km. The spring season correlation function is most consistent with the shape of the annual spatial correlation function. The spring season includes the months with the largest total rainfall depths (refer to Figure 6) implying that it should be consistent with the annual series characteristics. Again the increase in correlation is observed at a range of 25-30 km as found in the summer and fall seasons. In addition to the annual and seasonal spatial correlation functions, the spatial correlation function for each month was derived; for brevity these results are not included in this summary report and are available from the Investigators.

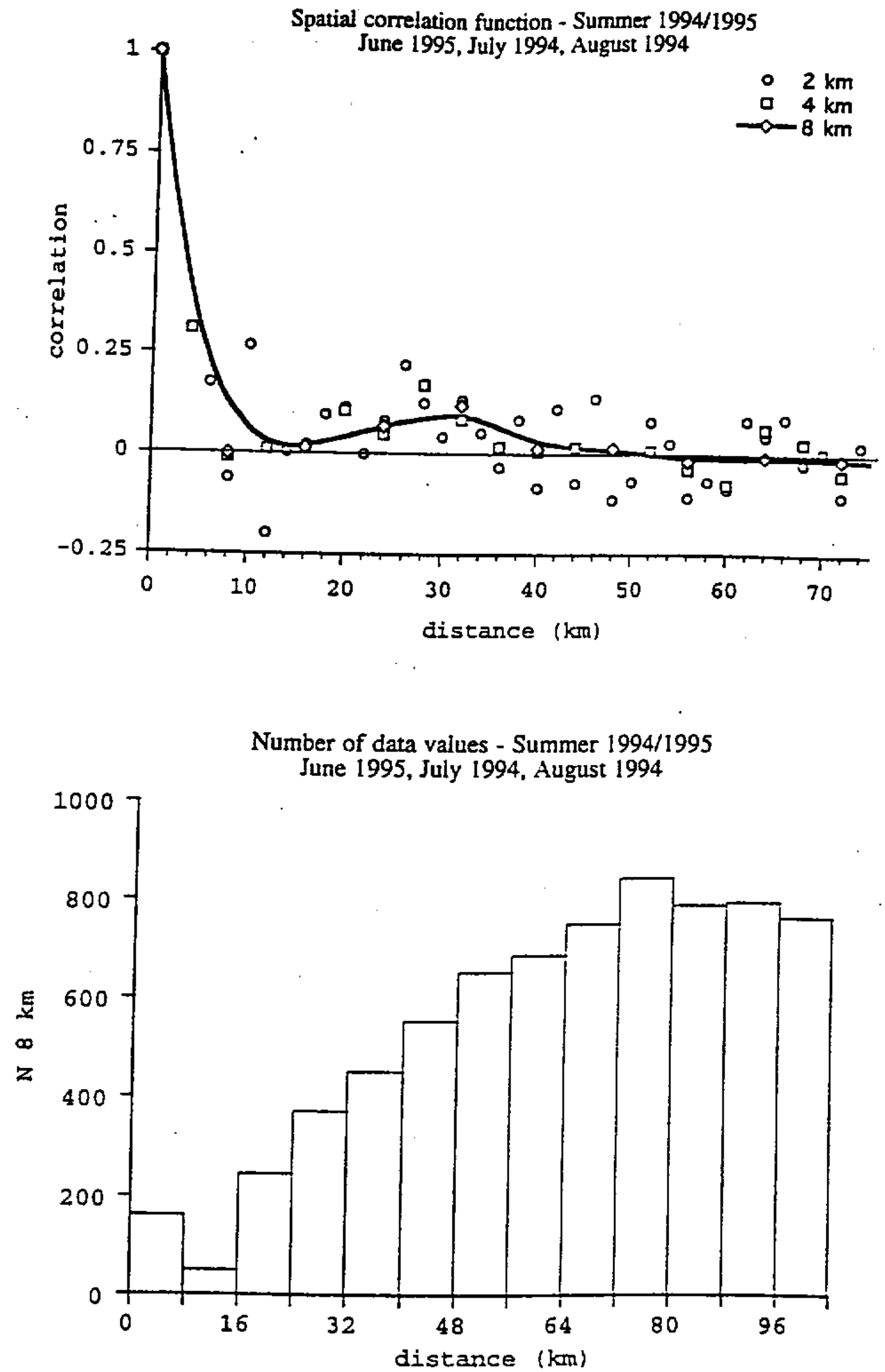


FIG. 8. Spatial Autocorrelation Function of the Summer Season (June 1995, July 1994, and August 1994) Total Rainfall Depths at all 161 IFLOWS Gages.

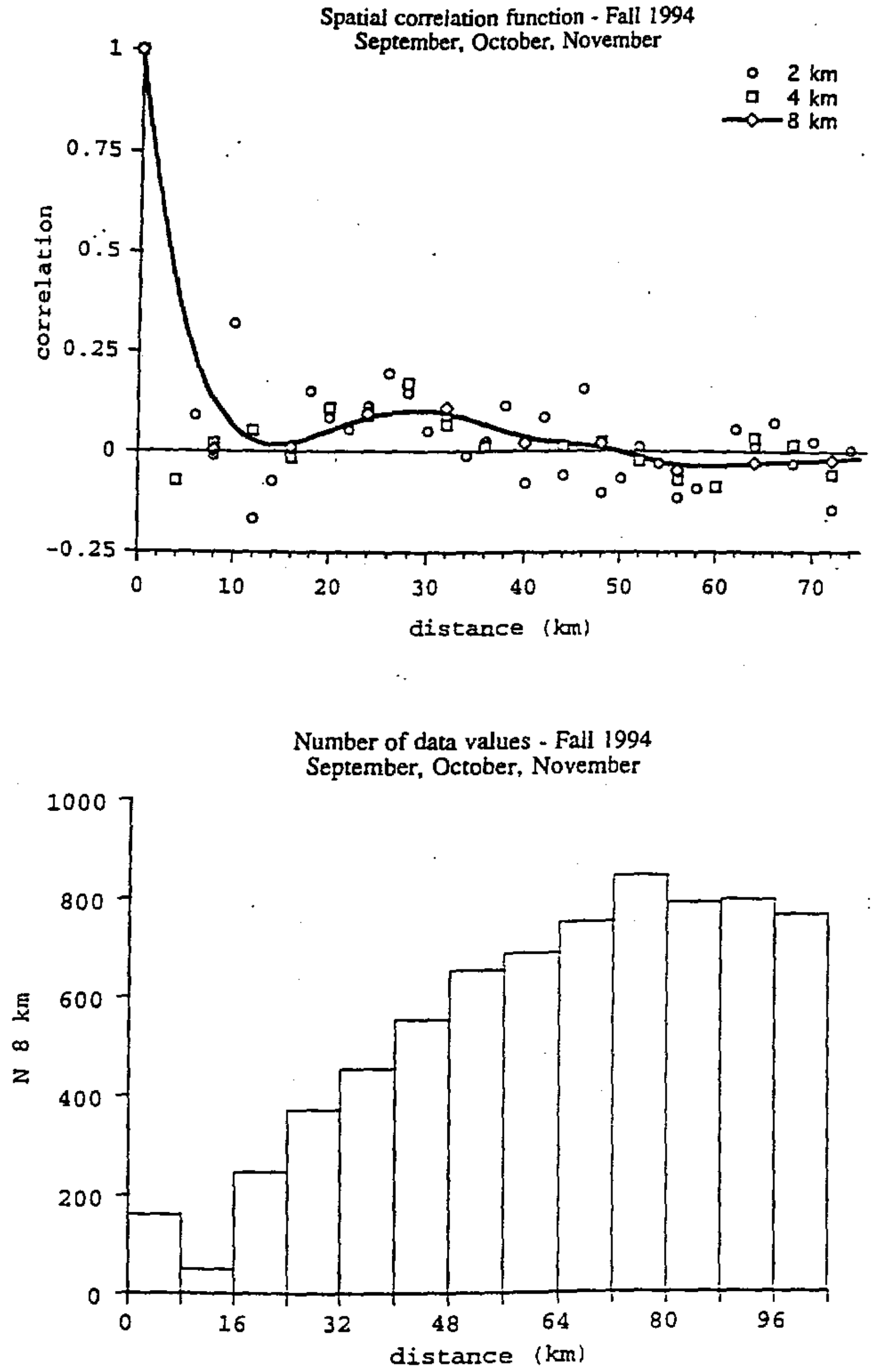
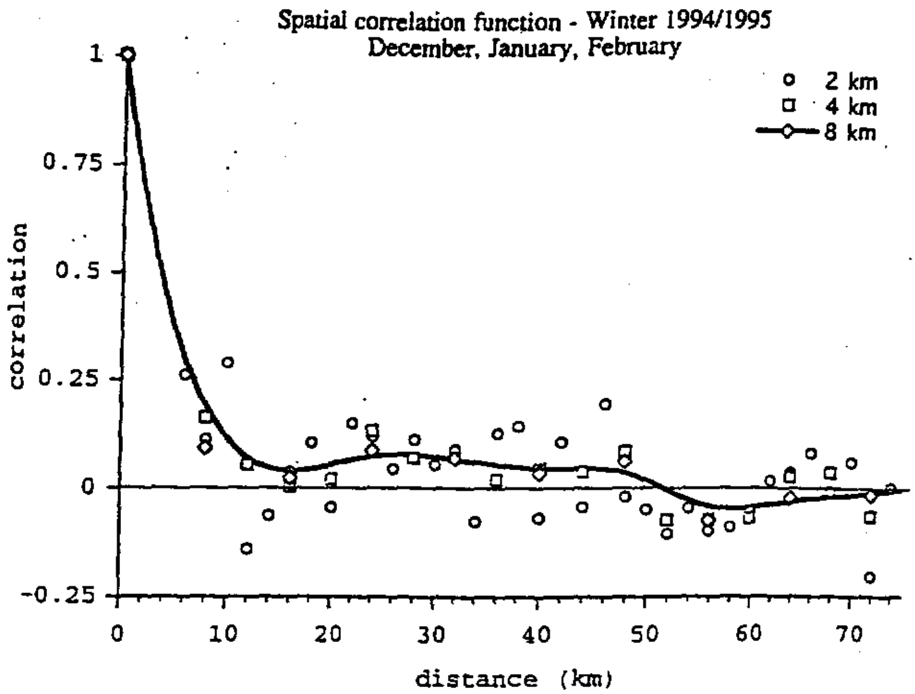


FIG. 9. Spatial Autocorrelation Function of the Fall Season (September 1994, October 1994, November 1994) Total Rainfall Depths at all 161 IFLOWS Gages.



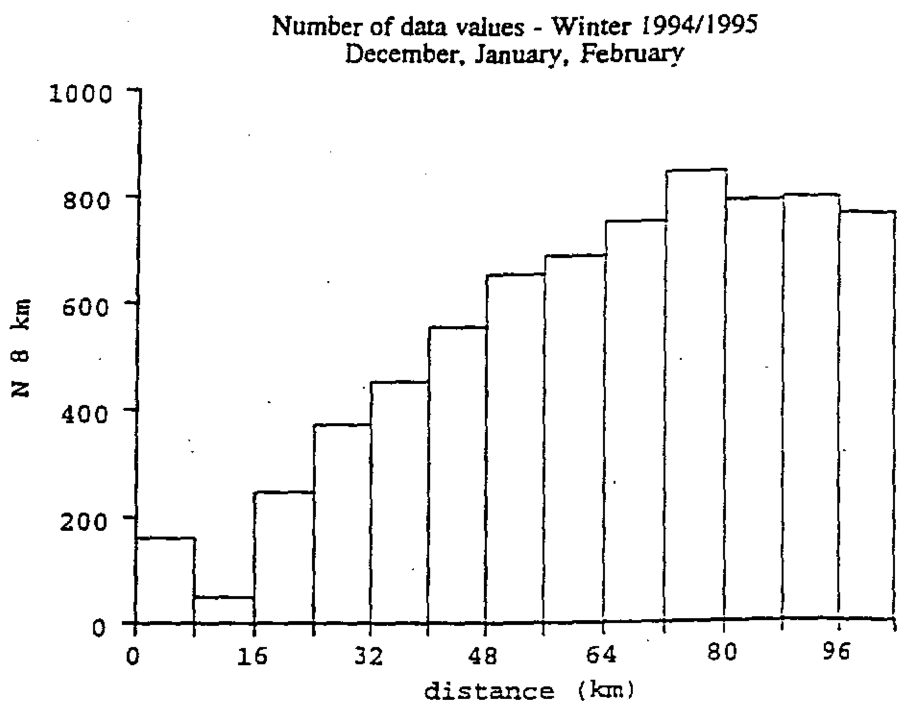
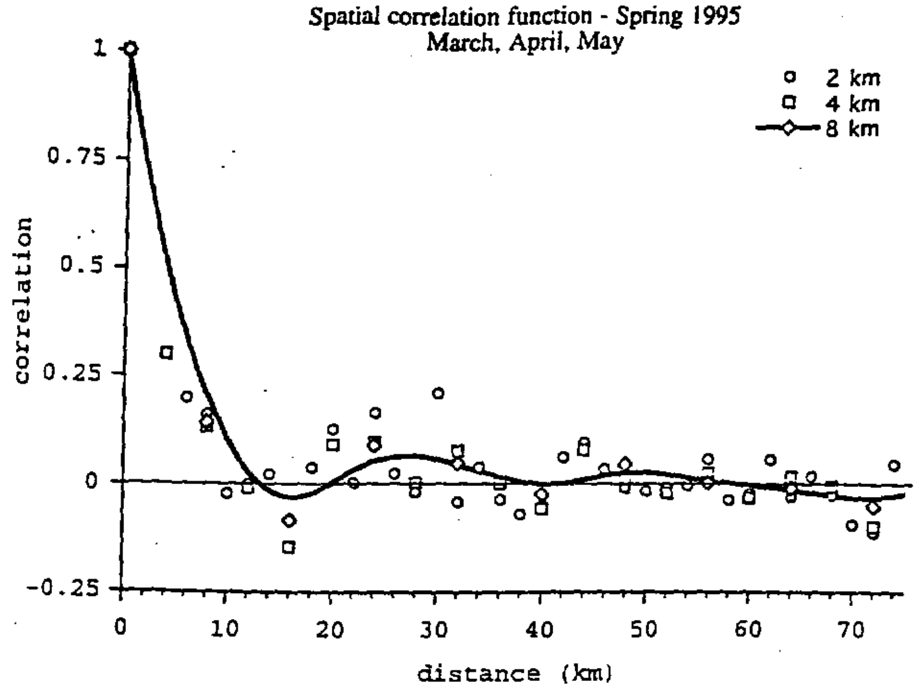


FIG. 10. Spatial Autocorrelation Function of the Winter season (December 1994, January 1995, February 1995) Total Rainfall Depths at all 161 IFLOWS gages.



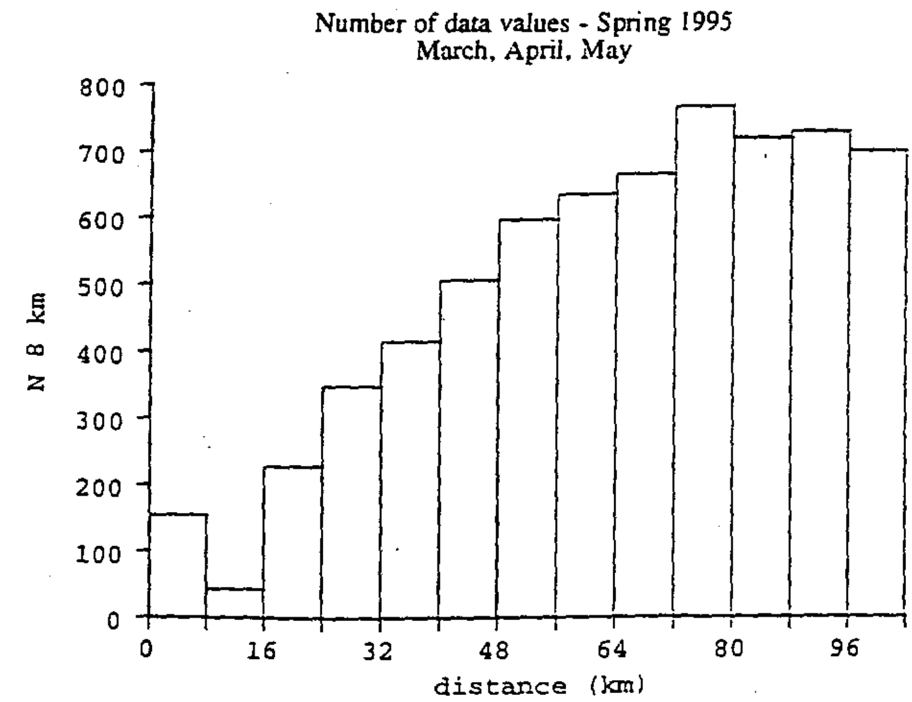


FIG. 11. Spatial Autocorrelation Function of the Spring Season (March 1995, April 1995, May 1995) Total Rainfall Depths at all 161 IFLOWS gages.

