LATE HOLOCENE PALEOFLOOD RECONSTRUCTION
OF LOWER BLACK BEAR CREEK IN
NORTH-CENTRAL OKLAHOMA

By

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CHAPTER I

INTRODUCTION

Flood frequency analysis for gauged rivers is based upon a limited number of data points restrained by the length of the gauging record. Large flood events with large recurrence intervals represent extreme events, and usually are not included in conventional, statistical approaches in flood frequency studies (Costa, 1978). Geomorphic evidence from flood events occurring in the recent geologic past can provide improved estimates of the recurrence interval of large floods. The Holocene stratigraphic flood record may enhance the methods for assessing human risk from outstanding floods, and extends the historical flood record thousands of years. The Holocene epoch is considered to extend from 10,000 years B.P. to the present.

Holocene paleoflood reconstruction is based upon the Principle of Uniformitarianism, the assumption that river processes are the same today as in the geologic past. The concept of Actualism (Playfair, 1802) is more realistic in paleoflood reconstruction, because precipitation processes generating floods have not been stationary during the Holocene. The acceptance of what has happened in the recent geologic past, however, is likely to happen in the geologic future, and is a likely assumption when dealing with the estimation of the return intervals of rare, flood events (Baker and Costa, 1987). Reconstruction of large historic floods can be extended through the application of Holocene stratigraphic deposits.

The most widely accepted and most accurate method involves the analysis of slackwater deposits. Slackwater deposits are fine-grained (usually fine sand and coarse silt) flood sediments deposited in areas of low velocities during flood events. These deposits provide a minimum estimate of the flood stage which emplaced them and allow an estimation of discharge through computer modelling. Flood frequency records can be extended by using paleoflood chronology produced from radiocarbon dating of slackwater deposits and the associated paleosols. Thus, radiocarbon dating of alluvial deposits provides a chronostratigraphy of events, and gives insight into temporal changes of flood events.

Paleoflood reconstruction using slackwater deposits and associated paleosols can be used as a long-term view of the changing hydrologic conditions as related to the climate (Knox, 1985). Paleohydrologic reconstructions can be used along with other climatic indices to evaluate the magnitude and impact of climatic shifts throughout the Holocene (Patton and Dibble, 1982).

The use of slackwater deposits, based upon paleoflood reconstruction, is well established in bedrock channels, and has been successfully applied to rivers in the southwestern United States. The alluvial geology of numerous stream valleys in the southern Great Plains of Texas and Oklahoma has been investigated during the past 12 years in conjunction with archaeological projects (Hall, 1990). None of these studies dealt exclusively with the reconstruction of rare, paleoflood events and the dating of these events using paleosols or slackwater deposits.

Human loss of life and property damage may be sustained when a flood with a return period longer than the historical gaging record occurs. Floodplain zoning and floodplain control structures are currently based on conventional, statistical analyses of records of stream flow or precipitation events which typically represent a small sample size (Kochel, 1980). A more representative sample of the population may be obtained by including the Holocene stratigraphic record. Large magnitude floods which occur during historical times may prove not to be outliers when the stratigraphic record of flood events is included in the sample. Overdesign or underdesign of flood control structures may be more realistically assessed when Holocene flood deposits are included in the statistical analysis of rare flood events.

This study was conducted in an alluvial channel in a nonglaciated portion of the southern Great Plains. Paleoflood reconstructions are based on slackwater deposits and radiocarbon dating of associated A horizons of buried soils. This dissertation shows that slackwater deposits in this region can assist in paleoflood studies and provide a conceptual framework that could be applied to flood studies in similar settings.

Purpose Of Study

Investigations in this study are based upon the chronosequence and reconstruction of paleofloods as generated by climatic characteristics of the Holocene in the Great Plains. The southern Great Plains is a region straddled by a transition zone of climatic fluctuations. Holocene stratigraphic deposits will be used to interpret flood events of the past. Although, alluvial channels in humid climatic settings have not been used in models for paleoflood reconstructions to any large extent, slackwater deposits and other paleostage indicators can be found in humid environments. Field work and laboratory methods in the study area have proven that evidence of paleoflooding has been preserved.

Paleoflood reconstruction of the Holocene assumes that the channel reach has been stable during the time of study to provide uniformity. Stability has been maintained in places by resistant limestone and sandstone bedrock which controls the alluvial channel course although how stability changes over time is not known. Prominent outcrops are present in the main channel and along tributary streams. Aerial photographs and Landsat imagery of the study reach exhibit stability ie., lack of oxbow lakes, and channel avulsions.

Precise dating of major flood events indicates that distinct depositional events have occurred. The minimum date of occurrence of a catastrophic flood event can be determined by dating the upper portion of a paleosol overlain by a distinct slackwater unit. Within the study area prominent paleosols have been found which are overlain by well-preserved slackwater sequences.

This study addresses the relevancy of paleoflood reconstruction and the relationship of geomorphic characteristics to climatic events in the region. Questions addressed are:

(1) Are the paleoflood records preserved along major tributaries representative of the paleoflood history of lower Black Bear Creek?
(2) Will the slackwater deposits provide a reasonable estimate of the stage of paleoflood events?
(3) Can Holocene stratigraphic deposits in humid, alluvial settings extend the historical record of flood frequencies?
(4) Can paleoclimates of the area be inferred from slackwater deposits and paleosol relationships?

The purpose of this study will be to provide answers to these questions, and to provide an assessment of the paleoflood history of this area.

Specific Objective

The specific objective is to investigate the applicability of using slackwater deposits in paleoflood reconstruction in alluvial channels within a humid climatic setting. Large paleoflows in the lower Black Bear Creek system are of particular interest. Climatic implications are inferred from several sites and supported by field and laboratory methods. Paleohydrologic reconstructions will be used along with other climatic indices to evaluate the impact of climatic shifts throughout the Holocene. This study will help to assess the importance of flood events in influencing the development of the fluvial landscape.

Study Area

Black Bear Creek, located in north-central Oklahoma, in Pawnee, Payne, Noble, and Garfield counties, is an east-west trending stream with its headwaters located approximately 8 kilometers east of Enid, Oklahoma (Figure 1.1). It has a total drainage area of fifteen hundred square kilometers. The stream flows eastward for one-hundred and five kilometers to its confluence with the Arkansas River six kilometers northeast of Skedee, Oklahoma.

Because of the size of the drainage basin, the study area has been designated as the lower portion of Black Bear Creek which includes the lower forty kilometers of the main stream and its tributaries between the town of Morrison and the Arkansas River (Figure 1.1). This drainage area of five hundred and fourty-one square kilometers includes eighty kilometers of actual channel length. Major tributaries of the study area, Turkey Creek, Pepper Creek, Skedee Creek, Camp Creek, and Crystal Creek, are labeled on Figure 1.1.

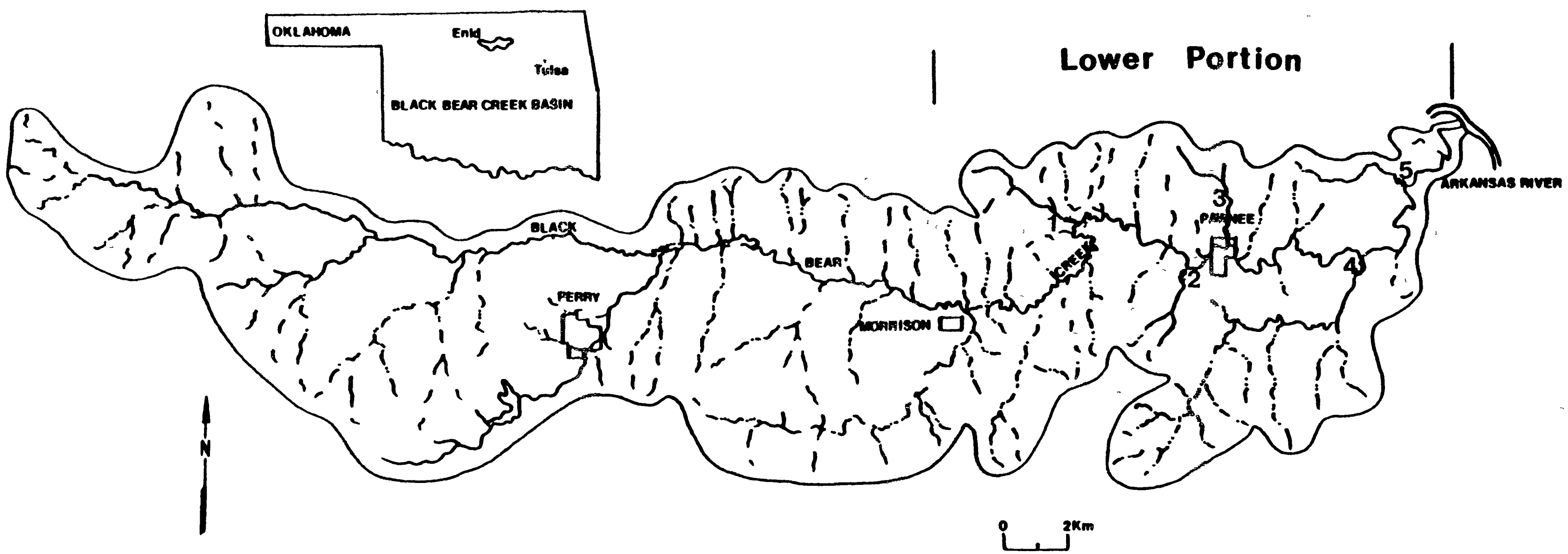

Figure 1.1. Location map of Black Bear Creek drainage basin and study reach. Numbers indicate tributaries used in study: 1. Turkey Creek; 2. Pepper Creek; 3. Skedee Creek; 4. Camp Creek; 5. Crystal Creek.

A gaging station and rain gage are located on the downstream side of the left pier of the bridge on Highway 18, located within the city limits of Pawnee. Discharge has been recorded since 1944 at the station. The mean annual discharge of Black Bear Creek is 5 cms, and the highest recorded discharge of 855 cms was in October, 1959 (Figure 1.2).

The lowest elevation in the study area is 231 meters a.m.s. at the confluence of Black Bear Creek with the Arkansas River, and the highest point is 268 meters a.m.s. located along Turkey Creek in T. 22 N., R. 3 E. The highest elevation in the basin is 360 meters located at the headwaters near Enid, Oklahoma. Local relief is generally less than 46 meters and decreases westward.

The average annual rainfall in Pawnee County is 870 mm, and is uniformly distributed throughout the year with a slight peak occurring in the spring. Average monthly precipitation for the Pawnee 5 North Rainfall station are shown in Figure 1.3 (Oklahoma Climatology Survey, 1991). Sixty-five percent of the total annual precipitation occurs in May through September. Average seasonal snowfall is 150 mm. Figure 1.4 gives average annual rainfall from 1948 through 1989 (Oklahoma Climatology Survey, 1991).

The study area is in the southern portion of the Central Plains Physiographic Province, according to the physiographic division of the United States by Atwood (1940). Curtis and Ham (1979), in describing the physio-

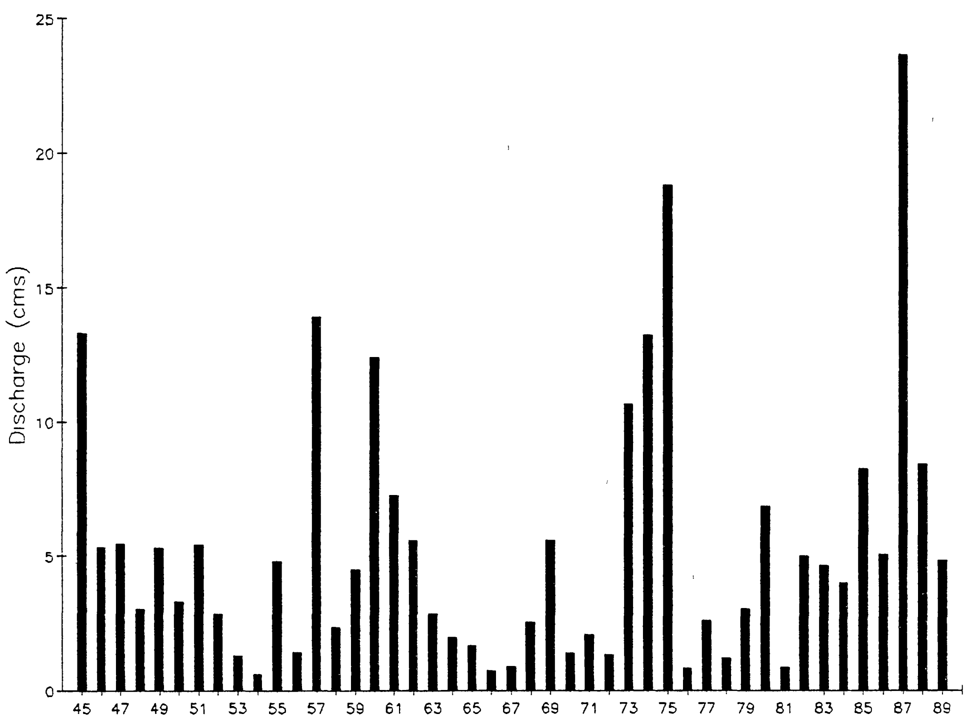

Figure 1.2. Mean annual discharge of Black Bear Creek from 1944 to 1989. The mean average discharge of Black Bear Creek is 5 cubic meters per second.

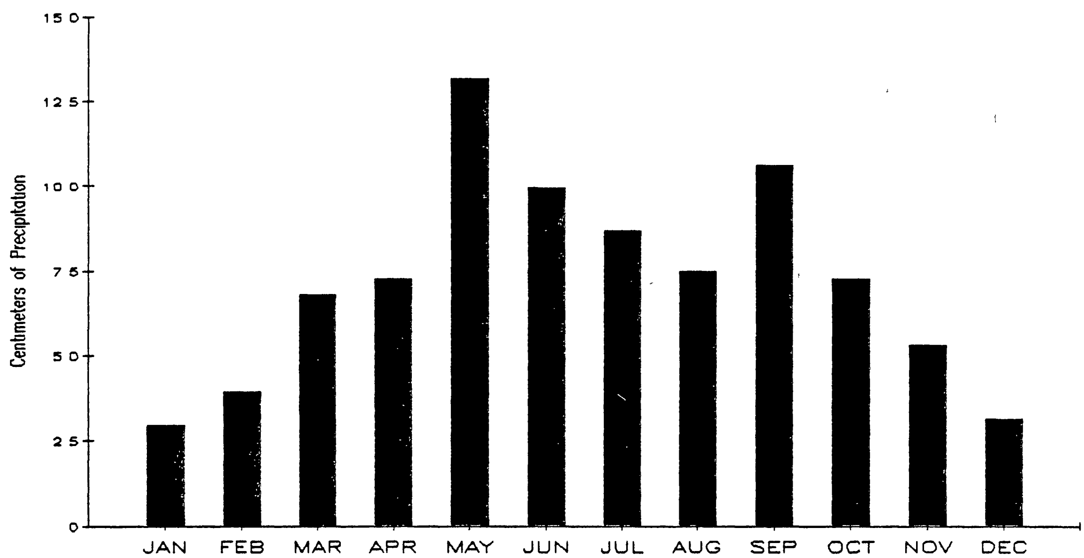

Figure 1.3. Average monthly precipitation from 1948 to 1989. Sixty-five percent of the total precipitation occurs in May through September.