Flash Flood Characterization

In the characterization of the selected events, consideration is given to the fact that during flash flooding certain portions of the hydrograph, namely the rising limb, the time to peak and the magnitude of the peak discharge are more important than others, in view of this the following parameters: i) the rising curve gradient (k) ii) the flood magnitude ratio (M) and, iii) flash flood response time (T_P). These parameters are assigned relative severity factors R_K, R_M, and R_T as discussed in Chapter 3. These severity factors are then added up to give the flash flood index, R_F, which is used in characterizing flash floods.

Out of the 30 selected events, three have been reported by the NWS as flash floods, and they occurred over Cutshin Creek, Johns Creek, and Tygarts Creek watersheds on May 18, 1995. Given in Tables 17 and 18 are the indexing parameters and precipitation characteristics associated with these events. Tables 17, 18 are summarized from Tables 11 and 13 respectively.

TABLE 17. Indexing Parameters (T_P, M and k) for reported Flash Floods.

Recording Gage	Date	T_P(hrs)	M	k (/day)
Cutshin Creek at Wooton	05/18/95	9	78.55	40.00
Johns Creek near Meta	05/18/95	9	37.34	11.00
Tygarts Creek at Olive Hill	05/18/95	8	28.29	11.10

TABLE 18. Storm Characteristics identified with reported Flash Floods

Recording Gage	Flood Date	Flash Flood Index (R_F)	P_{24}	P_{48}	P_{120}	I_M	I_A	T_M	T_D	T_H	S_I	S_A
Cutshin Creek at wooton	05/18/95	17	1.80	2.04	3.80	1.12	0.50	2.00	2.50	1.50	2.26	0.20
Johns Creek near Meta	05/18/95	11	1.28	1.68	2.60	0.48	0.26	5.50	8.00	4.50	1.85	0.38
Tygarts Creek at Olive Hill	05/18/95	10	1.94	1.94	2.34	1.56	0.20	3.25	9.00	2.00	7.72	0.31

As shown in Table 17, these events had a flash flood response time, T_P, of either 8 or 9 hours and a flood magnitude ratio, M, that ranged from 28 to 79. The relatively high flood magnitude ratio is characteristic of flash floods that exhibit high peak discharges as compared to the long-term mean streamflow discharge, and in some extreme cases, peak discharges have exceeded mean streamflow discharge by several hundred orders of magnitude. The rising curve gradient, k, as shown in the last column of Table 17, reflects the steep rising limb that characterizes flash flood hydrographs and especially the event that had the highest flash flood index, R_F, exhibits a very high k value of 40 day^{-1}. The flash flood event with the highest k and M values (Cutshin Creek at Wooton - 05/18/95) had the highest flash flood index, R_F, of 17, the other events that occurred on Johns Creek and Tygarts Creek watersheds had R_F values of 11 and 10, respectively. In this study, flood events with a flash flood index of ten or more are characterized as flash flood, and this is based on the lowest flash flood index of the three events reported by the NWS as flash floods.

Table 18 shows the flash flood index and associated rainfall characteristics for the above flash flood events. The significant difference in precipitation between P_{24} and P_{120} indicates that these flash floods were preceded by significant storm events that may have caused an increase in antecedent moisture and therefore serving to intensify these floods. This type of precipitation pattern is common with flash flooding.

Maximum rainfall intensities, I_M, varied between 0.48 in/hr to 1.56 in/hr, with two out of the three flash flood events showing rainfall intensities greater than 1.10 in/hr. Intensities of such magnitude are characteristic of mesoscale convective storms that tend to intensify flash flooding in regions such as eastern Kentucky. Flood events (flash floods) are usually associated with first and second quartile storms with a storm advancement ratios, S_A, between 0 and 0.5, such a trend is evident with these flash flood events. Figure 12 shows streamflow discharge and related rainfall for reported flash flood events. Hydrographs and associated rainfall for select flood events are given in Fig. B1 (Appendix B).

The relationship between flash flood index, R_F, and the indexing parametesr k, M, T_P., as presented in Figures 13, 14, and 15 respectively, show expected trends. The relationship with 24-hour Precipitation (P_{24}) as illustrated in Figure 16 showed that the amount of rainfall recorded prior to an flood event (flash flood) has a positive relationship with the severity of the flood event. However, a definite relationship is not evident when R_F, is plotted against the precipitation characteristics, namely 48-hour antecedent precipitation (P_{48}), 5-day antecedent precipitation (P_{120}), Storm Intensity Ratio (S_I), Average Rainfall Intensity (I_A), Storm Advancement Ratio (S_A), and Maximum Rainfall Intensity (I_M), as shown Figures 16, 17, 18, and 19 respectively.

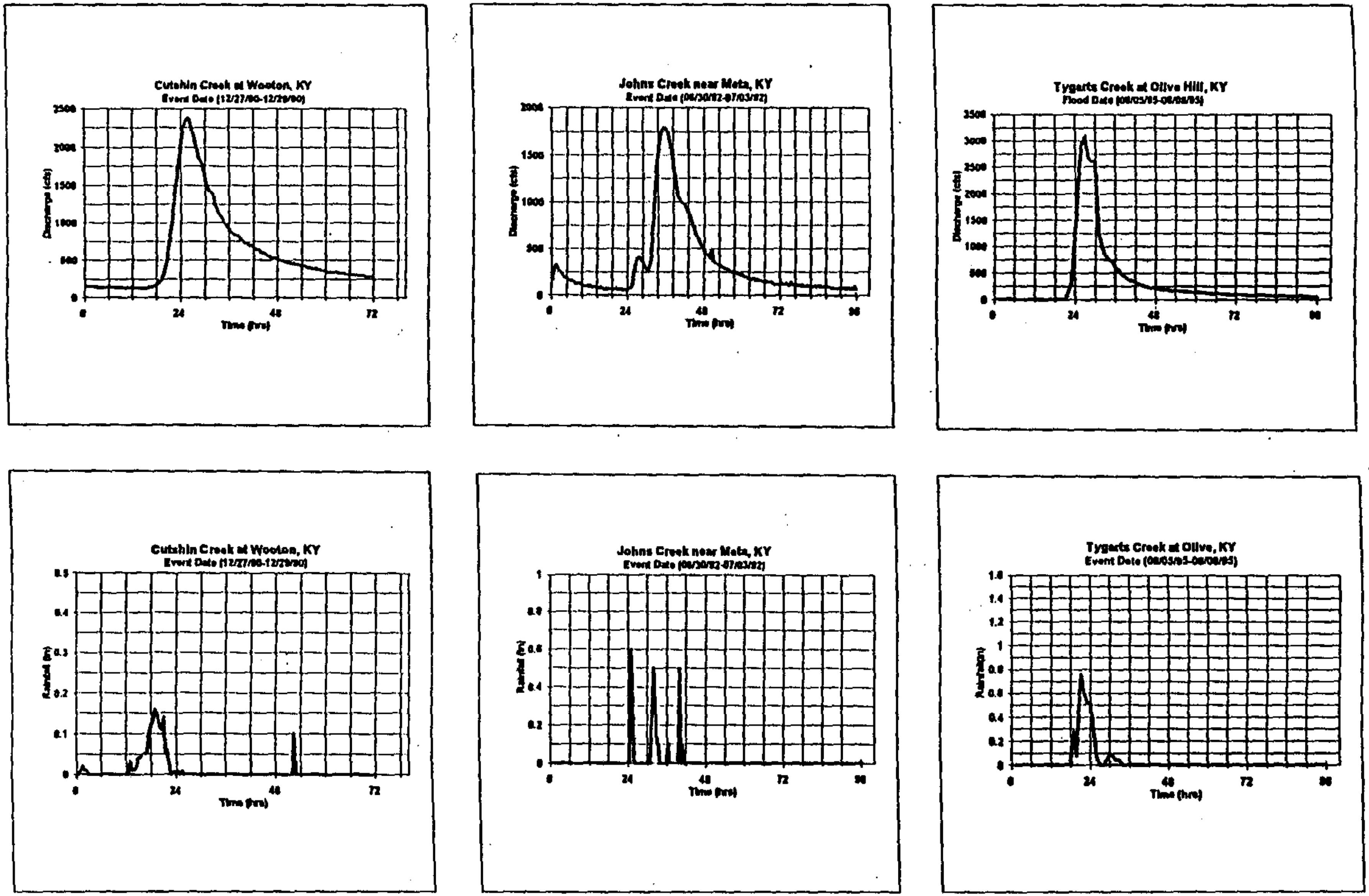


FIG. 12. Streamflow Discharge and Corresponding Rainfall for Reported Flash Flood Events.

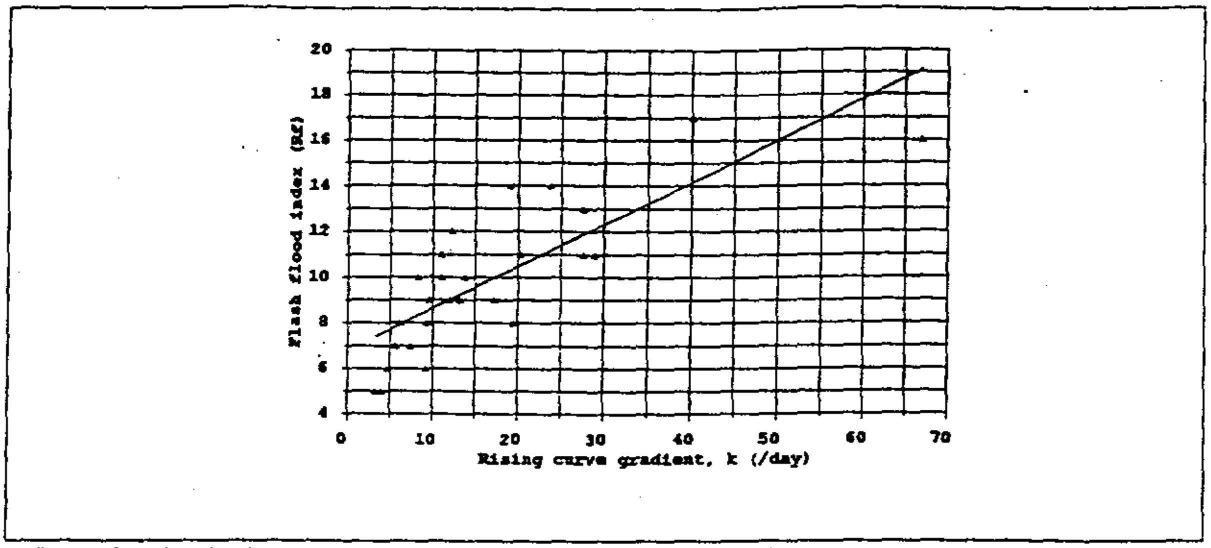


FIG. 13. Relationship between Flash Flood Index and Rising Curve Gradient

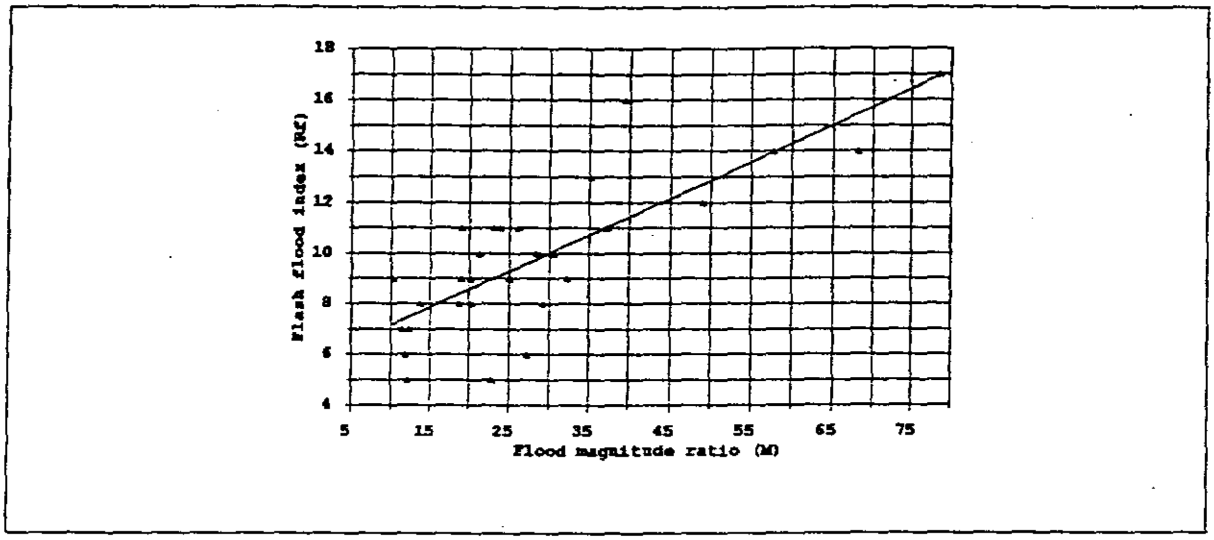


FIG. 14. Relationship between Flash Flood Index and Flood Magnitude ratio

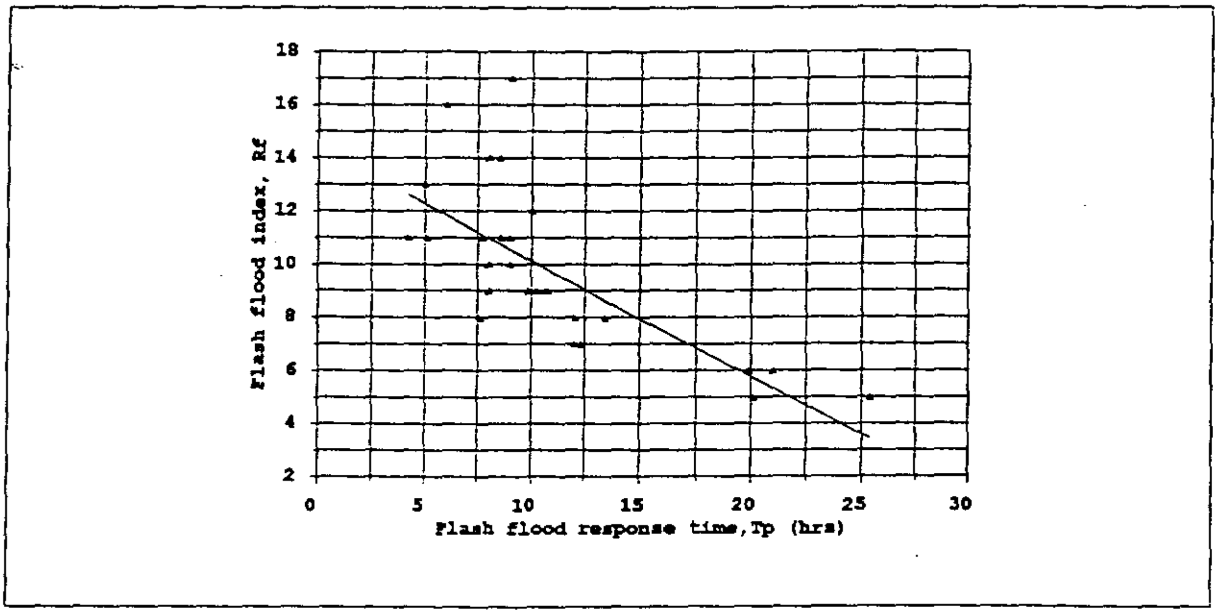


FIG. 15. Relationship between Flash Flood Index and Flash Flood Response Time

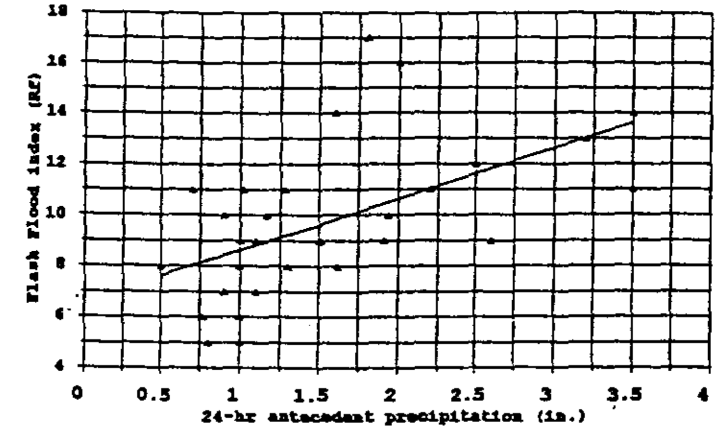


FIG. 18. Relationship between Flash Flood Index and 24-hr Antecedent Precipitation