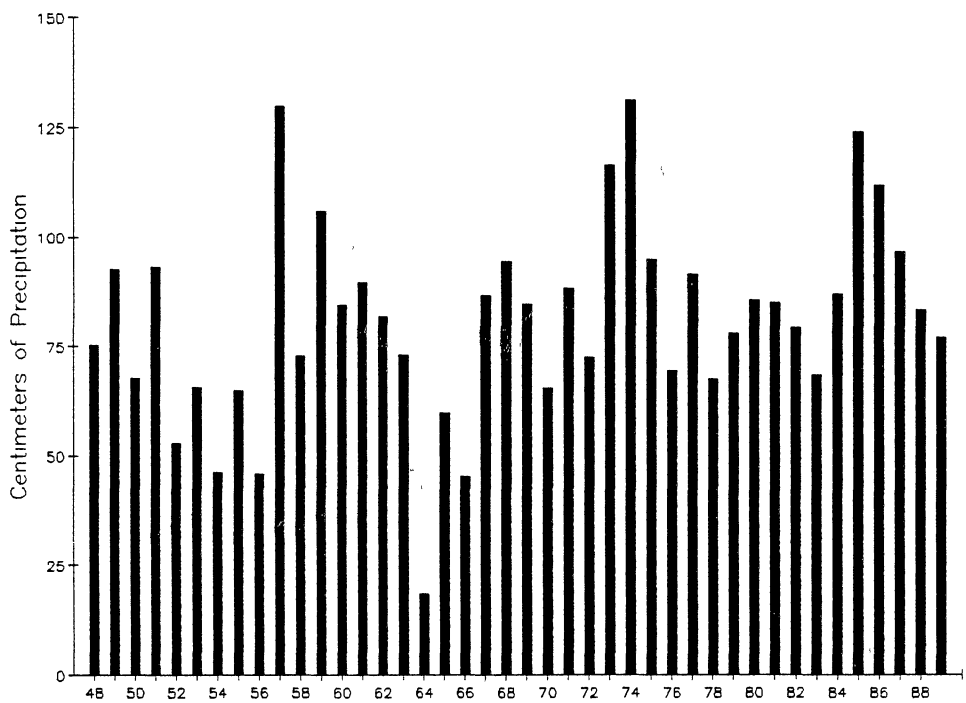

Figure 1.4. Average annual precipitation from 1948 through 1989.

graphic provinces of Oklahoma, places the western two-thirds of the watershed in the Northern Limestone Cuesta Plains Physiographic Area and the eastern third in the Eastern Sandstone Cuesta Plains Physiographic Area (Figure 1.5). The Northern Limestone Cuesta Plains are characterized by thin Permian limestones capping west-dipping cuestas that rise above broad shale plains. West-dipping Pennsylvanian sandstones forming cuestas that overlook broad shale plains are characteristic of the Eastern Sandstone Cuesta Plains.

The lower Black Bear Creek watershed is located on the north-central Oklahoma platform, bounded on the east and northeast by the Ozark uplift, on the south and southeast by the Arkoma basin, and on the west by the Nemaha Ridge (Figure 1.6). The watershed is also a part of the Prairie Plains homocline, a regional post-Permian structure in the Pennsylvanian and Permian beds west of the Ozark dome (Blakeley, 1959). Truncation of these beds has formed a series of parallel east-facing ridges or cuestas which trend due north following the strike of the beds. The cuestas are capped by resistant sandstone or limestone and are separated by broad valleys underlain by less resistant sandstones and limestones, and non-resistant shales (Greig, 1959). Regional strike of the formations in the watershed is north-south with a dip of less than one degree to the west.

Geologic formations in the watershed belong to the

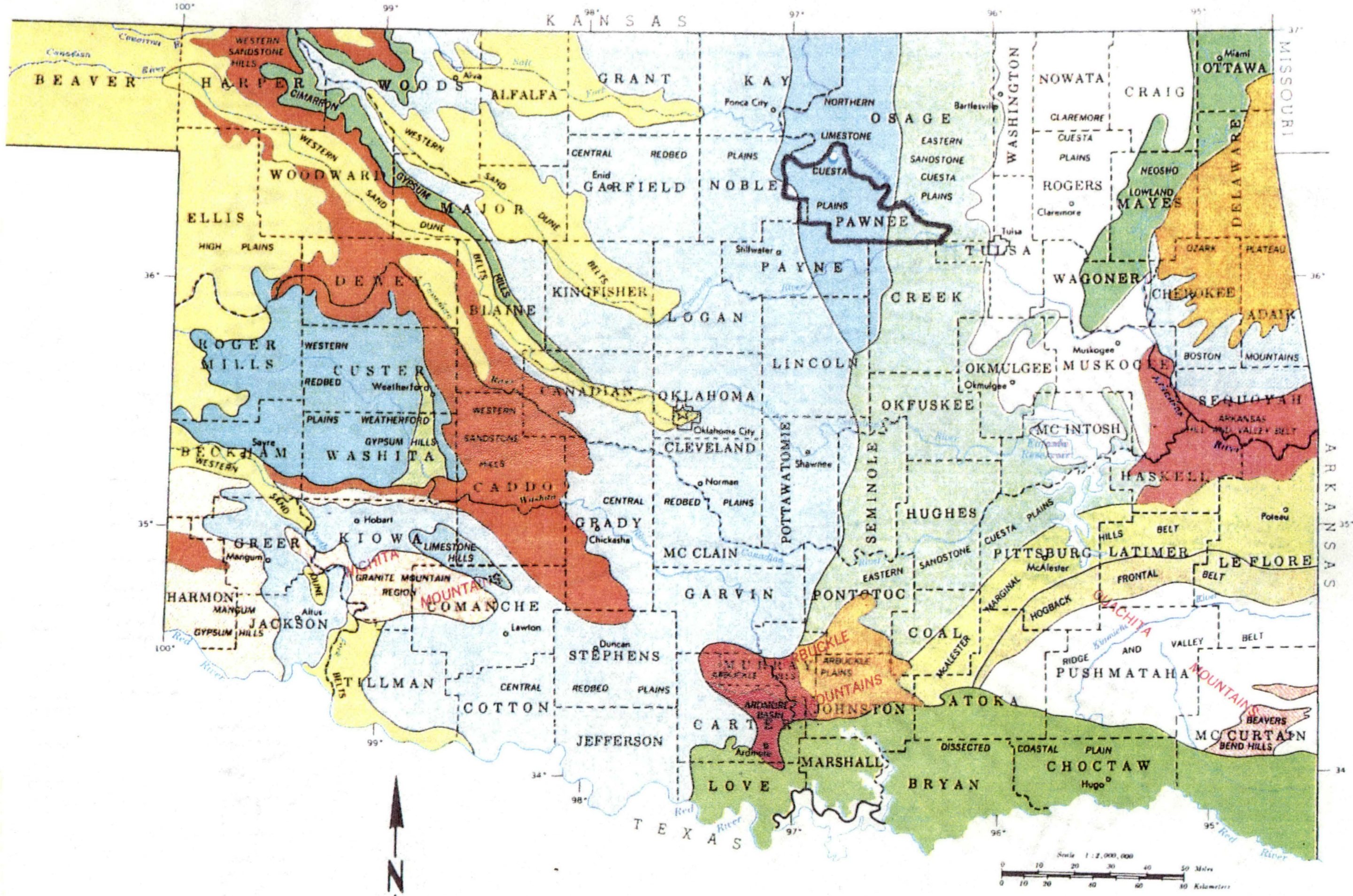

Figure 1.5. Physiographic provinces of Oklahoma. From Curtis and Ham (1979).