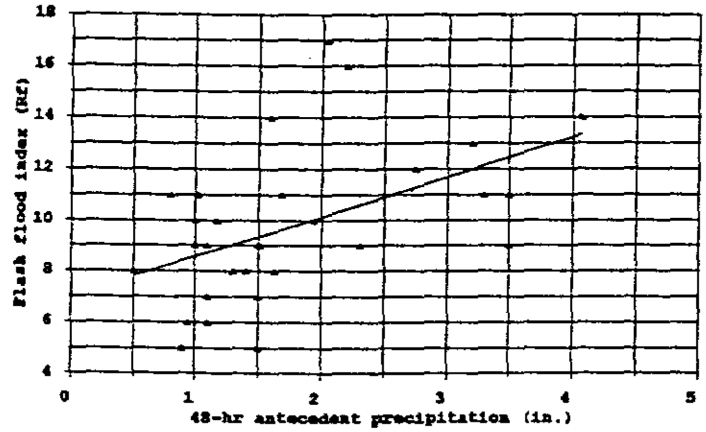


FIG. 17. Relationship between Flash Flood Index and 48-hr Antecedent Precipitation

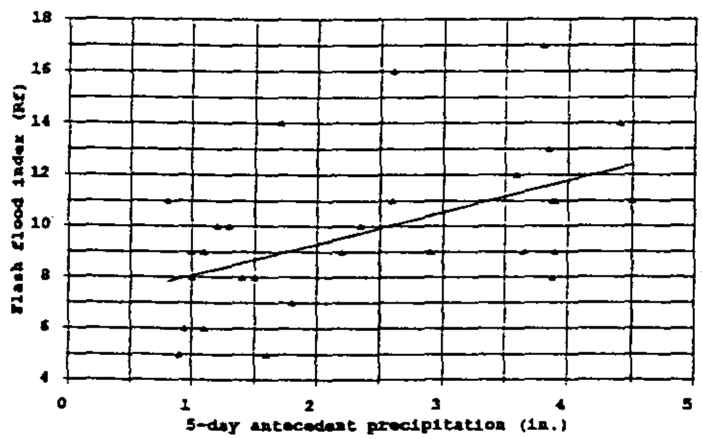


FIG. 18. Relationship between Flash Flood Index and 5-day Antecedent Precipitation

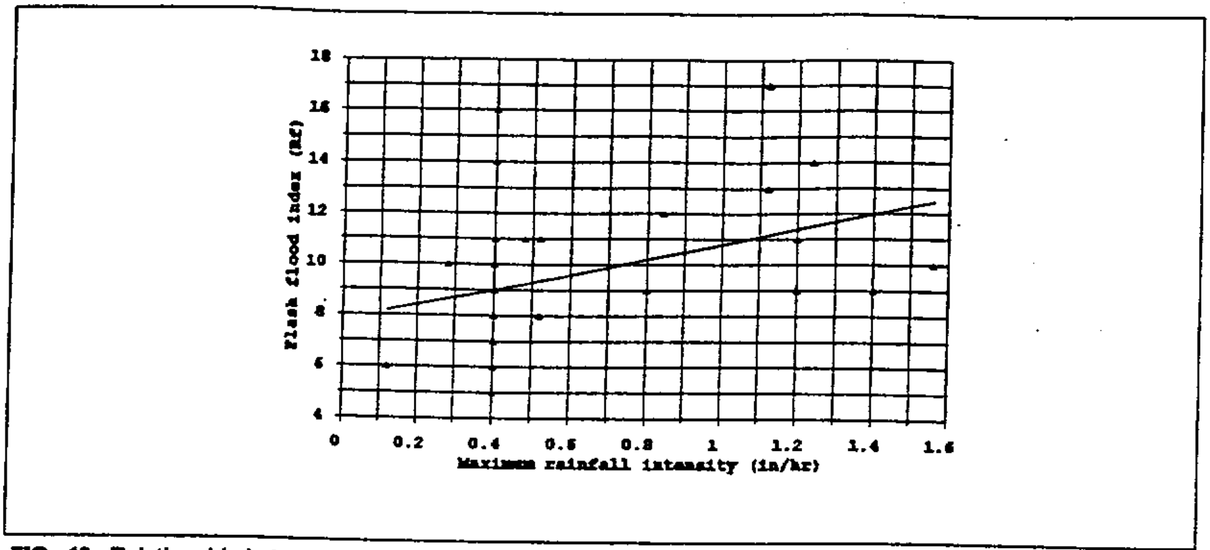


FIG. 19. Relationship between Flash Flood Index and Maximum Rainfall Intensity

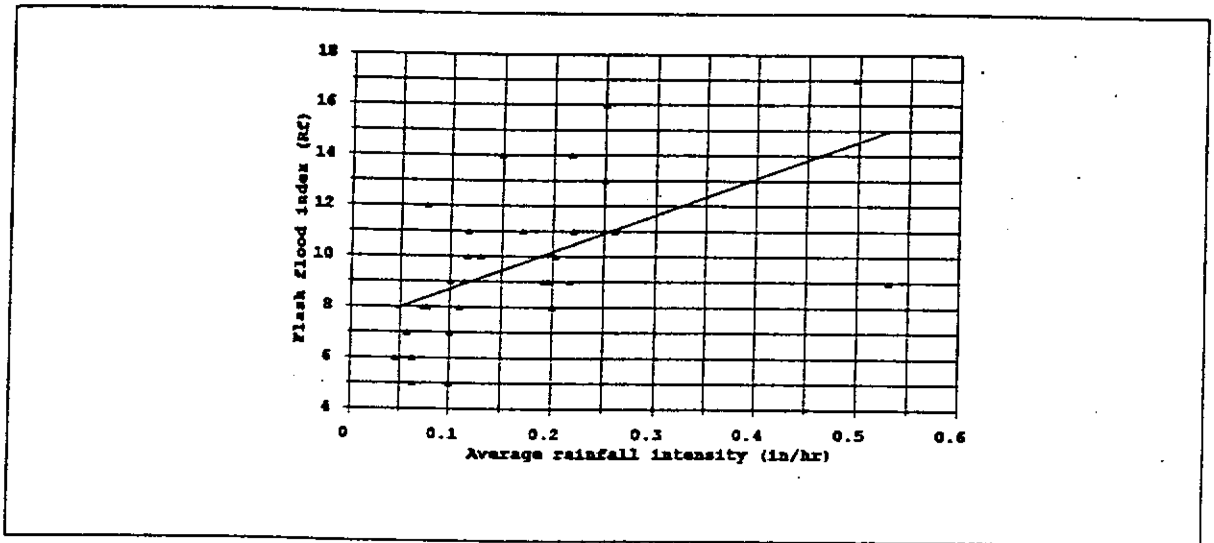


FIG. 20. Relationship between Flash Flood Index and Average Rainfall Intensity

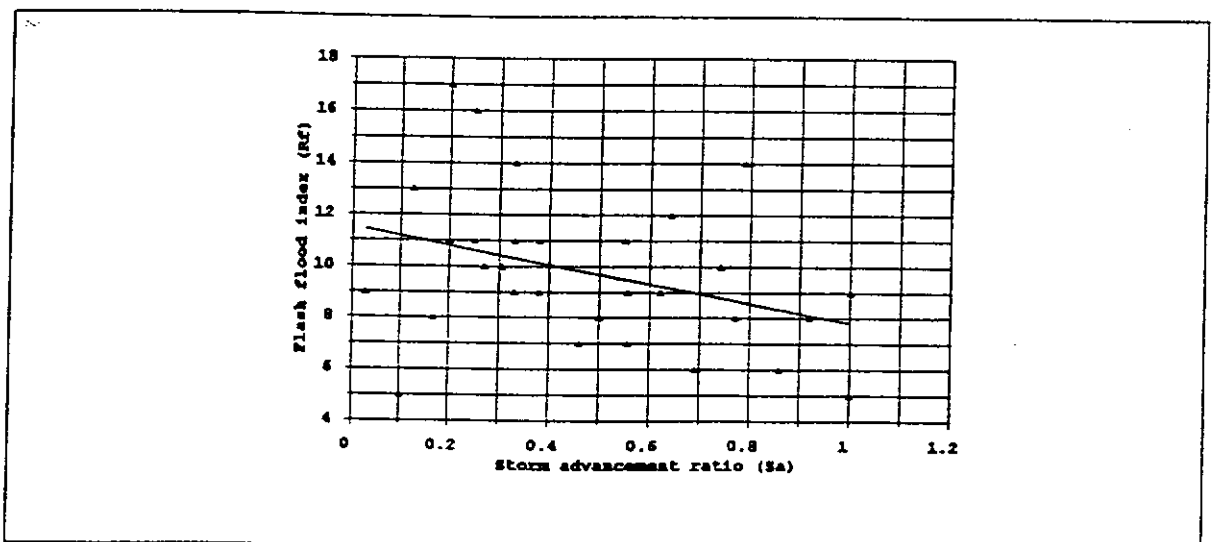


FIG. 21. Relationship between Flash Flood Index and Storm Advancement Ratio

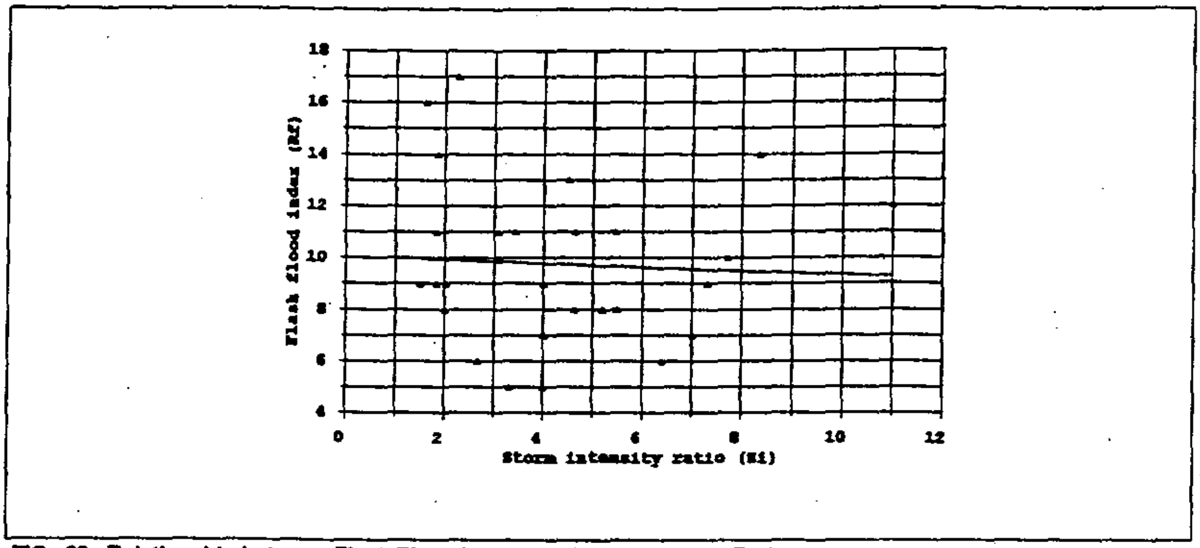


FIG. 22. Relationship between Flash Flood Index and Storm Intensity Ratio

Conclusion

The analysis conducted in this study using IFLOWS rainfall data investigated the potential for its use in characterizing the behavior and variability of rainfall in the eastern Kentucky region. The results of the study show that relatively consistent rainfall characteristics can be defined using the IFLOWS data. These results remain preliminary in nature and more extensive evaluation and further comparisons with rainfall data from other sources is necessary. The results from this type of study, with the addition of a longer record period, could be used for estimating the likelihood of specific rainfall amounts or rain amounts above a specific intensity or depth level. This project was limited to collection and analysis of one year (July 1994 - June 1995) of IFLOWS data. One month of daily and 15 minute time resolution data regularly archived by the National Weather Service was available for the preparation of this work (corresponding to July 1994). Due to the limited number of rainfall periods in July 1994, that resource was not sufficient to establish reliable comparisons between IFLOWS and NWS gage accumulations. A comprehensive comparison of IFLOWS gage accumulations with regularly archived hourly and daily rain accumulations remains to be investigated. The analysis procedures and the general indications of relationships defined from the IFLOWS data remain valid; as additional IFLOWS data becomes available this study may be updated using a larger data base and the validity of the results stated in more definite terms.

The Flash Flood Index, R_F, is a useful index for characterizing flash floods. In this study events with a Flash flood Index, R_F, of 10 or more were characterized as flash floods. Expected trends are realized when R_F, is plotted against each of the indexing parameters k, M, and T_P, however the relationship between R_F, and precipitation characteristics showed little or no evident trends. This study is an initial effort to characterize flash floods by quantifying the characteristics of flood hydrographs. Further research in this area involving a larger sample of flash flood events is necessary to develop a more conclusive statement concerning the interpretation of the results presented herein.

Ongoing Research

Several research projects were derived from this initial work. One involves the detection and characterization of orographic precipitation using IFLOWS and NWS gage data from this region (Schermerhorn 1967; Abbs and Jensen 1993; Daly et al. 1994; Michaud et al. 1995). Meteorological data is being used with the IFLOWS data set to define the presence of orographic enhancement of rainfall in the eastern Kentucky region. Preliminary results indicate that orographic effects are present and can be detected in the rainfall data.

A second project involves use of IFLOWS data, NWS rain gage data, and USGS stage/discharge data over a variety of time and space scales for performing a water budget modeling study for this area (Wallis et al. 1991). Preliminary modeling efforts are planned to investigate the applicability of unit hydrograph methods for selected watersheds and plans are being made to adapt the HEC1F model for rainfall/runoff modeling in this region. Eventually, integration of raster spatial rainfall data from NEXRAD into the flash-flood modeling approach is planned.

Limited aspects of this project are expected to continue after the end of direct funding -- the cooperative environment established between the University of Louisville and the agencies involved will be maintained. A future plan calls for the establishment of a hydro-climatological data set for this region of the Appalachians and publication of the summary results in a scientific journal.

References

Abbs, D.J., and J.B. Jensen, 1993. Numerical Modeling of Orographically Forced Postfrontal Rain. Monthly Weather Review, 121(1) 189-206.

American Meteorological Society, 1993. Prediction and Mitigation of Flash Floods, A policy statement of the American Meteorological Society as adopted by the Executive Committee on 16 April 1993. Bulletin of the American Meteorological Society, 74(8) 1586-1587.

Buer, S. M., 1988: Program Manual: Headwater Forecasting Using HED71. California Department of Water Resources, Division of Flood Management. Sacramento, CA. September, 48 pp.

Changnon, S.A.Jr., and J.L. Vogel, 1981. Hydro Climatological Characteristics of Isolated Severe Rainstorms. Water Resources Research, 17(6) 1694-1700.

Chow, V., Maidment, D., and Mays, L., 1988. Applied Hydrology, McGraw Hill, New York.

Cooper, C.F., 1967. Rainfall Intensity and Elevation in Southwestern Idaho. Water Resources Research, AGU, 3(1) 131-137.

Crane, R.K., 1990. Space-Time Structure of Rain Rate Fields. Journal of Geophysical Research, AGU, 95(D3) 2011-2020.

Curtis, D.C., Dotson, H.W., 1993. Rain Gage Network for an Automated Flood Warning System. Engineering Hydrology, ASCE, 1-5.

Daly, C., R.P. Neilson, and D.L. Phillips, 1994. A Statistical-topographic Model for Mapping Climatological Precipitation over Mountainous Terrain. Journal of Applied Meteorology, AMS, 33(2) 140-158.

Fontaine T.A. (1995). Rainfall-Runoff Model Accuracy for an Extreme Flood. Journal of Hydraulic Engineering, ASCE, Vol. 121, No. 4.

Foufoula-Georgiou, E. and L. Wilson, 1990. In Search of Regularities in Extreme Rainstorms. Journal of Geophysical Research, AGU, 95(D3), 2061-2072.

Fread, D.L., R.C. Shedd, G.F. Smith, R. Farnsworth, C.N. Hoffeditz, L.A. Wenzel, S.M. Wiele, J.A. Smith, and G.N. Day, 1995. Modernization in the National Weather Service River and Flood Program. Weather and Forecasting, AMS, 10(3) 477-484.

Gupta, V. and E. Waymire, 1990. Multiscaling Properties of Spatial Rainfall and River Flow Distributions. Journal of Geophysical Research, AGU, 95(D3), 1999-2009.

Henz, J.F., 1993. Re-Constitution of the August 18, 1991 Virginia Canyon Flash Flood's Precipitation Using A Numerical Cloud Model, Radar and Conventional Meterorological Observations: Henz Meteorological Services Report 93-2, Denver, Colorado, prepared for Urban Drainage and Flood Control District of Denver, Colorado, 17 pp.

Henz, J. F. and R. A. Kelly, 1988. Innovative uses of Rainfall Prediction in Urban Flash Flood Forecasting: ASCE Third Water Resources Operations and Management Workshop: Computerized Decision Support Systems for Water Managers, Fort Collins, Colorado, June 27-30.

Hevesi, J.A., A.L. Flint, and J.D. Istok, 1992b. Precipitation Estimation in Mountainous Terrain Using Multivariate Geostatistics. Part II: Isohyetal Maps. Journal of Applied Meteorology, AMS, 31(7) 677-688.

Hevesi, J.A., J.D. Istok, and A.L. Flint, 1992a. Precipitation Estimation in Mountainous Terrain Using Multivariate Geostatistics. Part I: Structural Analysis. Journal of Applied Meteorology, AMS, 31(7) 661-676.