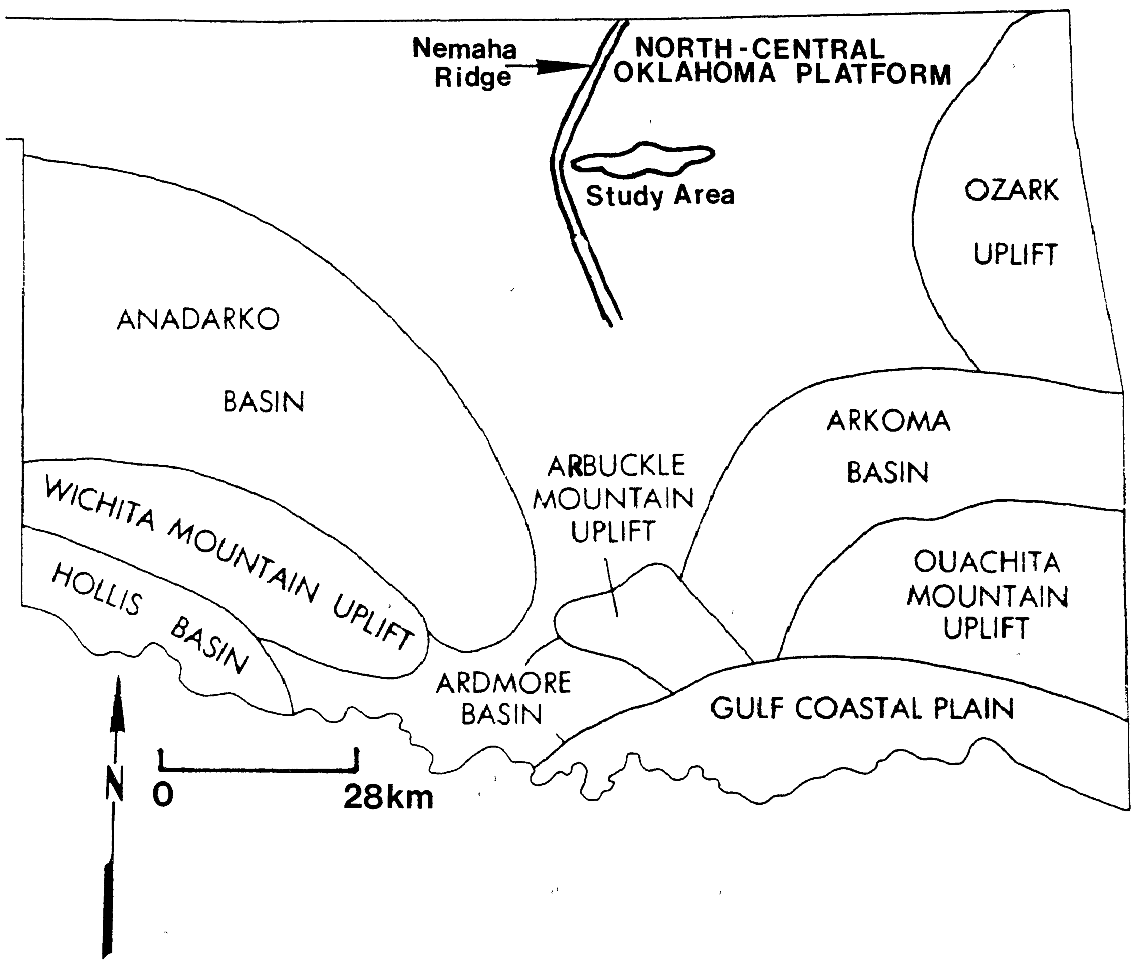

Figure 1.6. Geologic provinces of Oklahoma with study area outlined. After Oklahoma Geological Survey (1972).

Chase, Council Grove and Admire Groups, Wolfcamp Series of the Permian System, and the Wabaunsee Group, Virgil Series of the Pennsylvanian System (Miser, H., 1954). All four geologic groups are composed largely of red to gray shale, and lenticular, cross-bedded sandstones with interbedded thin limestones (Figure 1.7).

Soils in the watershed are associated with the Central Rolling Red Prairie Land Resource Area with scattered areas in the eastern half of the watershed associated with the Cross Timbers Land Resource Area (Figure 1.8). Soil mapping units of the lower Black Bear Creek floodplain belong to the Mixed Alluvial Land; Lela; Port; and Yahola groups.

The Mixed Alluvial Land consists of alluvial sediments of recent origin with narrow bodies occurring along Black Bear Creek and all its tributaries. The sediments vary in color from dark brown to yellowish red, and in texture from fine sandy loam to clay loam. This land type consists of slopes ranging from 1 to 15 percent, and elevations ranging from 30 to 90 meters. Approximately 30 percent of the area consists of stream channels; 10 percent of steeply sloping embankments, and edges of higher adjacent lands; and 60 percent resembles the Yahola soils with which the Mixed Alluvial Land is associated.

The Yahola Soil Series are formed from alluvium that have a brown, friable surface layer and a reddish-brown to yellowish-red substratum of sandy loam. These soils occur along the low floodplains of Black Bear Creek, and have

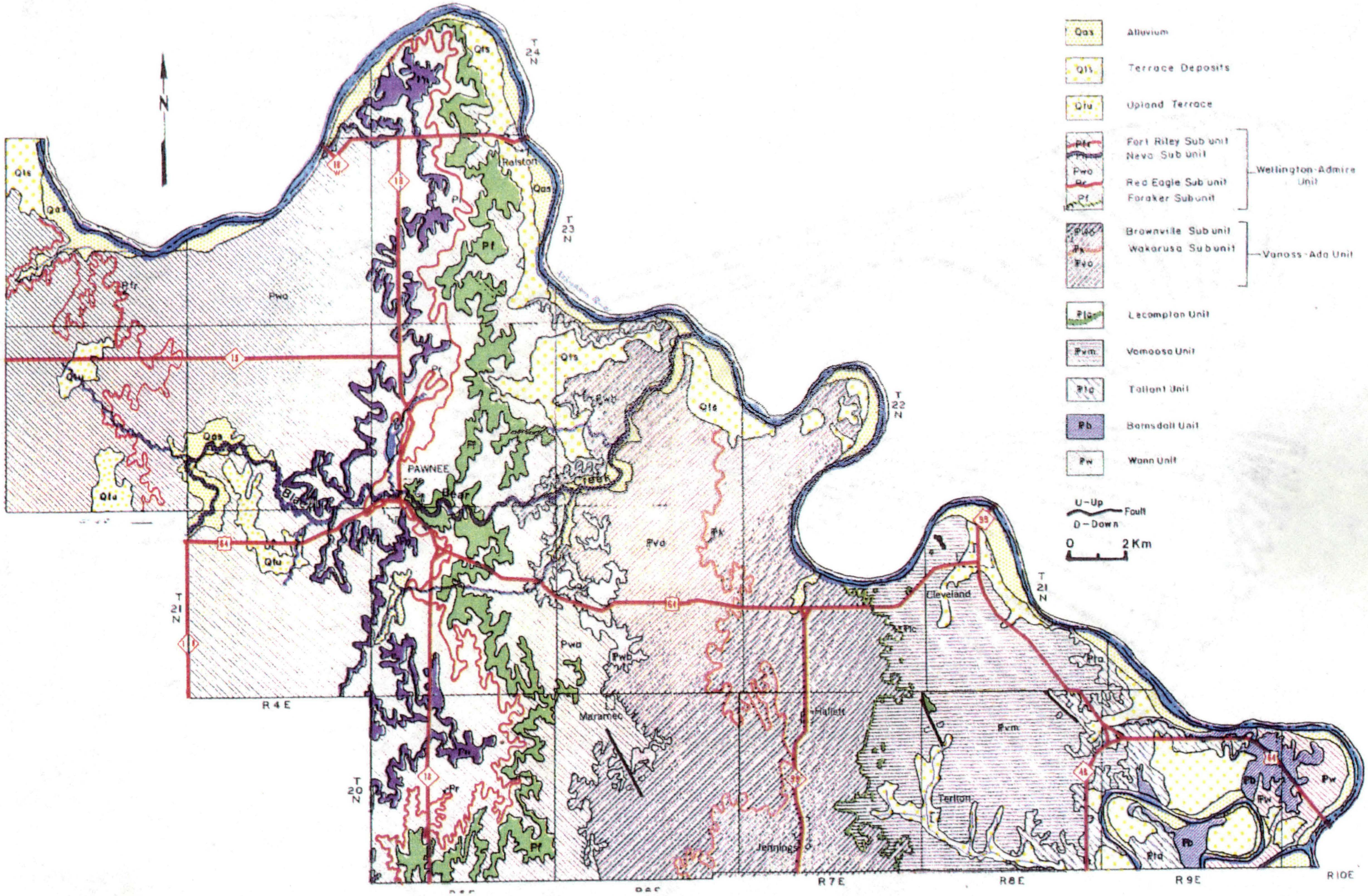

Figure 1.7. Geologic map of research area. After Greig (1959).