Hoxit, L.R., R.A. Maddox, C.F. Chappell, F.L. Zuckerburg, Scofield, 1978: Meteorological analysis of the Johnstown, Pennsylvania, flash flood, 19-20 July 1977. NOAA Tech. Rep. ERL 401- APCL 43, U.S. Dept. Of Commerce, 71 pp.

Huff, F.A., 1967. Time Distribution of Rainfall in Heavy Storms. Water Resources Research, AGU, 3(4) 1007-1019.

Hydrologic Engineering Center (HEC), 1983b. Water Control Software: Forecast and Operations. U.S. Army Corps of Engineers, Davis, California.

Hydrologic Engineering Center (HEC), 1990. Flood Hydrograph Package. U.S. Army Corps of Engineers, Davis, California.

U.S. Department of Commerce, IFLOWS - Integrated Flood Observing and Warning System Program Office, Office of Hydrology, 1993. Integrated Flood Observing and Warning System Management Guide. National Weather Service/National Oceanic and Atmospheric Administration,, 140 pp.

Julien, P. and Sagafian, B., 1991. CASC2D USER'S MANUAL- A Two Dimensional Watershed Rainfall-Runoff Model. A Computer Program Provided by the Hydrologic Modeling Group of ARO Center for Geosciences at Colorado State University, 1.

LaPenta, K.D., B.J. McNaught, S.J. Capriola, L.A. Giordano, C.D. Little, S.D. Hrebenach, G.M. Carter, M.D. Valverde, and D.S. Frey, 1995. The Challenge of Forecasting Heavy Rain and Flooding throughout the Eastern Region of the National Weather Service. Part I: Characteristics and Events. Weather and Forecasting, AMS, 10(1) 78-90.

Larson, L.W., R.L. Ferral, E.T. Strem, A.J. Morin, T.R. Carroll, M.D. Hudlow, L.A. Wenzel, G.L. Schaefer, and D.E. Johnson, 1995. Operational Responsibilities of the National Weather Service River and Flood Program. Weather and Forecasting, AMS, 10(3) 465-476.

Lovell, T.L., Killen, J.R., Eichert, B.S., 1993. Reservoir Regulation and Real-Time Models for Trinity River Flood Prevention and Control. Engineering Hydrology, ASCE, 778-781.

McPherson, R.D., 1994. The National Centers for Environmental Prediction: Operational Climate, Ocean, and Weather Prediction for the 21st Century. Bulletin of the American Meteorological Society, AMS, 75(3) 363-373.

Michaud, J.D., B.A. Auvine, and O.C. Penalba, 1995. Spatial and Elevational Variations of Summer Rainfall in the Southwestern United States. Journal of Applied Meteorology, AMS, 34(12) 2689-2703.

Mimikou, M.A., Baltas, E. A., and Borga, M., 1993. Flash-Flood by Using the HEC1F Model. Engineering Hydrology, ASCE, 85-90.

National Oceanic and Atmospheric Administration, 1977: Johnstown, Pennsylvania, flash flood of July 19-20, 1977. Natural Disaster Survey Report 77-2, U.S. Dept. of Commerce, 60 pp.

National Weather Service, 1972: Natural disaster survey report-Shadyside, OH, flash floods June 14, 1990. NOAA, U.S. Dept. of Commerce, 124 pp.

US Dept. of Commerce, 1991. Shadyside, Ohio, Flash floods June 14, 1990. NWS, NOAA, Silver Spring, MD, January 1991, 43 pp.

U.S. Dept. of Commerce, 1993. Integrated Flood Observing and Warning System Management Guide. NWS, NOAA, Silver Spring, MD, August 1993, 42 pp.

Okamoto, Y. 1993, A Method for Conducting Real Time Flood Forecast. Engineering Hydrology, ASCE, 790-795.

Opitz, H.H., Summer, S.G., Wert, D.A., Snyder, W.R., Kane, R.J., Brady, R.H., Stokols, P.M., Kuhl, S.C., and G.M. Carter, 1995. The Challenge of Forecasting Heavy Rain and Flooding throughout the Eastern Region of the National Weather Service. Part II: Forecast Techniques and Applications. Weather and Forecasting, AMS, 10(1) 91-104.

Pabst, A.F. and J. C. Peters, 1983. A Software System to Aid in Making Real-Time Water Control Decisions. Paper presented at the Technical Conference on Mitigation of Natural Hazards Through Real-Time Data Collection and Hydrologic Forecasting. (Also available as Technical Paper No. 89 from Hydrologic Engineering Center, Davis, California.)

Peters, J.C., and P.B. Ely, 1985. Flood-Runoff Forecasting with HEC1F. Water Resources Bulletin, AWRA, 21(1) 7-13.

Polyak, I. and G. North, 1995. The Second-Moment Climatology of the GATE Rain Rate Data. Bulletin of the American Meteorological Society, AMS, 76(4) 535-550.

Redmond, K., Doesken, N.J., 1993. Precipitation Data in the Mountains of the Western United States: Do We Have What We Need? Engineering Hydrology, ASCE, 109-114.

Rhea, J. O., Hartzell, C. L., 1993. Combining Orographic Precipitation and Runoff Models for Improving Reservoir Operations. Engineering Hydrology, ASCE, 103-108.

Ruhl K.J., 1993. Effectiveness of The Streamflow-Gaging Network in Kentucky in providing Regional Streamflow Information. USGS Water Resources Investigations Report 93-4106, US Geological Survey, Washington D.C.

Ruhl J.K. and Martin G.R., 1991. Low Flow Characteristics of Kentucky Streams. USGS Water-Resources Investigations Report 91-4097, US Geological Survey, Washington D.C.

Schermerhorn, V.P., 1967. Relations between Topography and Annual Precipitation in Western Oregon and Washington. Water Resources Research, AGU, 3(3) 707-711.

Smith, J., and A. Karr, 1990. A Statistical Model of Extreme Storm Rainfall. Journal of Geophysical Research, AGU, 95(D3), 2083-2092.

Tweedy, D., 1990. Mesoscale Precipitation Patterns in Extratropical Cyclones and Implications for Cyclone Development. Journal of Geophysical Research, AGU, 95(D3), 1987-1997.

U.S. Army Corps of Engineers, 1988. Development, Calibration and Application of Runoff Forecasting Models. Technical, Paper, No. 121.

U.S. Department of Commerce, 1990. Natural Disaster Survey Report, Shadyside, Ohio, Flashfloods. National Weather Service/National Oceanic and Atmospheric Administration, 124pp.

U. S. Geological Survey, 1983. Hydrology of Area 13, Eastern Coal Province, Kentucky, Virginia, and West Virginia. Water-Resources Investigations Report 82-505, Washington, D.C.

U. S. Geological Survey, 1982. Hydrology of Area 15, Eastern Coal Province, Kentucky and Tennessee. Water-Resources Investigations Report 81-809, Washington, D.C.

U. S. Geological Survey, 1991. Low-Flow Characteristics of Kentucky Streams. Water-Resources Investigations Report 91-4097, 38-44, Washington, D.C.

Wallis, J.R., D.P. Lettenmaier, and E.F. Wood, 1991. A Daily Hydroclimatological Data Set for the

APPENDICES

APPENDIX A

TABLE A1: Station Index for IFLOWS Rain Gages

STATION INDEX	STATE	COUNTY	NAME	LATITUDE	LONGITUDE
3001	KY	BATH	OLYMPIA SPRINGS	38 03 52	83 38 52
3003	KY	BATH	PEELED OAK	38 03 41	83 47 52
3002	KY	BATH	REYNOLDSVILLE	38 11 30	83 49 00
3159	KY	BELL	ARJAY	36 48 30	83 39 00
3157	KY	BELL	KEWS 10-6	36 43 49	83 46 25
3160	KY	BELL	MIDDLESBORO	36 36 34	83 42 39
3158	KY	BELL	MINGO MOUNTAIN	36 33 32	83 43 45
3161	KY	BELL	YELLOW CREEK	36 40 05	83 41 19
3096	KY	BOYD	BOYD EOC	38 28 34	82 38 03
3098	KY	BOYD	HURRICANE	38 25 11	82 40 09
3097	KY	BOYD	PRINCESS	38 23 08	82 44 23
3099	KY	BOYD	WILDWOOD LAKE	38 26 57	82 39 15
3007	KY	BRACKEN	LENOXBURG	38 44 11	84 13 09
3009	KY	BRACKEN	POWERSVILLE	38 39 20	84 06 40
3008	KY	BRACKEN	TRIUMPH	38 39 20	84 06 40
3132	KY	BREATHITT	BEAN FORK	37 3434	83 31 31
3138	KY	BREATHITT	BELCHER	37 31 21	83 26 52
3133	KY	BREATHITT	EVANSTON	37 33 30	83 01 32
3134	KY	BREATHITT	KEWS 13-7	37 35 00	83 20 32
3135	KY	BREATHITT	ROBINSON	37 28 02	83 09 28
3137	KY	BREATHITT	SUGAR LUMP BR.	37 35 30	83 18 45
3139	KY	BREATHITT	TOWNHILL	37 32 42	83 23 50
3076	KY	CARTER	GLOBE	38 17 11	83 15 30
3078	KY	CARTER	KEWS 14-5	38 22 59	83 02 03
3079	KY	CARTER	SINKING CREEK	38 15 47	83 02 30
3077	KY	CARTER	WOLF	38 23 40	83 06 51
3187	KY	CLAY	BIG CREEK	37 09 38	83 33 30
3186	KY	CLAY	ONEIDA	37 17 38	83 37 34
3033	KY	ELLIOT	AULT	38 11 45	83 12 37
3034	KY	ELLIOT	DOCTOR TOWER	38 05 00	83 45 00
3032	KY	ELLIOT	ROCKY BRANCH	38 05 18	83 02 30
3072	KY	ELLIOT	SANDY HOOK	38 05 15	83 07 27
3010	KY	ESTILL	CHESTNUT STAND	37 43 32	83 56 53
3012	KY	FLEMING	CHESTNUT STAND	37 43 32	83 56 53
3015	KY	FLEMING	BEECHBURG	38 26 48	83 38 33
3013	KY	FLEMING	FAIRVIEW	38 26 37	83 53 23
3014	KY	FLEMING	FLEMINGSBURG	38 25 22	83 45 00
3011	KY	FLEMING	MUSE HILL	38 22 11	83 31 38
3103	KY	FLOYD	DAVID	37 36 52	82 52 06
3109	KY	FLOYD	DEWEY LAKE	37 42 28	82 44 33
3105	KY	FLOYD	LEFT BEAVER	37 30 20	82 42 36
3104	KY	FLOYD	MELVIN	37 21 49	82 41 06
3107	KY	FLOYD	MUD CREEK	37 27 00	82 41 20
3108	KY	FLOYD	RIGHT BEAVER	37 31 15	82 47 20
3106	KY	FLOYD	STANVILLE	37 33 53	82 37 53
3092	KY	FRANKLIN	BOONE CENTER	38 11 23	84 54 00
3086	KY	GREENUP	CULP CREEK	38 28 04	82 48 04
3087	KY	GREEN UP	GREEN UP E.C.	38 34 42	82 50 10
3085	KY	GREEN UP	OLD TOWN	38 26 12	82 54 13
3084	KY	GREEN UP	SHAPE	38 34 50	83 02 30
3142	KY	HARLAN	BIG BLACK	36 54 52	82 53 41
3146	KY	HARLAN	CUMBERLAND	36 58 26	82 59 38
3145	KY	HARLAN	E. JOHNS FARM	36 48 40	83 24 34
3144	KY	HARLAN	MARY HELEN	36 48 44	83 14 48
3141	KY	HARLAN	PUTNEY	36 55 36	83 13 26
3022	KY	JACKSON	MCKEE	37 27 52	84 00 40
3020	KY	JACKSON	POND LICK	37 19 17	83 59 35
3021	KY	JACKSON	SAND GAP	37 29 35	84 05 30
3117	KY	JOHNSON	FLAT GAP	37 55 21	82 52 25
3116	KY	JOHNSON	LEANDER	37 45 13	82 52 30
3120	KY	JOHNSON	LINDY BRANCH	37 52 03	82 5410
3121	KY	JOHNSON	OAK LOG	37 46 20	82 42 10
3119	KY	JOHNSON	PAINTSVILLE DAM	37 50 07	82 53 08
3118	KY	JOHNSON	PAINTSVILLE RADI	37 47 45	82 48 08

3179	KY	KNOTT	BIG BRANCH	37 17 05	82 59 12
3178	KY	KNOTT	BILL D. BRANCH	37 17 08	82 48 57
3180	KY	KNOTT	KEWS 13-9	37 20 29	82 52 59
3177	KY	KNOTT	OLD HOUSE BR.	37 22 02	82 45 32
3155	KY	KNOX	COLLINS FORK	37 00 08	83 48 15
3150	KY	KNOX	FLAG BRIDGE	36 43 16	83 52 52
3154	KY	KNOX	HELTON BRANCH	36 52 41	83 56 59
3151	KY	KNOX	HONEYCUTT BR.	36 51 52	83 45 57
3152	KY	KNOX	KEWS 10-5	36 56 42	83 58 10
3156	KY	KNOX	PIDGEON FORK	36 55 44	83 34 22
3153	KY	KNOX	STONEY FORK	36 49 01	83 52 59
3082	KY	LAWRENCE	BLAINE	38 02 30	82 49 23
3080	KY	LAWRENCE	KEWS 14-3	38 07 02	82 48 05
3083	KY	LAWRENCE	LOUISA	38 06 37	82 36 38
3023	KY	LEE	BEATTYVILLE	37 33 28	83 41 37
3026	KY	LEE	DELVINTA	37 30 17	83 47 17
3025	KY	LEE	KEWS 7-9 BEAR KY	37 37 33	83 46 15
3024	KY	LEE	LEECO	37 42 42	83 41 44
3181	KY	LESLIE	CUTSHIN	37 04 07	83 10 36
3185	KY	LESLIE	GREASY CREAK	37 00 09	83 15 25
3184	KY	LESLIE	KEWS 13-5	36 58 59	83 26 02
3182	KY	LESLIE	LUCINDA	37 08 28	83 28 42
3183	KY	LESLIE	POTATO KNOB	36 58 00	83 29 13
3165	KY	LETCHER	KEWS 13-10	37 04 36	82 48 07
3162	KY	LETCHER	KINGDOM COME	36 59 47	83 59 12
3163	KY	LETCHER	WHITESBURG AIR	37 13 09	82 52 25
3164	KY	LETCHER	YONTS FORK	37 14 01	82 42 32
3029	KY	LEWIS	DUNAWAY	38 27 28	83 31 21
3030	KY	LEWIS	ESKALAPIA	38 31 09	83 30 58
3028	KY	LEWIS	ROSE HILL	38 20 14	83 13 57
3031	KY	LEWIS	UPPER INDIAN	38 24 37	83 26 15
3027	KY	LEWIS	WALNUT RIDGE	38 19 45	83 19 35
3122	KY	MAGOFFIN	BACK BRANCH	37 42 28	83 07 59
3113	KY	MAGOFFIN	ELK KNOB	37 47 00	83 06 16
3110	KY	MAGOFFIN	FALCON (CASSIDY)	37 47 30	83 00 00
3115	KY	MAGOFFIN	FLAT FORK	37 50 18	83 02 29
3112	KY	MAGOFFIN	LITTLE HALF MTN.	37 40 08	83 00 14
3114	KY	MAGOFFIN	SIGNAL KNOB	37 29 05	82 55 46
3111	KY	MAGOFFIN	TRACE MOUNTAIN	37 50 00	83 10 24
3196	KY	MARTIN	BUFFALO HORN	37 56 40	82 30 56
3193	KY	MARTIN	INEZ	37 52 17	82 32 13
3194	KY	MARTIN	LAUREL FORK	37 45 57	82 29 12
3195	KY	MARTIN	MT. STERLING	37 45 16	82 20 55
3192	KY	MARTIN	SPRING KNOB	37 50 40	82 40 06
3018	KY	MASON	LEWISBURG	38 33 27	83 46 47
3016	KY	MASON	SARDIS	38 32 19	83 56 56
3017	KY	MASON	UNION CHURCH	38 35 39	83 54 56
3037	KY	MENIFEE	DAN	37 57 14	83 27 18
3035	KY	MENIFEE	FAGAN	37 54 45	83 41 40
3036	KY	MENIFEE	STONE QUARRY	37 59 24	83 37 33
3041	KY	MONTGOMERY	LULBEGRUD	38 00 44	83 57 01
3042	KY	MONTGOMERY	PRUITT RD	38 02 08	84 00 42
3039	KY	MONTGOMERY	SALT WELL	30 05 43	83 53 53
3038	KY	MONTGOMERY	SCIENCE RIDGE	37 58 41	83 48 51
3040	KY	MONTGOMERY	SHEDD CREEK	38 02 34	83 53 34
3044	KY	MORGAN	CHANNEL CITY	37 47 30	83 16 35
3043	KY	MORGAN	GRASSY CREEK	37 51 03	83 21 12
3045	KY	MORGAN	MAYTOWN	37 50 56	83 27 49
3047	KY	MORGAN	MIMA	37 55 22	83 03 29
3048	KY	MORGAN	WOLFPEN	38 03 36	83 17 09
3091	KY	NICHOLAS	NICHOLAS	38 19 00	84 07 00
3052	KY	OWSLEY	BOONEVILLE	37 29 24	83 37 46
3053	KY	OWSLEY	BUFFALO	37 22 46	83 38 25
3051	KY	OWSLEY	CLAY GAP	37 20 22	83 23 21
3166	KY	OWSLEY	KEWS 13-6	37 22 54	83 34 44
3054	KY	OWSLEY	LITTLE SURGEON	37 27 24	83 48 38
3159	KY	PERRY	BUFFALO	37 11 37	83 11 13

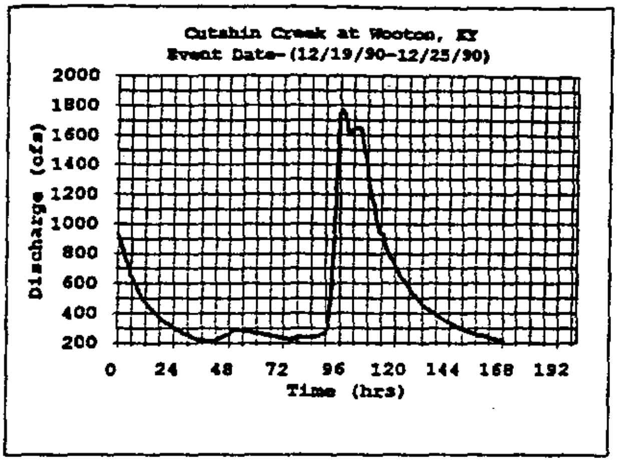
TABLE A2: Streamflow Characteristics for Continuous - Recording Gaging Stations in Eastern Kentucky (USGS 1991)

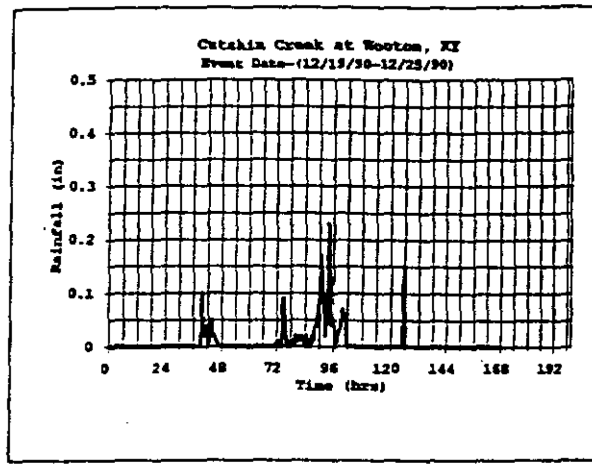
Station Number	Station Name	Drainage Area (mi^2)	Station Streamflow Variability index	Station Streamflow Recession Index (days/log cycle)	7-day 2-year low flow (ft^3/s)	7-day 10-year low flow (ft^3/s)
03208000	Levisa Fork Fishtrap Dam	392.0	0.655	18	8.60	1.3
03209500	Levisa Fork at Pikeville	1231.0	0.634	19	25.00	5.2
03210000	Johns Creek near Meta	56.3	0.720	19	0.68	0.0
03216500	Little Sandy River at Grayson	400.0	0.705	27	6.90	2.8
03216540	East Fork Little Sandy River near Fallsburg	12.2	1.06	18	0.00	0.0
03216800	Tygarts Creek at Olive Hill	59.6	0.829	22	0.34	0.0
03217000	Tygarts Creek near GREEN UP	242.0	0.746	18	2.40	0.3
03237900	Cabin Creek near Tollesboro	22.4	0.926	17	0.02	0.0
03248500	Licking River near Salyersville	140.0	0.711	28	2.10	0.0
03249500	Licking River at Farmers	827.0	0.676	25	18.00	4.8
03250100	North Fork Triplett Creel near Morehead	84.7	0.913	19	0.28	0.0
03277450	Carr Fork near Sassafras	60.6	0.704	23	0.92	0.0
03277500	North Fork Kentucky River at Hazard	466.0	0.627	29	8.80	2.1
03280000	North Fork Kentucky River at Jackson	1101.0	0.645	24	24.00	3.1
03280600	Middle Fork Kentucky River near Hyden	202.0	0.701	22	2.30	0.0
03280700	Cutshin Creek at Wooton	61.3	0.698	21	0.86	0.1
03281000	Middle Fork Kentucky River at Tallega	537.0	0.724	20	6.90	0.8
03281040	Red River near Big Creek	155.0	0.667	24	2.20	0.7
03281100	Goose Creek at Manchester	163.0	0.703	25	1.80	0.3
03281500	South Fork Kentucky River at Booneville	722.0	0.705	21	11.00	1.0
03282500	Red River at Hazel Green	65.8	0.764	20	0.45	0.0
03283500	Red River at Clay City	362.0	0.606	27	12.00	3.8
03400500	Poor Fork at Cumberland	82.3	0.488	33	9.40	4.6
03401000	Cumberland River near Harlan	374.0	0.523	33	32.00	13.0
03402000	Yellow Creek near Middlesboro	60.6	0.554	31	5.20	2.5
03403000	Cumberland River near Pikeville	809.0	0.566	32	50.00	16.0

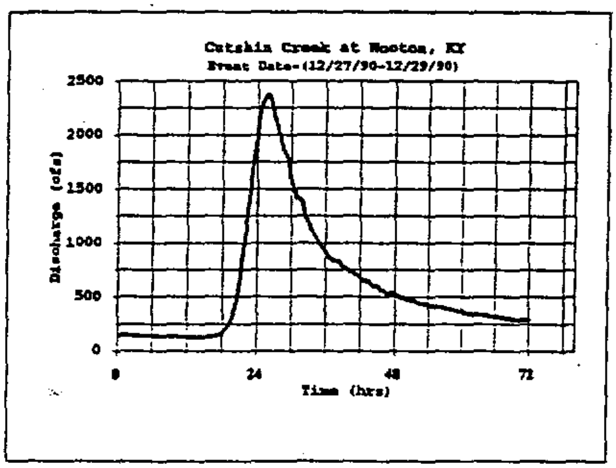
APPENDIX B

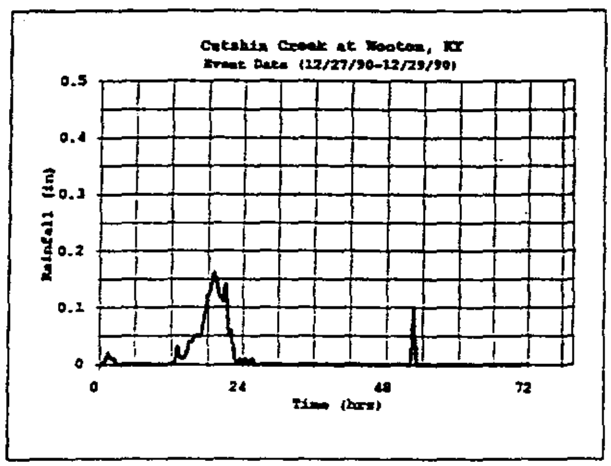
FIG. B1. STREAMFLOW DISCHARGE AND CORRESPONDING RAINFALL FOR SELECTED FLOOD EVENT IN THE FOLLOWING EASTERN KENTUCKY WATERSHEDS