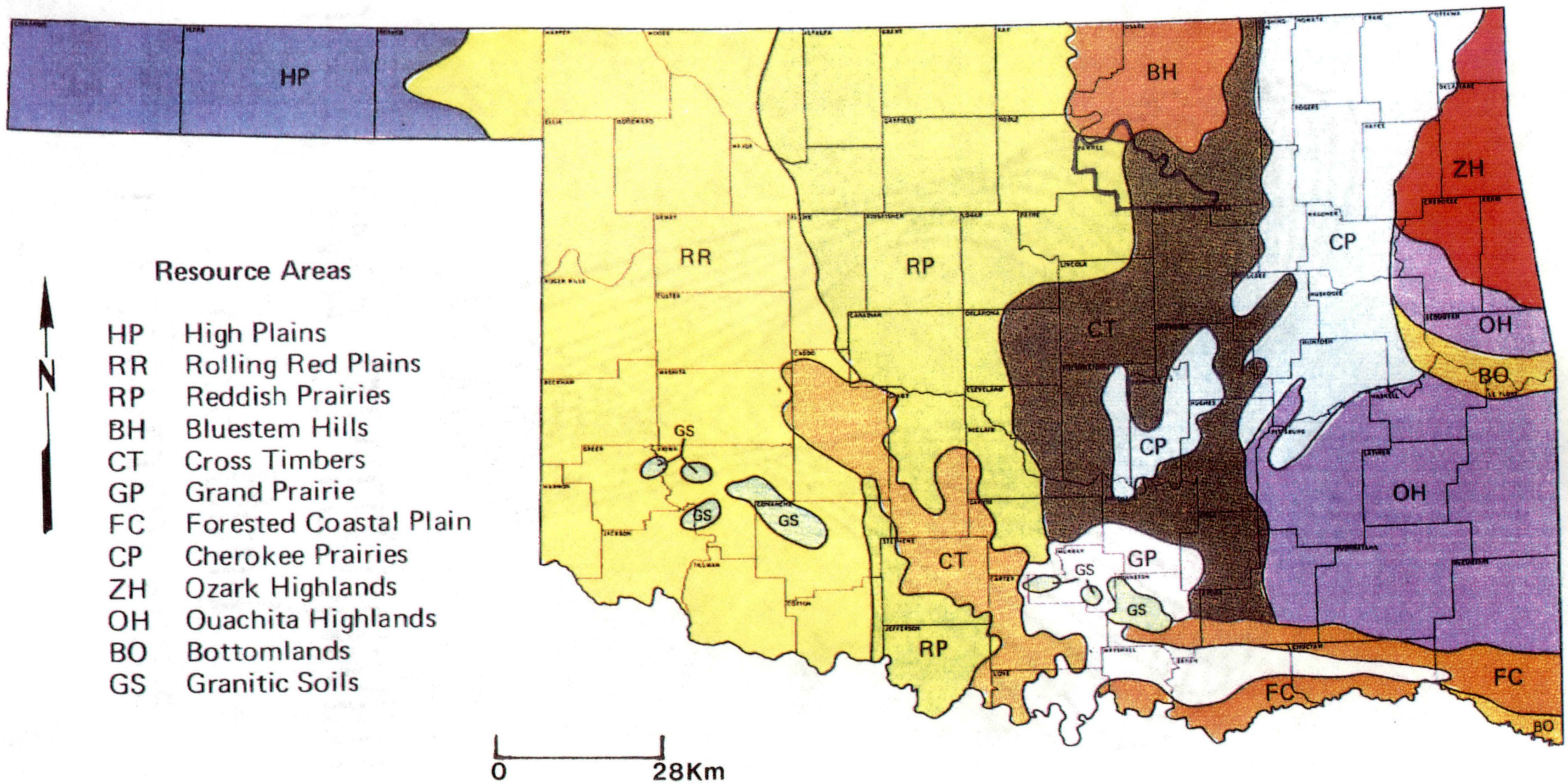

Figure 1.8. Land Resource Areas of Oklahoma. From U.S.D.A. Soil Conservation Service (1979).

developed on alluvial sediments. The source of the sediments is from mixed Permian redbeds and Tertiary deposits on the High Plains to the west. The Yahola is located along the stream channels, and on natural dikes several hundred meters wide. The thickness of the soil ranges from 20 to 50 centimeters, and the texture varies from very fine sandy loam to loamy fine sand. Approximately 15 percent of the soil occurs on areas having a wavy surface and ridges parallel to the stream channel. Surface gradients are as much as 4 percent on the sides of the ridges.

The Lela series consists of alluvial soils that have dark-brown granular surface layers, and the texture is predominantly reddish silty clays and clays. The soils develop under hardwood forests in backwater areas of Black Bear Creek, and most of the area is underlain by Permian redbeds.

Soils of the Port Series are alluvial typically silt loam or clay loam with a clay loam substratum stratified with silt loam. Buried soils commonly occur in the Port Series and are numerous in the Black Bear floodplain (Pawnee County Soil Survey, 1982).

In summary, this chapter presents the objectives of the study, provides a description of the study area, and contains general background information concerning the principles of paleoflood reconstruction. A detailed review of previous studies, and of slackwater deposits used as paleoflood indicators are discussed in chapter 2.

CHAPTER II

LITERATURE REVIEW

Introduction

The topic of paleoflood hydrology has been developed to understand how fluvial systems change over time. The need to accurately assess flood recurrence intervals has grown with increased risk to human activity on floodplains. A comprehensive review of paleoflood investigations and slackwater deposits as paleoflood indicators is presented in this chapter. This literature review will follow the sequence of a comprehensive review of prominent paleoflood investigations, describing slackwater deposit stratigraphy, defining areas of deposition and maximum preservation of slackwater units, reviewing paleoflood modelling techniques utilizing slackwater deposits, establishing methods of reconstructing flood chronologic histories from radiocarbon dating of flood deposits, and extending flood frequencies by the statistical analysis of slackwater deposits.

Paleoflood Hydrology Defined

According to Baker, et al. (1988) flood geomorphology is defined as "the study of the role of floods in shaping the landscape, including the analysis of flood causes, flood processes, resistance factors to flood-induced landscape change, and changes in flood-related processes and forms through time". Costa (1986) interprets paleoflood hydrology as "the study of the movements of water and sediment in channels before the time of continuous hydrologic records or measurements". Paleoflood hydrology can produce estimates of magnitude and frequency of large floods occurring in the past that are beyond the record that can be obtained by conventional engineering hydrology methods (Kochel and Baker, 1982).