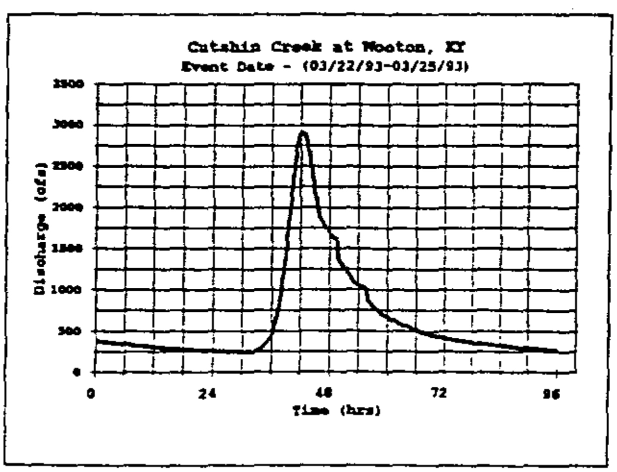
CUTSHIN CREEK AT WOOTON

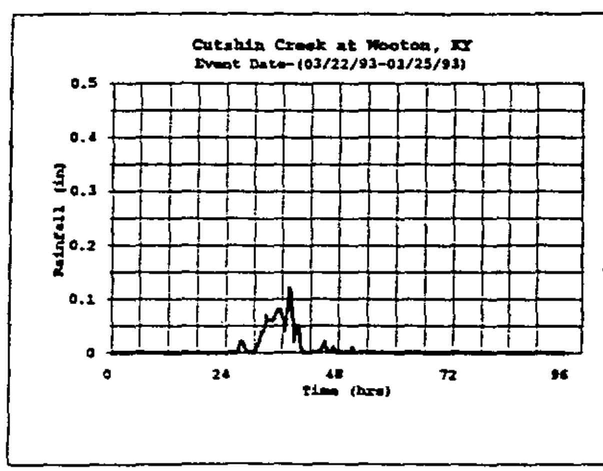


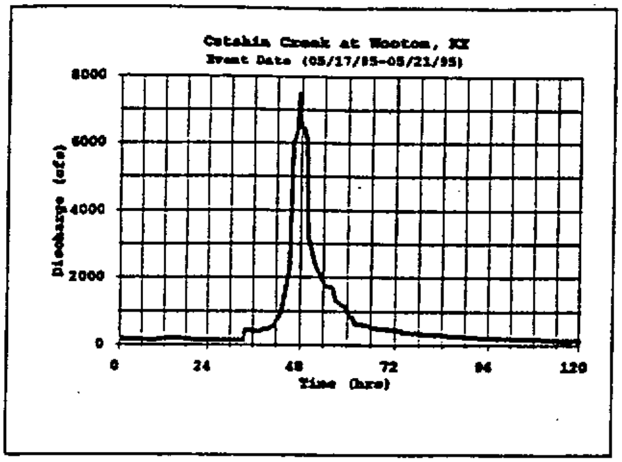


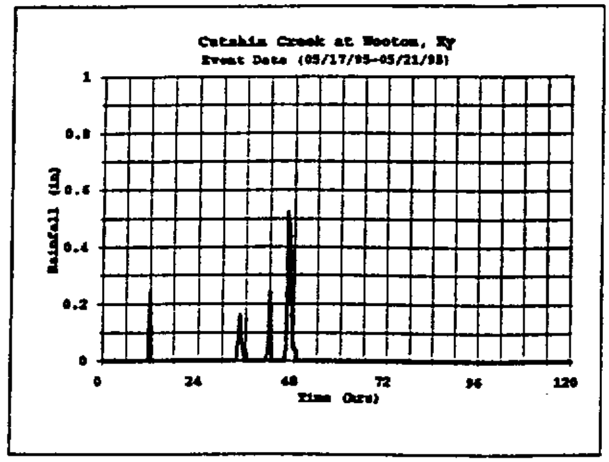




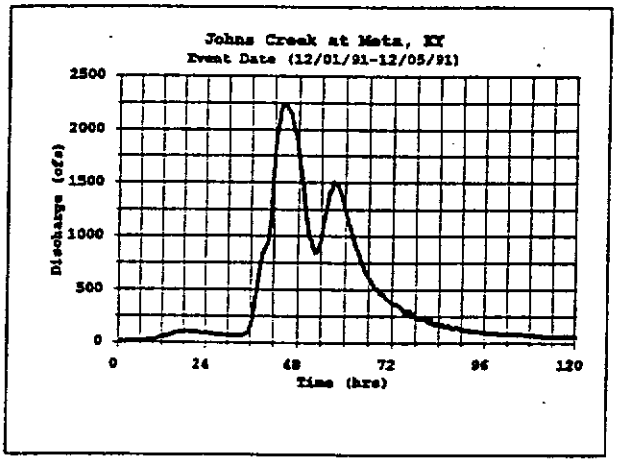


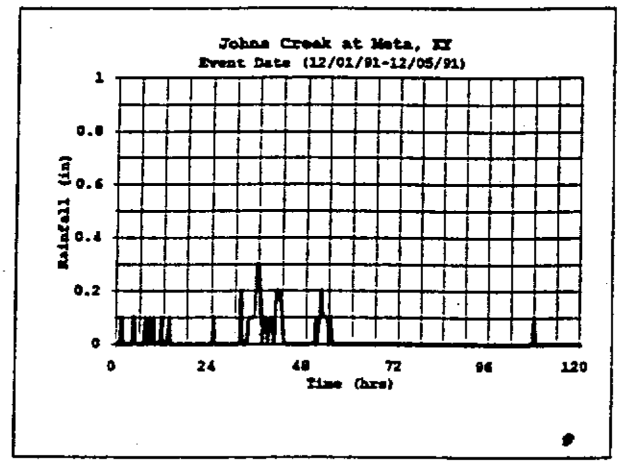


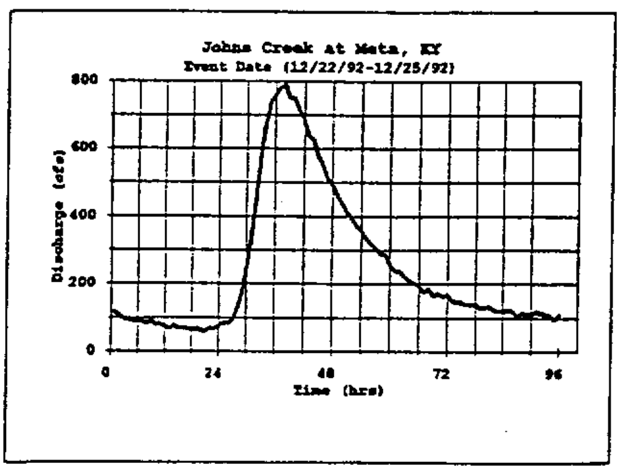


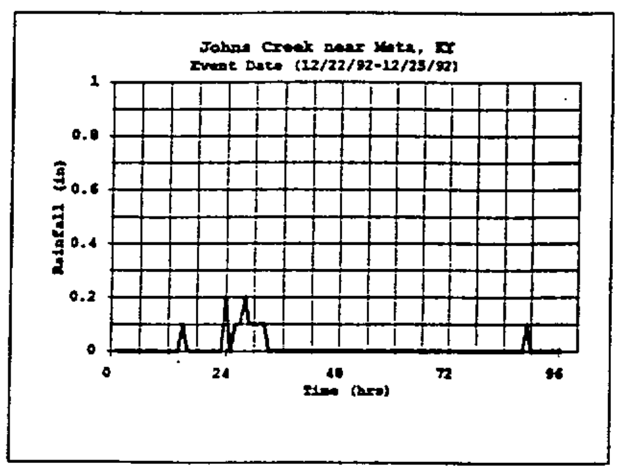


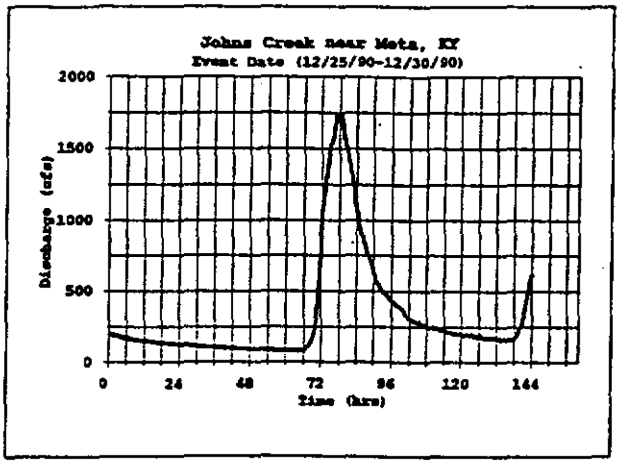
JOHNS CREEK AT META

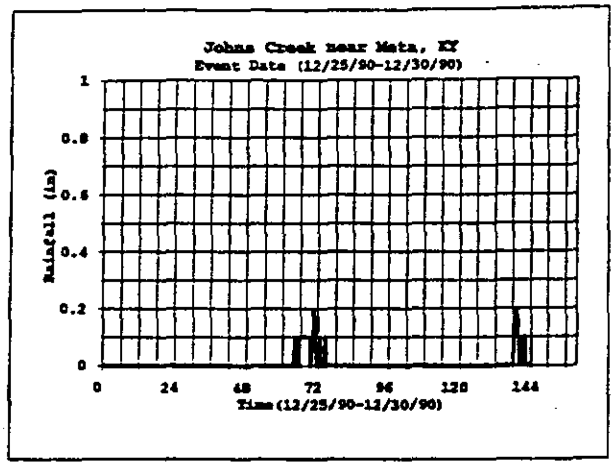


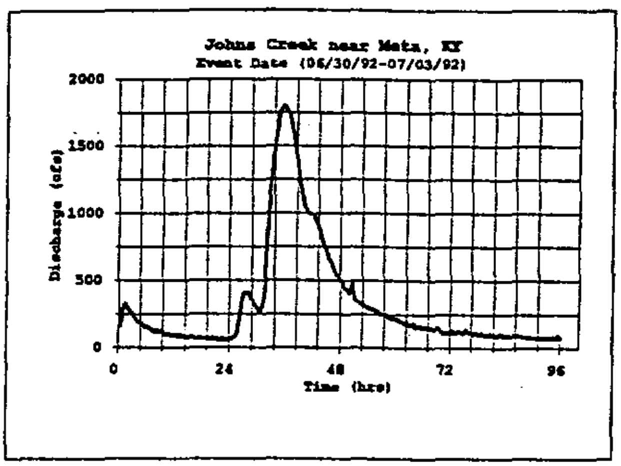


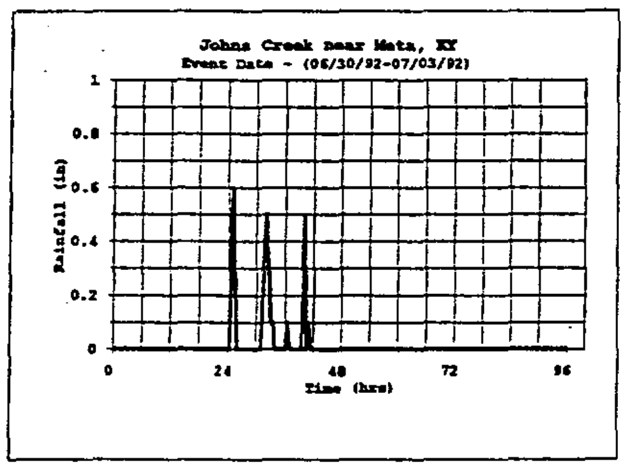


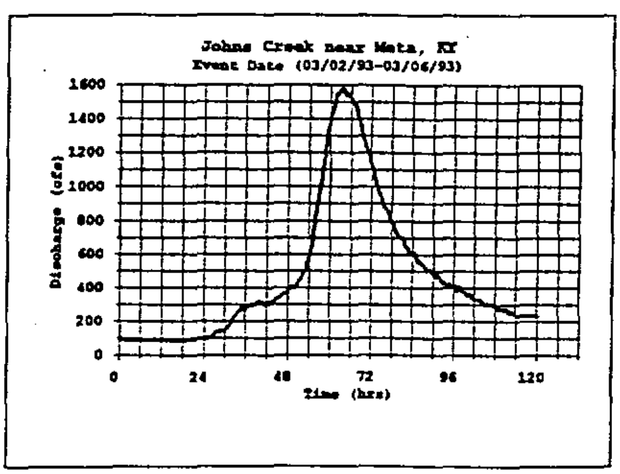


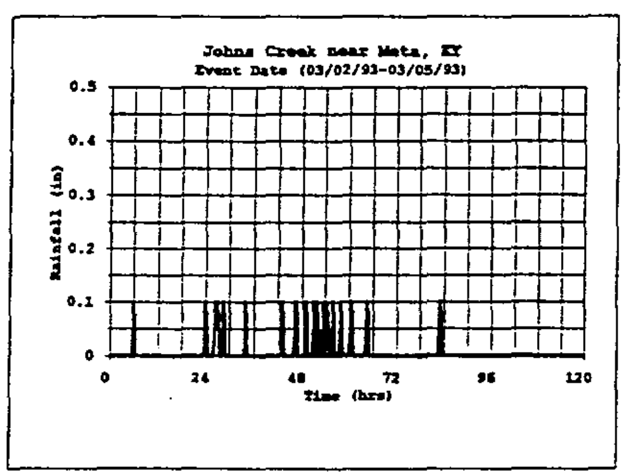

Johns Creek near Meta, KY
Event Date (12/25/90-12/30/90)
Discharge (cfs)
2000
1500
1000
500
0
0
24
48
72
96
120
144
Time (hrs)

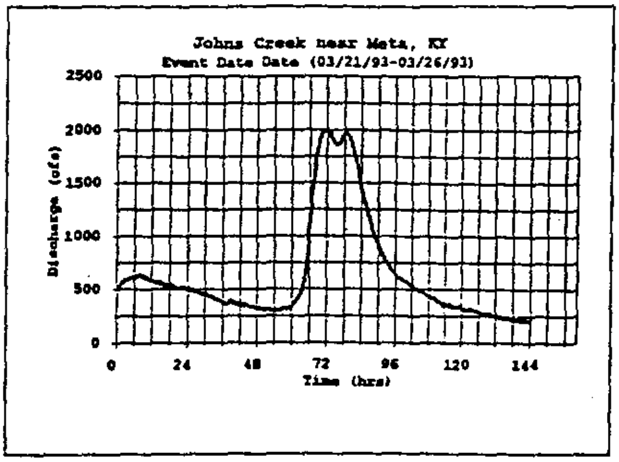

Johns Creek near Meta, KY
Event Date (12/25/90-12/30/90)
Rainfall (in)
1
0.8
0.6
0.4
0.2
0
0
24
48
72
96
120
144
Time(12/25/90-12/30/90)

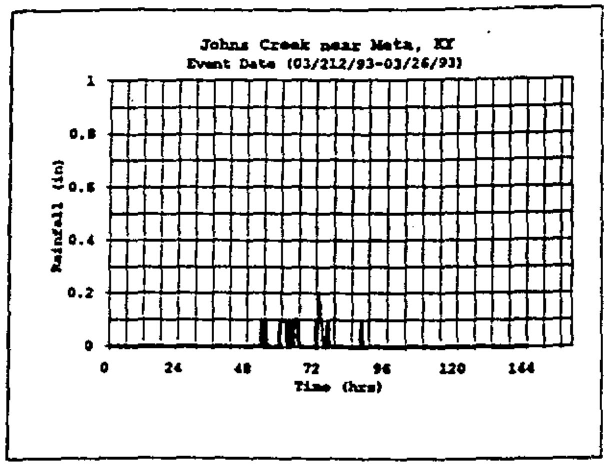

Johns Creek near Meta, KY
Event Date (06/30/92-07/03/92)
Discharge (cfs)
2000
1500
1000
500
0
0
24
48
72
96
Time (hrs)

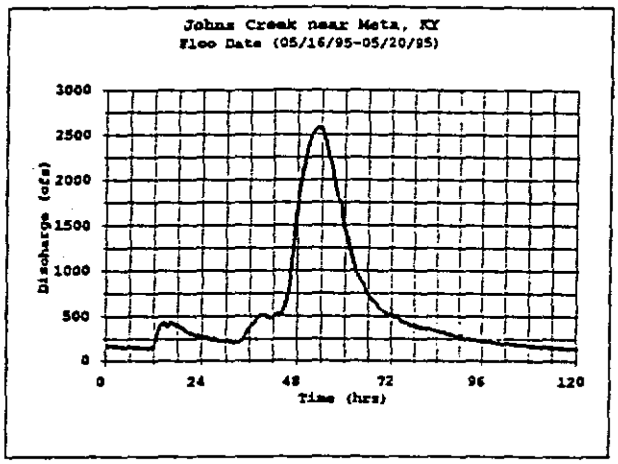

Johns Creek near Meta, KY
Event Date - (06/30/92-07/03/92)
Rainfall (in)
1
0.8
0.6
0.4
0.2
0
0
24
48
72
96
Time (hrs)

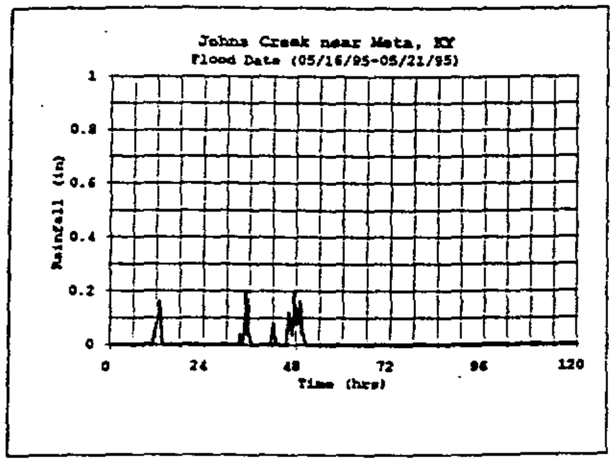

Johns Creek near Meta, KY
Event Date (03/02/93-03/06/93)
Discharge (cfs)
1600
1400
1200
1000
800
600
400
200
0
0
24
48
72
96
120
Time (hrs)


Johns Creek near Meta, KY
Event Date (03/02/93-03/05/93)
Rainfall (in)
0.5
0.4
0.3
0.2
0.1
0
0
24
48
72
96
120
Time (hrs)

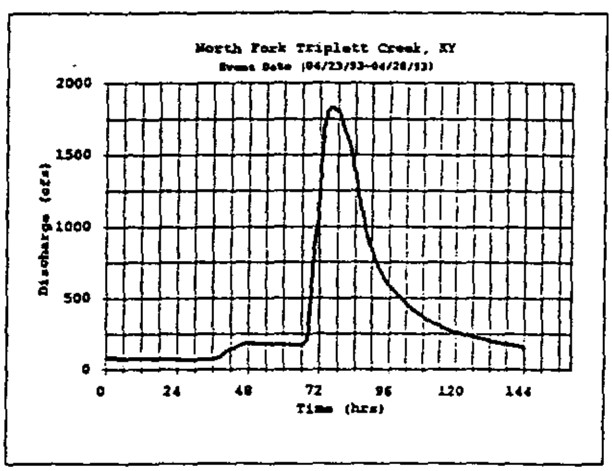


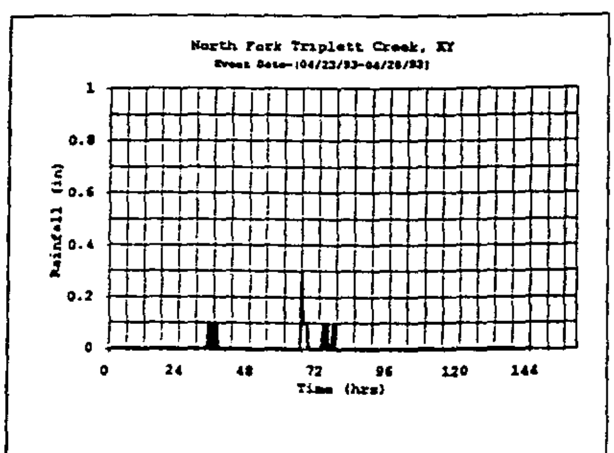


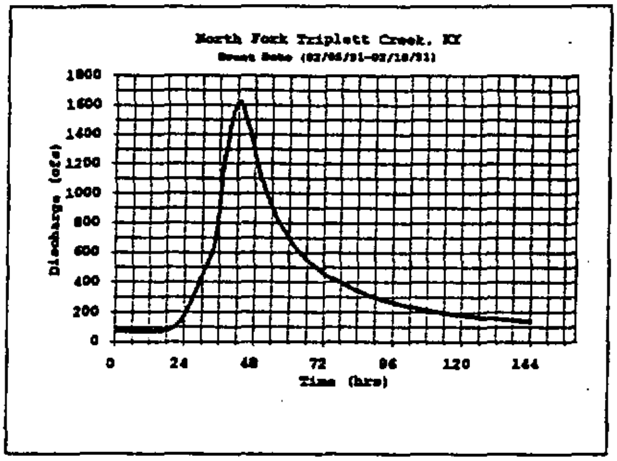


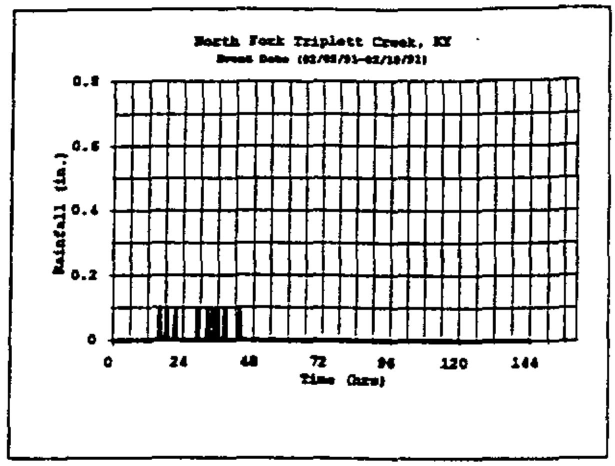


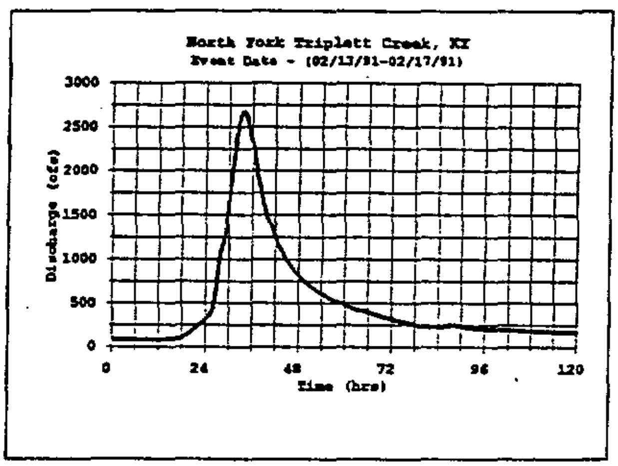
NORTH FORK TRIPLETT CREEK NEAR MOREHEAD

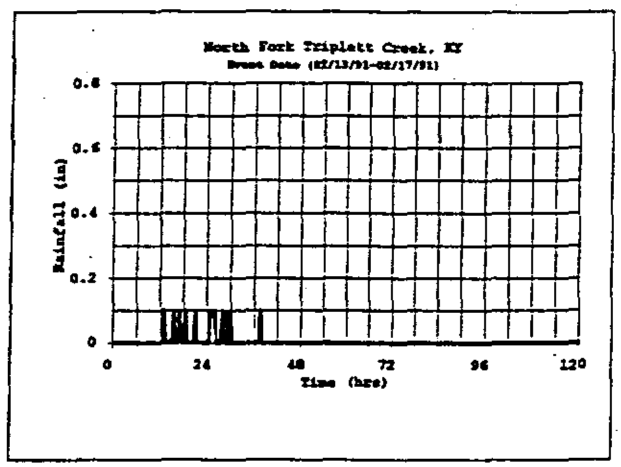


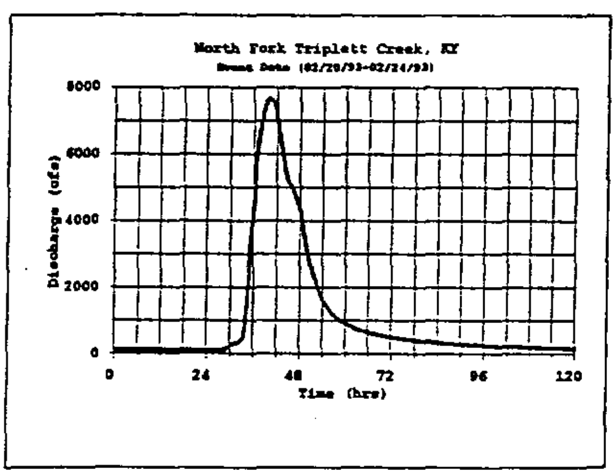


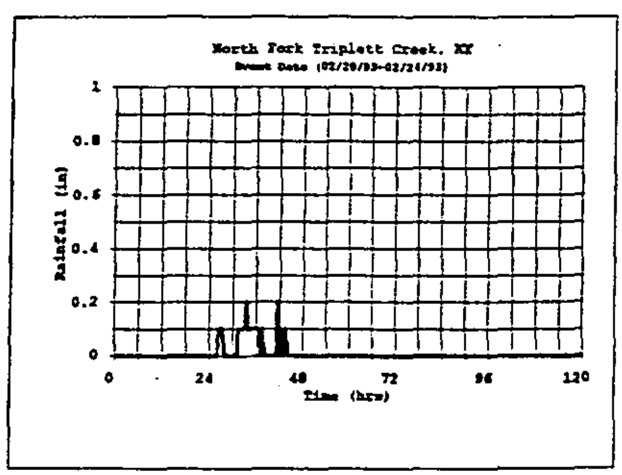

North Fork Triplett Creek, KY
Discharge (cfs)
Time (hrs)

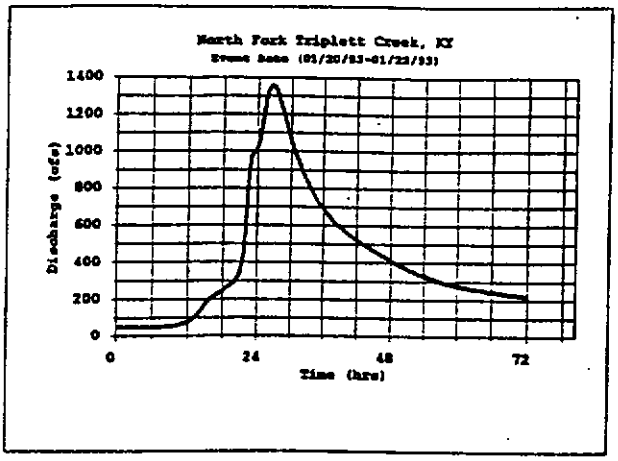

North Fork Triplett Creek, KY
Rainfall (in.)
Time (hrs)