The origin and development of paleoflood hydrology into a useful tool for extending flood frequency estimates beyond the period of record is now becoming more appreciated by many hydrologists. Geologists have been the primary developers and users of paleoflood techniques, because of their familiarity with the interpretation of sediment deposits and landforms and their use of dating methods, such as radiocarbon dating (Costa, 1986). Much of the pioneering work in paleoflood hydrology has been available in the published literature for many years, and is now becoming an integral part in water resources investigations. Costa (1986) provided a comprehensive documentation on the history of paleoflood hydrology in the United States, and Baker (1988) prepared a detailed summary on the background of fluvial geomorphology.

Extension Of The Flood Frequency Record By Historical Flood Information

In the United States European settlers kept records of noteworthy floods as early as 1635, however, the accounts were mainly about economic losses and human suffering rather than floodwater elevations or discharges (Cook, 1987). The historical record in Europe and China is of greater value in flood frequency analysis, because the length of records are considerably longer.

Sutcliffe (1987) noted that in Britain exceptional floods are often recorded by physical marks, especially in historic cities where plaques are frequently found near bridges. He showed from historical flood levels at the Ouse Bridge in York that the 1947 flood (largest in living memory) was found to be the fourth highest of a series of flood peaks from 1625 to present. Similar principles were employed to extend flood events in Nottingham and Norwich in Wales and England.

The inclusion of historical flood information in China has increased the years sampled and has improved the reliability of estimation. Numerous dams have been constructed in China since 1950. The design of the dams have included flood frequency analysis based upon a combination of gaging station data and historical floods. Gaging station records in China were established after Liberation, and only 20 to 30 years of observed records typically exist. In China historical records of over 4,000 years are used to identify extraordinary floods and to determine the return periods (Shi-Quian, 1987).

Review Of The History Of Paleoflood Hydrology

Unlike historical flood analysis, paleoflood hydrology is not limited by the time period or by the locations of past human observations and recording devices (Baker, 1987). The paucity of historical flood records in the United States has led American geologists/geomorphologists to research and utilize indirect lines of evidence.

During the seventeenth and eighteenth centuries, common scientific practice tried to reconcile the surface features of the Earth with cataclysmic events, such as the Noachian flood (Baker, 1988). Thompson in 1800 and Mitchell in 1818 made the earliest assessments of paleoflood hydrology in the United States. They developed qualitative descriptions of the origins of wind and watergaps in the Appalachian Mountains by explaining the origins as resulting from the occurrence of rare floods through the gaps (Costa, 1986).

Quantitative estimates of the velocities of deluge floodwaters were calculated by von Buch in 1811 from elevation differences and boulder deposits in the Jura Mountains, Switzerland. Jackson in 1839 established that the diluvial waters depths in the United States on the basis of observations of erosional and depositional features on

Mount Katahdin, Maine (now known to be glacial in origin) (Costa, 1986).

Agassiz in 1838, in Europe, brought to the American geomorphologist a new mechanism to explain large flood events other than the Biblical deluge. His glacial theory allowed glaciers to replace Noah's flood as the source of large quantities of water (Costa, 1986).

Dana in 1882 proposed that the formation of several high terraces along the Connecticut River valley were the result of the melting of Quaternary glaciers in New England. His methods for reconstructing flood characteristics were not appreciably different from some modern paleoflood hydrology techniques (Costa, 1986).

The Origin Of Slackwater Deposits Used As Paleoflood Indicators

Slackwater deposits in the channeled Scablands of eastern Washington were described by Bretz in 1923. He proposed that a single, catastrophic flood event known as the Pleistocene Lake Missoula Flood had created the topography of this area (Baker, 1988). Although, his theory has recently been accepted as the correct origin of the scablands, the number of floods producing the landscape is still unresolved (Baker, 1973; Waite,1985; Baker and Bunker, 1985).

J.E. Stewart in 1923 prepared an unpublished report determining historic flood peaks in the Skagit River basin, Washington, after a flood occurred in 1921 (Costa, 1986). He determined the stages of the two largest historical floods on Skagit River, which occurred in 1815 and 1856 from flood deposited sand and gravel bars, and flood sediments lodged in the bark of old cedar trees and deposited in cracks in canyon walls (Costa, 1986). McKee in 1938 studied flood deposits from the Colorado River in the Grand Canyon, and gave a detailed description of the stratigraphy and sedimentology of slackwater deposits. Janhs in 1947 concluded from stratigraphic evidence that the terraces along the Connecticut River valley were flooded in 1936 for the first time since they had ceased to be active floodplain surfaces, which was estimated to have been 2500-6000 years ago (Costa, 1986).

Botanical Aspects Of Flood Geomorphology

Sigafoos (1964) used botanical techniques (tree ring dating) from the Potomac River floodplain to quantitatively assess information on floods and floodplain deposition. His botanical techniques were used to reconstruct the paleoflood history. New techniques have been developed for interpreting direct botanical evidence of large floods. Yanosky (1982) perfected the use of ring anomalies to identify flood induced stress. Hupp (1986) advanced dating procedures for analyzing flood related corrosion scars and adventitious sprouts. Hupp identified the dates of occurrence of large flood events on Passage Creek in northwestern Virginia over a 260-year period. Osterkamp and Hupp in 1984 showed consistent relationships among bottomland vegetation patterns and fluvial landforms in northern Virginia (Stedinger and Baker, 1987).

Recent Investigations Using Slackwater Deposits In Paleoflood Analysis

Baker et al., (1980) used slackwater deposits to determine maximum flood levels along the Finke River in the Northern Territory, Australia. Slackwater deposits indicated flood levels had been exceeded by at least four meters since floods had been observed on the river for the past ninety-one years. This study concluded that flood slackwater sediments can identify paleofloods which greatly exceed the documented magnitudes recorded in gauged river systems.

Kochel et al., (1982) used slackwater deposits to extend the frequency estimates over 10,000 years in the lower Pecos and Devils Rivers of southwestern Texas. They concluded that this technique offers an inexpensive and rapid procedure to determine the risk of catastrophic floods on a river.

Tullis and Koslow (1983) collected Holocene slackwater deposits on the Big Lost River in Idaho. They were able to discern four separate high magnitude flood events. Patton

(1984) in the Housatonic River basin of western Connecticut used slackwater deposits to reveal a stratigraphic record of floodplain development dated to over 12,000 years B.P., and detected the occurrence of large, rare paleofloods. Ely and Baker (1985) used slackwater sediments to approximate peak stages of the associated floods of the Verde River in Arizona. Stratigraphic analysis, radiocarbon and archaeological dating, and correlation between slackwater sites along the study reach revealed multiple floods, including two paleofloods that predate the eighty year observational record of flows on the Verde River.

Linton and Kite (1987) used slackwater deposits along the Cheat River in east-central West Virginia to determine the recurrence interval of the November 5, 1985, flood event. This represented the largest flood event in historic times; however, they determined the event was only a four hundred year event. Partridge and Baker (1987) identified a minimum of four flood events that antedate 59 years of gauged records along the Salt River in east-central Arizona. They used the analysis of slackwater deposits and paleostage indicators.

Miller (1990) compared hydrologic records and geomorphic effects of several historic floods in the central Appalachian region of the eastern United States. The most geomorphic effective floods had large values of unit stream power to reaches with erodible alluvial bottomlands.

Holocene Paleoflood Reconstructions Used To Indicate Paleoclimatic Changes

The relationship between floodplain processes and flood magnitudes supports the notion that even modest changes of climate can be an important contribution to episodic mobility and storage of sediments in watersheds. Reconstructions of Holocene paleohydrology provides useful approximations that indicate directions and relative magnitudes of the hydrologic response to potential future climate changes (Knox, 1985).

Webb and Baker, (1986) reconstructed the late Holocene flood history and associated channel changes for the Escalante River in south-central Utah. Flood-frequencies associated with large flood events were attributed to subtle shifts in climate. Wohl (1988) used slackwater deposits to reconstruct the flood record of three rivers in northern Australia. She concluded the temporal distribution of floods reflects the causal circulation pattern, and that paleoflood data are restrictive reflections of climatic conditions, representing one component of the climate of a region.