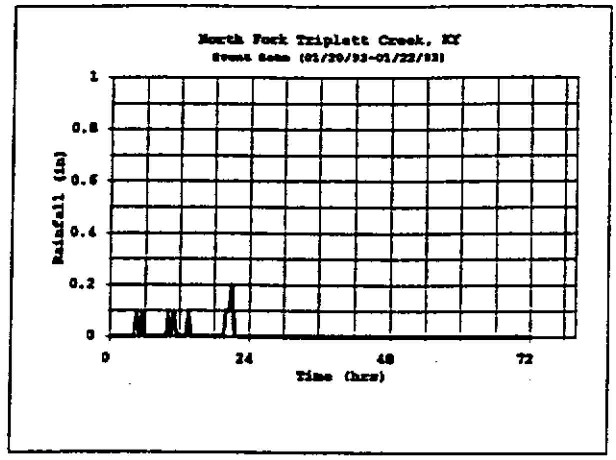

North Fork Triplett Creek, KY
Event Date - (02/13/91-02/17/91)
Discharge (cfs)
Time (hrs)

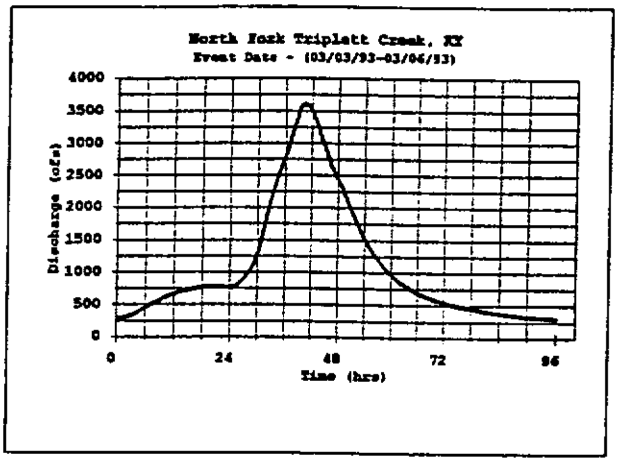

North Fork Triplett Creek, KY
Rainfall (in)
Time (hrs)

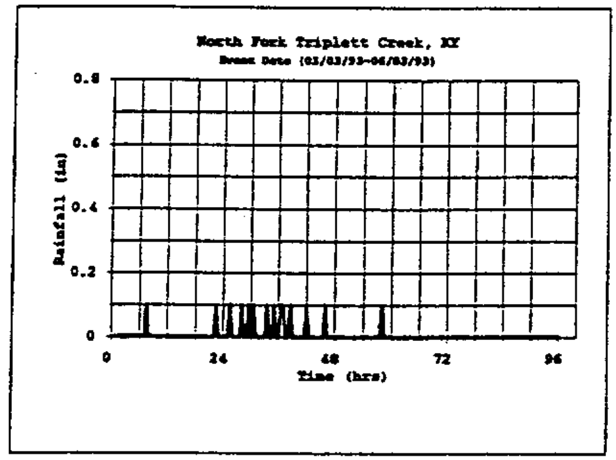

North Fork Triplett Creek, KY
Discharge (cfs)
Time (hrs)

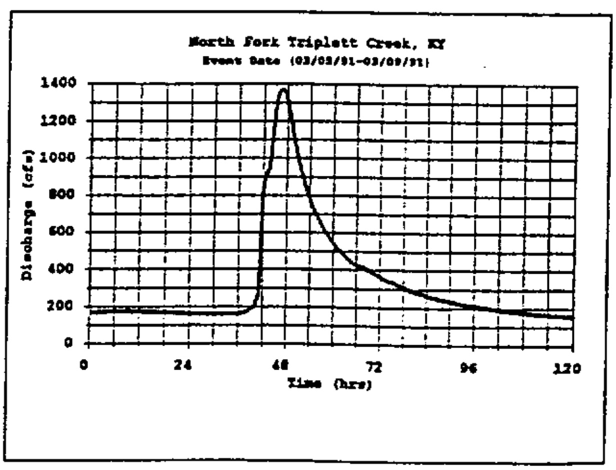

North Fork Triplett Creek, KY
Rainfall (in)
Time (hrs)

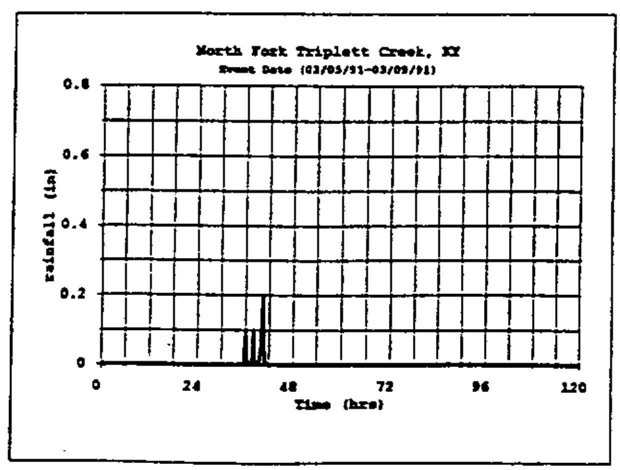

North Fork Triplett Creek, KY
Event Date (01/20/93-01/22/93)
1400
1200
1000
800
600
400
200
0
Discharge (cfs)
0
24
48
72
Time (hrs)

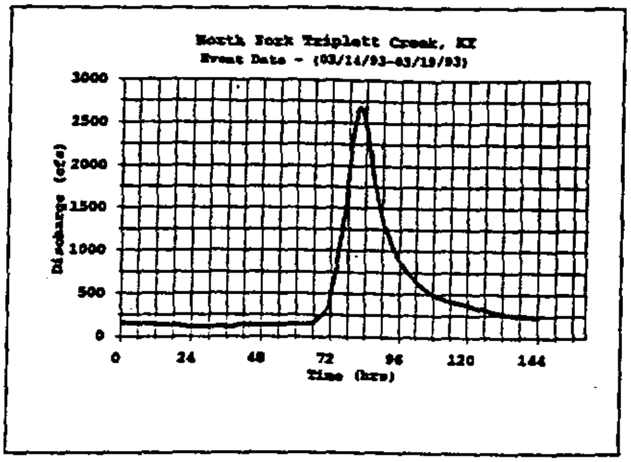

North Fork Triplett Creek, KY
Event Date (01/20/93-01/22/93)
1
0.8
0.6
0.4
0.2
0
Rainfall (in)
0
24
48
72
Time (hrs)

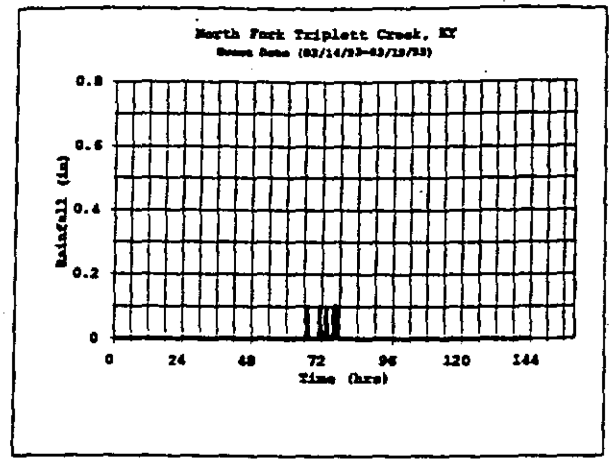

North Fork Triplett Creek, KY
Event Date - (03/03/93-03/06/93)
4000
3500
3000
2500
2000
1500
1000
500
0
Discharge (cfs)
0
24
48
72
96
Time (hrs)

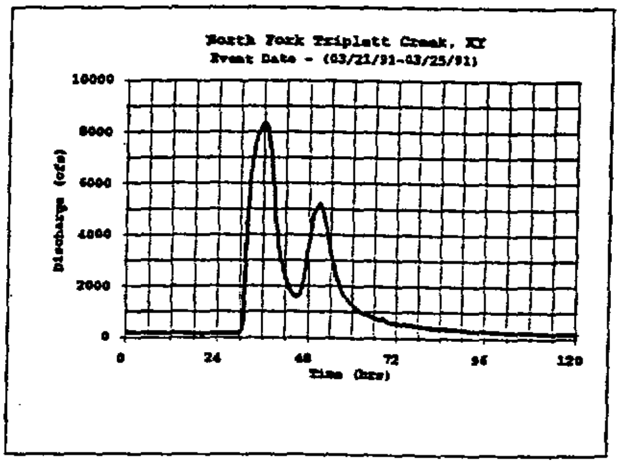

North Fork Triplett Creek, KY
0.8
0.6
0.4
0.2
0
Rainfall (in)
0
24
48
72
96
Time (hrs)

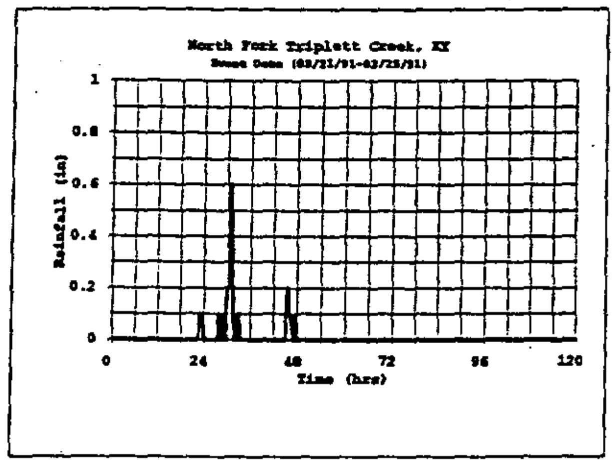

North Fork Triplett Creek, KY
1400
1200
1000
800
600
400
200
0
Discharge (cfs)
0
24
48
72
96
120
Time (hrs)


North Fork Triplett Creek, KY
0.8
0.6
0.4
0.2
0
rainfall (in)
0
24
48
72
96
120
Time (hrs)

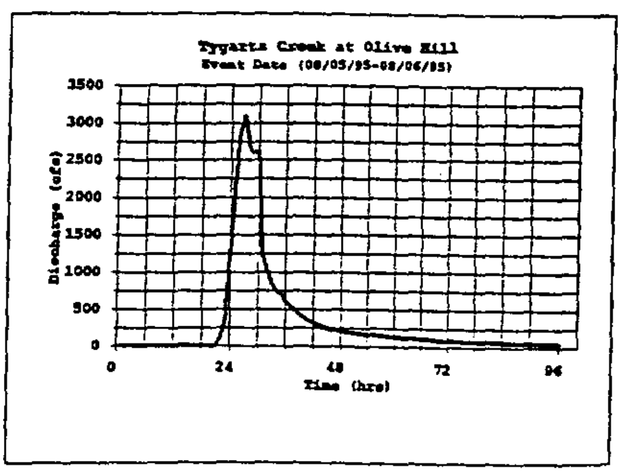


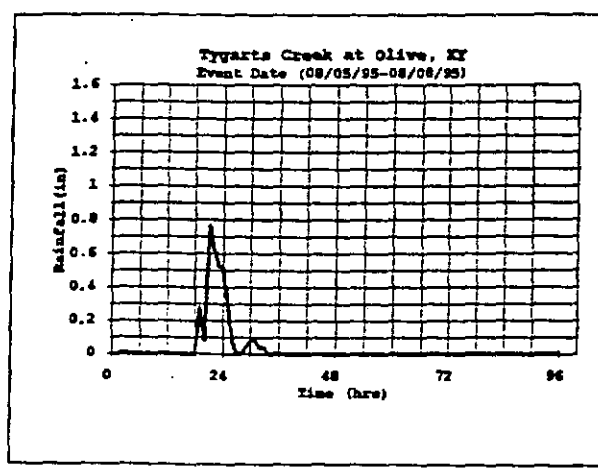


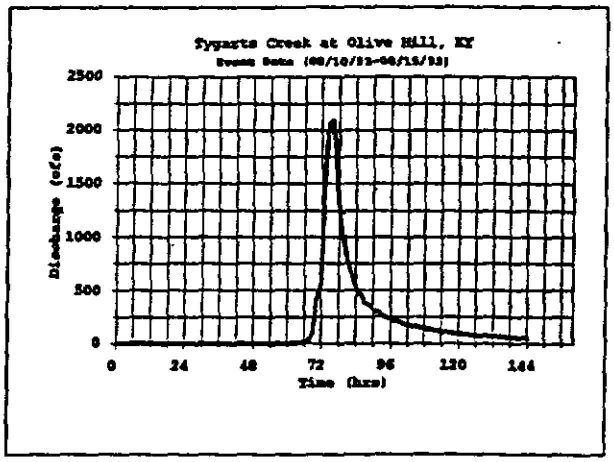




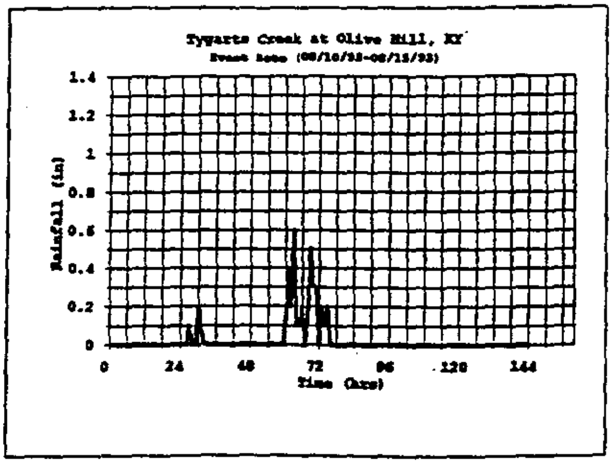
TYGARTS CREEK AT OLIVE HILL



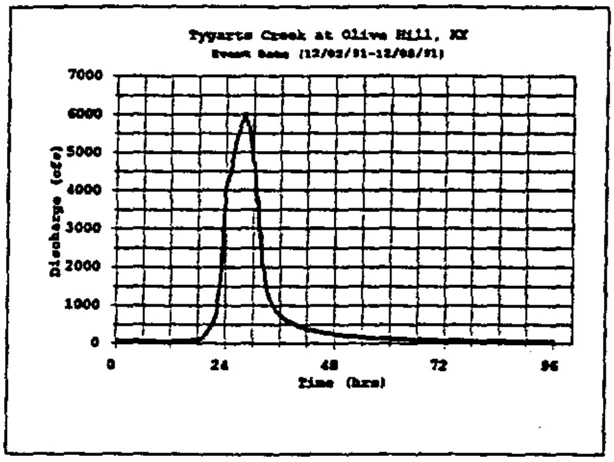




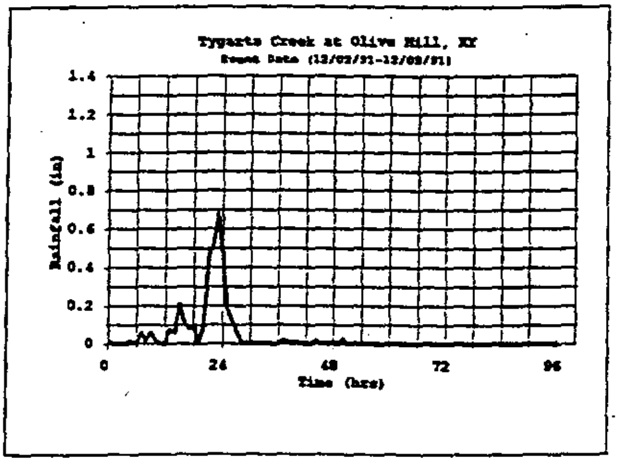
Tygarts Creek at Olive Hill, KY
Event Date (08/10/93-08/15/93)
Discharge (cfs)
2500
2000
1500
1000
500
0
0 24 48 72 96 120 144
Time (hrs)



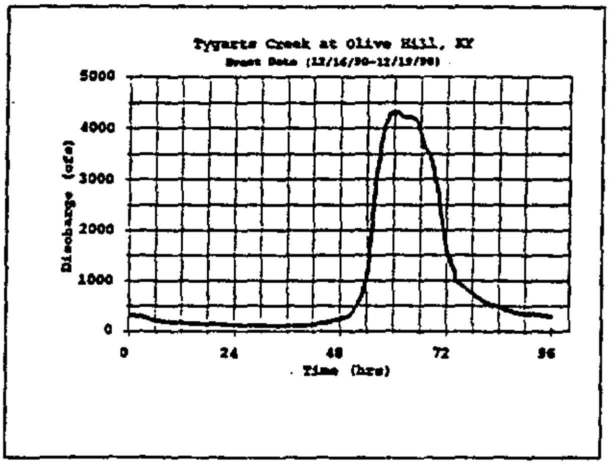
Tygarts Creek at Olive Hill, KY
Event Date (08/10/93-08/15/93)
Rainfall (in)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0 24 48 72 96 120 144
Time (hrs)