Alluvial geology, palynology, and molluscan paleontology investigations were conducted by Hall (1988) to reconstruct Holocene environments in north-central Oklahoma. He concluded that widespread soil development and alluvial records could serve as indicators to paleoenvironmental conditions existing during the Holocene.

Hall (1990) used detailed stratigraphic evidence and radiocarbon dates from fifteen alluvial sites in the southern Great Plains in conjunction with many convergent lines of well-dated paleoenvironmental evidence to document an episode of late Holocene channel trenching. He associated trenching with a regional climate change which occurred at 1 ka.

These studies and others indicate the importance of field investigations in paleoflood reconstruction and to the understanding of climatic changes.

Review Of Slackwater Deposits Utilized As Paleoflood Indicators

Paleoflood reconstruction using slackwater deposits as a paleoflood indicator has been applied by many investigators especially in bedrock channels of semi-arid to arid climates. Description of the technique involved in the utilization of this indirect method follows.

Slackwater Stratigraphy

According to Brakenridge (1988), meandering rivers create floodplains by the combined operation of lateral channel migration and suspended-load fallout from slow moving or still water during higher than normal river stages. Two assemblages of sedimentary facies result, channel bed deposits, and bank and overbank deposits (Friedman and Sanders, 1978; and Brakenridge, 1988) (Figures 2.1a and 2.1b).

Floodplain sediments deposited during overbank flow were named by Allen (1969) undivided top-stratum deposits which are described typically as fine sand, silt, and clay layers (occasionally gravel) which fine upwards. Jahns (1947), McKee (1938), McKee et al., (1967), Baker (1973), and Costa (1974) provide detailed stratigraphic analysis of different types of floodplain deposits and their various depositional environments. This study will focus on slackwater deposit stratigraphy and depositional environments.

Baker (1973) described a typical vertical sequence of a slackwater flood units as: a basal layer of structureless, upward-fining coarse sand and gravel (in proximal areas), horizontally-stratified medium sand, ripple-drift-laminated fine sand, and parallel laminated fine sand and silt.

Costa (1978) defined a slackwater deposit as a fine-grained deposit typically comprised of fine sand and coarse silt which accumulate in areas of low velocity during flood flows. These sediment laden waters quickly deposit the loads from suspension in areas where the flow becomes separated from the main thread of flood flow (Costa, 1978; Kochel and Baker, 1988). An example of a slackwater unit is shown in Figure 2.2.

Sedimentary structures existing in slackwater deposits usually are of two types, horizontal laminations or structureless. Rhythmic slackwater deposits described by Bretz

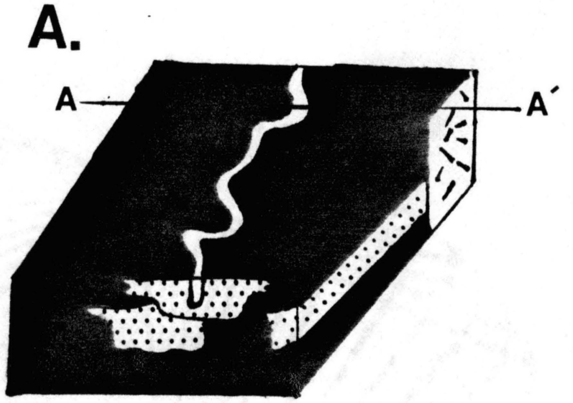

Figure 2.1a. Two assemblages of sedimentary facies, channel bed deposit and overbank deposit, on a meandering river floodplain (after Allen, 1965).

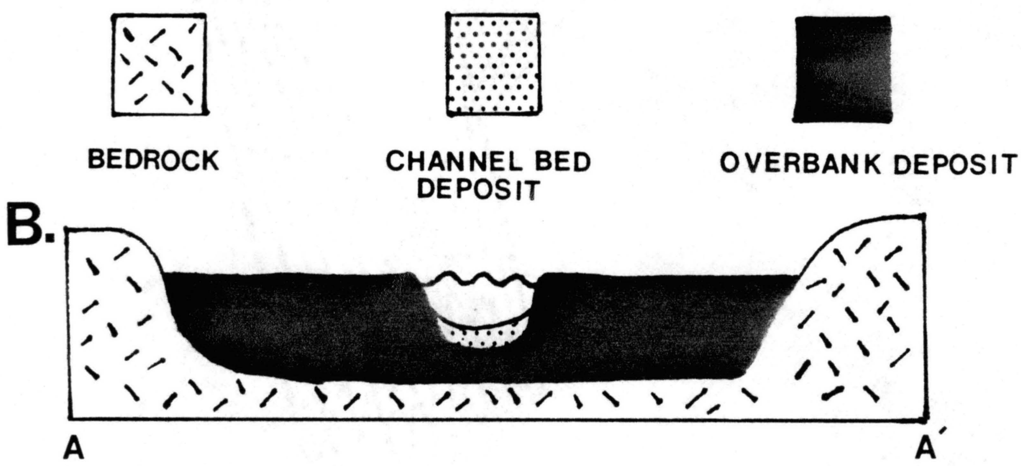

Figure 2.1b. Cross-section A-A′ of meandering river floodplain showing fine-grain overbank deposit and coarse-grain channel bed deposit (after Plummer, 1987).

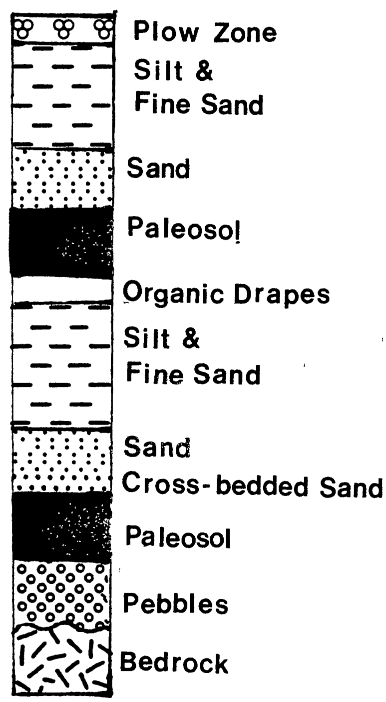

Figure 2.2. Typical stratigraphic section of slackwater development overlying a paleosol (buried soil) within study area.

in 1929 of the Lake Missoula flood are uncommon. The majority of slackwater deposits lack primary sedimentary structure and are structureless because of very rapid deposition of sediments. Structureless units consist typically of fine sand and silt, contain few or no silt or organic rich partings, and exhibit no grading.

Horizontal lamination is the dominant sedimentary structure where primary structures are visible according to Baker (1987). These are considered to form as the result of migration of bedforms such as small ripples up the tributaries during rapid sedimentation resulting from rapid influx of backflood waters. Variable grain sizes within laminations are attributed to variations in the rate of sediment supply and current velocity (Kochel, 1980).

Flume studies and field investigations conducted by Baker and Kochel (1988) show that cross-bedding occurs at scales from ripple drift features a few centimeters high to foresets with amplitudes up to 50 centimeters. Cross-bedding occurred most often near the base of thick sandy slackwater units.

Preservation And Depositional Sites Of Slackwater Deposits

Previous investigators (Baker, 1973; Costa, 1978; Kochel, 1980; and Partridge and Baker, 1987) have shown that maximum preservation of slackwater deposits occurs at tributary mouths; in shallow caves along the bedrock channel walls; downstream from major bedrock and/or talus obstructions; in areas of dramatic channel widening; and as overbank accumulations on high terraces. Table 2.1 provides different settings of slackwater depositional sites found in stable, alluvial channels.