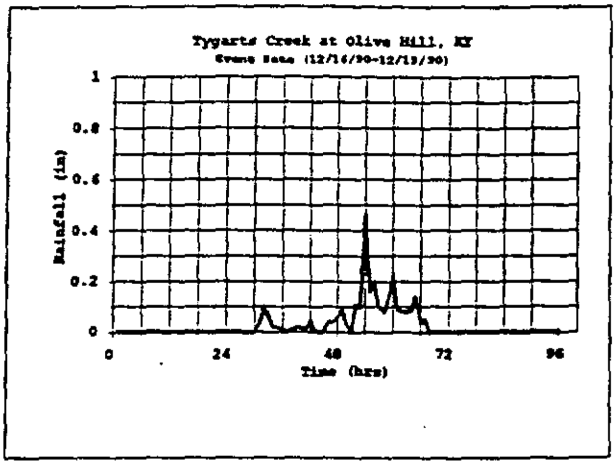
Tygarts Creek at Olive Hill, KY
Event Date (12/02/91-12/06/91)
Discharge (cfs)
7000
6000
5000
4000
3000
2000
1000
0
0 24 48 72 96
Time (hrs)



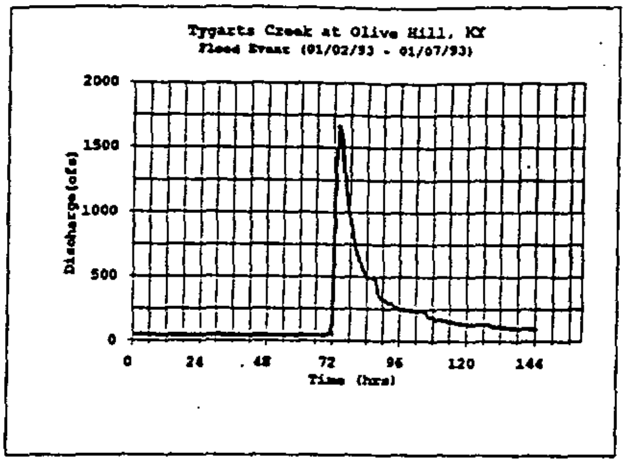
Tygarts Creek at Olive Hill, KY
Event Date (12/02/91-12/06/91)
Rainfall (in)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0 24 48 72 96
Time (hrs)

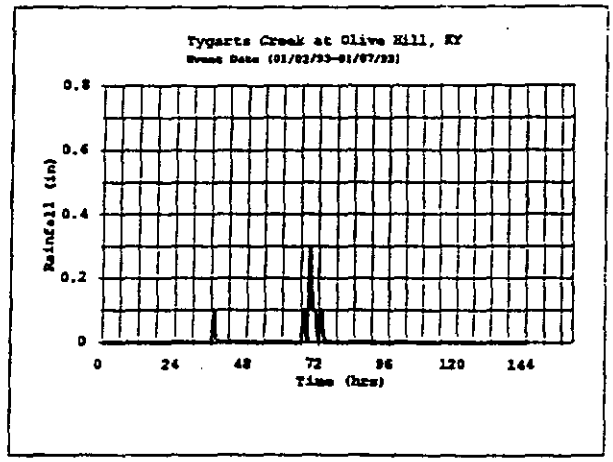


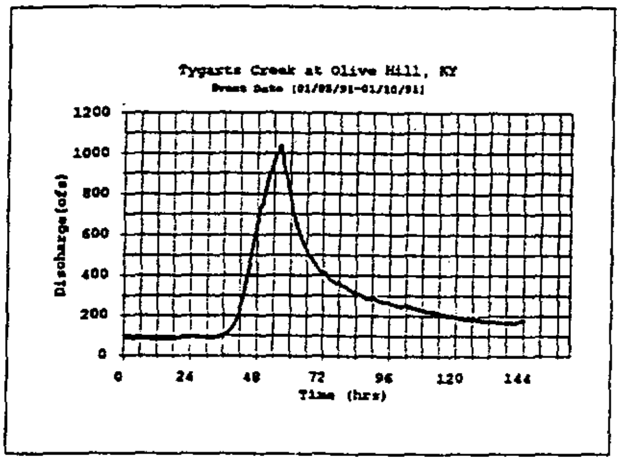
Tygarts Creek at Olive Hill, KY
Event Date (12/16/90-12/19/90)
Discharge (cfs)
5000
4000
3000
2000
1000
0
0 24 48 72 96
Time (hrs)

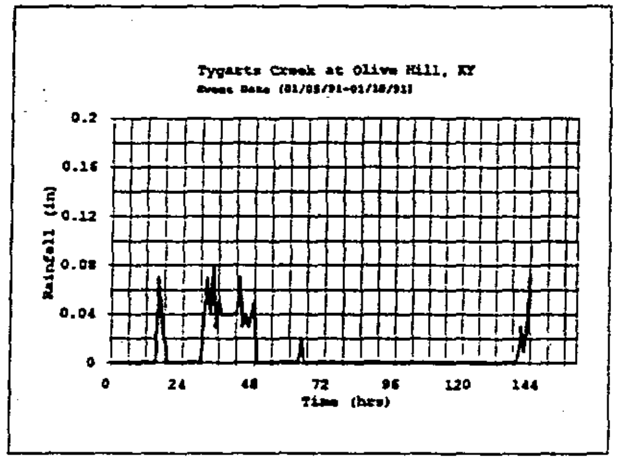


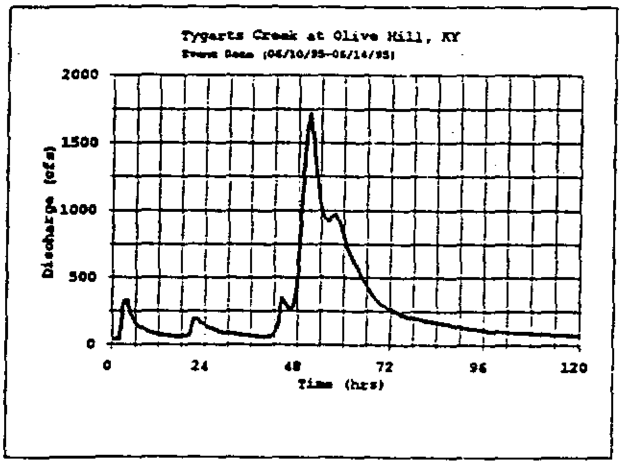
Tygarts Creek at Olive Hill, KY
Event Date (12/16/90-12/19/90)
Rainfall (in)
1
0.8
0.6
0.4
0.2
0
0 24 48 72 96
Time (hrs)

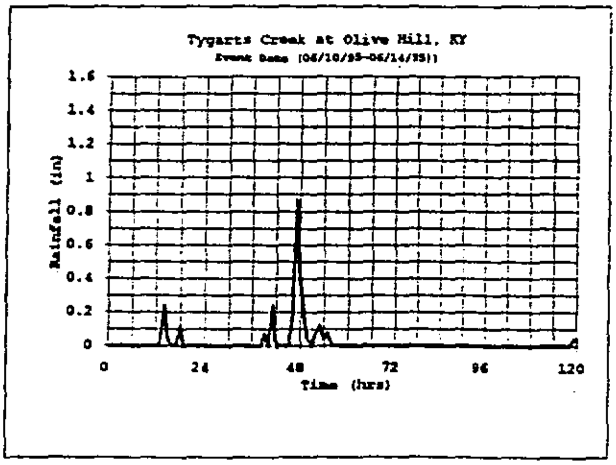

Tygarts Creek at Olive Hill, KY
Flood Event (01/02/93 - 01/07/93)
Discharge(cfs)
2000
1500
1000
500
0
0
24
48
72
96
120
144
Time (hrs)

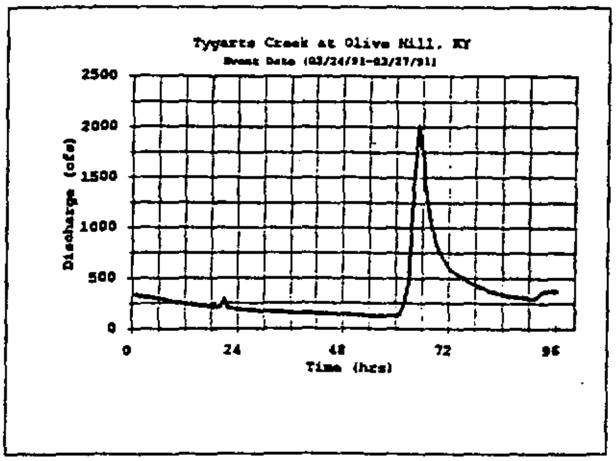

Tygarts Creek at Olive Hill, KY
Rainfall (in)
0.8
0.6
0.4
0.2
0
0
24
48
72
96
120
144
Time (hrs)

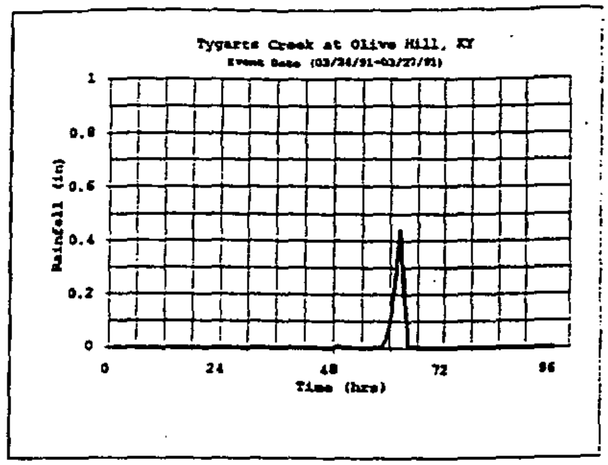

Tygarts Creek at Olive Hill, KY
Discharge(cfs)
1200
1000
800
600
400
200
0
0
24
48
72
96
120
144
Time (hrs)

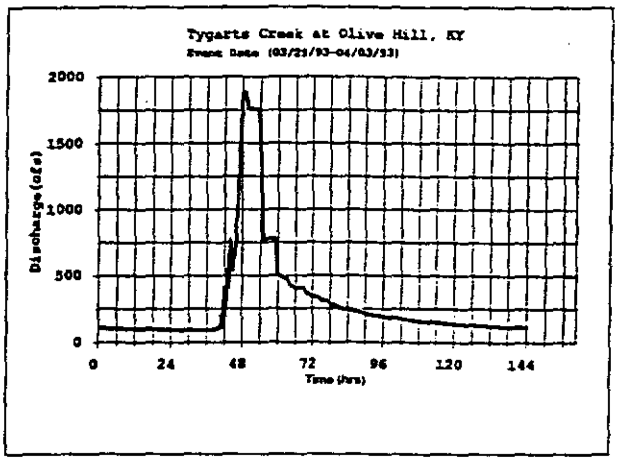

Tygarts Creek at Olive Hill, KY
Rainfall (in)
0.2
0.16
0.12
0.08
0.04
0
0
24
48
72
96
120
144
Time (hrs)

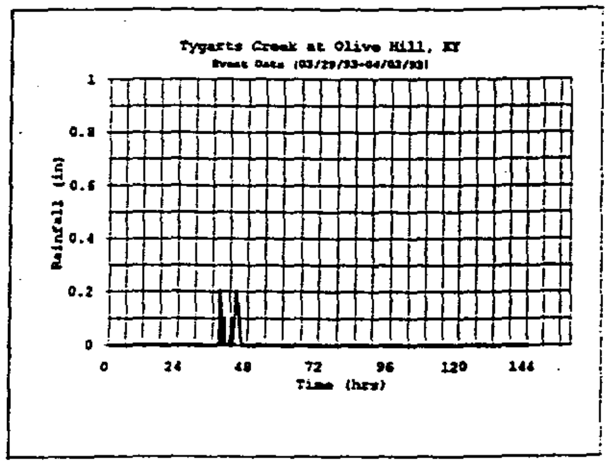

Tygarts Creek at Olive Hill, KY
Discharge (cfs)
2000
1500
1000
500
0
0
24
48
72
96
120
Time (hrs)

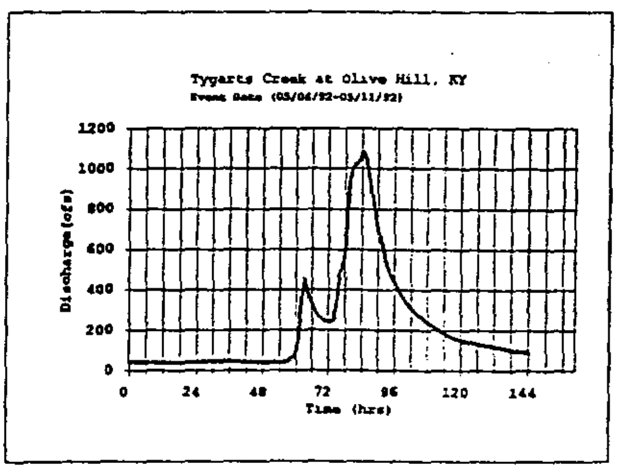

Tygarts Creek at Olive Hill, KY
Rainfall (in)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
24
48
72
96
120
Time (hrs)

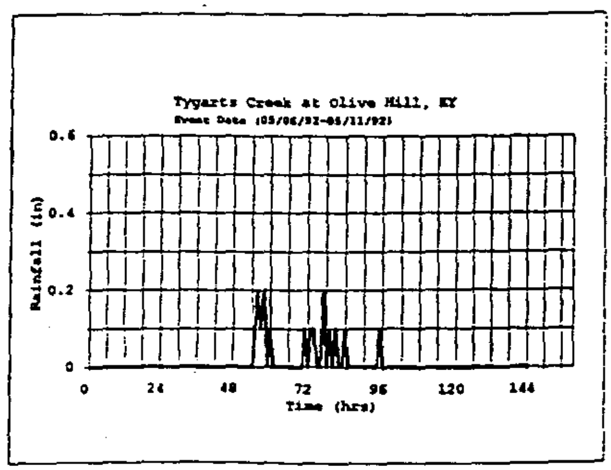

Tygarts Creek at Olive Hill, KY
Discharge (cfs)
Time (hrs)

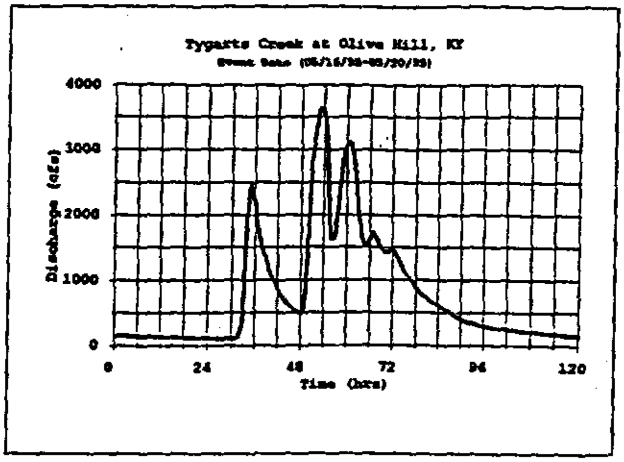

Tygarts Creek at Olive Hill, KY
Rainfall (in)
Time (hrs)

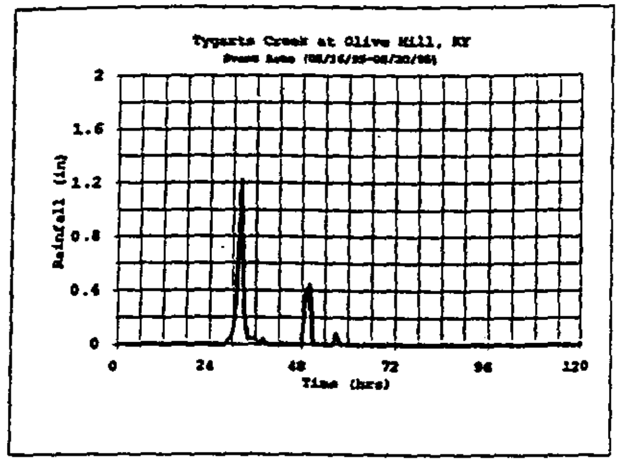

Tygarts Creek at Olive Hill, KY
Discharge(cfs)
Time (hrs)


Tygarts Creek at Olive Hill, KY
Rainfall (in)
Time (hrs)


Tygarts Creek at Olive Hill, KY
Discharge(cfs)
Time (hrs)


Tygarts Creek at Olive Hill, KY
Rainfall (in)
Time (hrs)


Tygarts Creek at Olive Hill, KY
4000
3000
2000
1000
0
Discharge (cfs)
0
24
48
72
96
120
Time (hrs)


Tygarts Creek at Olive Hill, KY
2
1.6
1.2
0.8
0.4
0
Rainfall (in)
0
24
48
72
96
120
Time (hrs)