Slackwater sequences result when each successive flood event equals or exceeds the preexisting level of slackwater sediment accumulation, therefore, each flood unit behaves as a threshold level for subsequent floods. The paleoflood history, reconstructed from any site, must be regarded as a minimum record, because the possibility exists that flows were not recorded, or were eroded by subsequent flows (Wohl, 1988). Reconstruction of past flood events depends upon the continuous preservation of slackwater sediments within a stratigraphic section. Slackwater deposits may represent one catastrophic event or a combination of several events. An accurate study relies upon a thorough search for all paleoflood remnants. Recognition of multiple slackwater deposits within a single unit can be discerned by color changes, buried mudcracks, abrupt vertical grain size changes, and the presence of paleosols (Baker, 1987). Table 2.2 shows how numerous sedimentologic principles contribute to the discrimination of flood events. An abrupt change in particle size may indicate that a portion of an older event was removed by a younger flood event. This can be discerned in the laboratory by particle

TABLE 2.1

TYPES OF LOCAL SLACKWATER DEPOSITIONAL SITES IN STABLE ALLUVIAL SETTING

Type of site	Depositional Sites	Special considerations
Mouth of tributaries during flood event	Edge of trunkstream floodplain junction with tributary	Tributary gradient lower than mainstream gradient for backfooding to occur
Abrupt channel expansion	Deposits occur downstream on terraces adjacent to the main channel	Occurs downstream of flow separation
Abrupt channel constriction	Accumulation of sediment is upstream of narrow channel neck or log jam	Requires an extremely large flood for most constrictions to function in this way
Caves and rockshelters	Deposition occurs in cave mouth	Stratification and contacts have excellent preservation because of minimal bioturbation
Slackwater terraces	Vertical accretion of overbank deposits onto the floodplain	Large accumulations dependent upon flood size

Modified from Baker (1987)

TABLE 2.2

CRITERIA FOR THE RECOGNITION OF MULTIPLE SLACKWATER DEPOSITS WITHIN A SINGLE UNIT

Property	Description
Silt-clay and organic drapes	A capping of fine-grained material deposited last from flood backwaters marking the end of a slackwater deposit
Buried paleosols	Developed on the paleoground surface between flood events; higher organic carbon than overlying slackwater deposit
Organic layers	Accumulate as litter on the paleoground surface between flood events; partly decomposed leaves, twigs, and grasses
Slope colluvium	Interfinger with mainstream slackwater deposits
Abrupt vertical grain size variations	Reflect emplacement by individual flow events and may indicate erosion of slack-water units
Mudcracks	Indicate subaerial exposure of a flood deposit
Color changes	Caused by differential chemical weather-ing in the flood layers

Modified from Baker (1987)

size distribution tests and by dating the sequence (Wohl, 1988).

Correlation between multiple sites using physical stratigraphic methods and radiocarbon dates can also help to minimize the problem of the recognition of multiple slackwater deposits within a single unit. Most slackwater deposits are capped by silt drapes or fine-grained organic detritus that was concentrated in the upper few meters of floodwaters (Baker and Kochel, 1988). These organic rich drapes can provide the most accurate radiocarbon dates from that particular flood event.

Tributary basin characteristics play an important role in the accumulation of a thick slackwater deposit. Maximum slackwater thickness results where the trunk stream is able to backflood efficiently into tributary mouths. Kochel (1980), Kochel and Ritter (1986), and Baker and Kochel (1988), have shown through field investigations and flume studies, this occurs when tributary junction angles are between 55 degrees and 125 degrees to the mainstream. They have found that at angles less than 45 degrees mainstream floodwaters tend to bypass tributaries, and at angles greater than 130 degrees, mainstream flood flows can be highly erosive to preexisting slackwater deposit. Optimum preservation occurs where tributary junction angles are close to 90 degrees to the main channel.

Tributaries with high flash flood potential are not conducive to continuous slackwater sediment sequences.

These tributaries are prone to floods that destroy accumulations of slackwater deposits in the mouths (Kochel, 1980). Studies conducted by Kochel and Baker (1988) along Texas rivers showed the most favorable location for slackwater sediments occurred along the inside of tributary meander bends a few tens of meters from the mainstream.

Paleoflood Modelling Using Slackwater Deposits

Paleostages determined from slackwater deposits can be used to estimate paleoflood discharge. The maximum height of slackwater deposits can provide a minimum estimate of the paleostage level of a flood event, and the elevation can then be used to estimate paleodischarge.

Assumptions must be made in order to use paleostage indicators. Baker et al. (1986), Partridge and Baker (1987), and Williams and Costa (1988), suggest the following assumptions be made in order to use paleostage indicators in paleoflood modelling:

1. Slackwater deposits must be associated with the modern flow regime of the river. Hydrologic phenomena of the Holocene must not be significantly different than what is occurring today.
2. Cross-sections chosen must represent a stable channel portion where scour and fill during flood events is at a minimum, and should be measured at right angles to the paleochannel. Channel stability must be nearly constant.
3. Channel aggradation or degradation over the Holocene should be small.
4. The elevation of the slackwater deposit records the maximum peak flood stage. Tracing flood units up the tributaries to determine the elevation where they pinch out gives a better estimate of paleoflood stage (Kochel, 1980). Better accuracy in

> correlation of peak stages is obtained when the number of sites is large.

The slope-area method was utilized in the first slackwater/paleostage indicator studies (Kochel, 1980; and Kochel et al., 1982). The slope-area method is inadequate in dealing with energy losses in cross-sections where irregularities in the channel margin exist, and is restricted to cross-sections where stage indicators are present (Partridge and Baker, 1987).

Advances in computer models have included the introduction of models which include in the analysis the geomorphology of paleoflood indicators. Step-backwater models, such as the Hydrologic Engineering Center (HEC 2), allow water surface profiles for various discharges to be compared to flood scars, silt lines, slackwater deposits, and other paleostage indicators (Stedinger and Baker, 1987). The flow profiles can be used as a correlation tool to test inferences about relationships between various slackwater sites (Baker, 1987).

The computer program HEC-2, Water Surface Profiles, originated from a step-backwater program written in BASIC by Bill S. Eichert in 1964. The program was revised and expanded in 1968, 1984, and 1990. The program is intended for calculating water surface profiles for steady gradually varied flows in natural or man-made channels. The computational procedure, known as the standard step method, is based on the solution of the one-dimensional energy equation with energy loss from friction evaluated with Manning's equation. The two equations are solved by the iterative procedure to calculate an unknown water surface elevation at a cross-section,

Where:

= water surface elevations at ends of reach
= mean velocities (total discharge / total flow areas) at ends of reach
= velocity coefficients for flow at ends of reach
= acceleration of gravity
= energy head loss
= discharge-weighted reach length
= representative friction slope for reach
= expansion or contraction loss coefficient

According to Partridge and Baker (1987), the essential data for the program can be grouped in two basic categories:

1. Geometrical parameters from which the program determines channel slopes and cross-sectional areas. These are determined from surveyed cross-sections, control stations, and distances between cross-sections.
2. Roughness elements from which the program calculates energy losses along the channel reach. These include Manning n roughness coefficients and expansion/contraction coefficients.

The input values for the Manning n are used to calculate conveyances of each cross-sectional component (left overbank areas, channel, right overbank areas) which are used in computations of velocity coefficients and friction slopes. The computed profiles of the water surface are affected by three variables, Manning n values, starting water surface elevation, and designated discharge (Partridge and Baker, 1987).

An example of the computer sequence follows. Stage and discharge are given for the initial cross-section. Cross-section data is traditionally oriented looking downstream (subcritical flow). Channel geometry and roughness values determined in detailed cross-sectional surveying are designated by the operator. Variables such as water surface elevation, mean channel velocity, depth of flow, and head loss are computed for subsequent cross-sections in an iterative process. Each cross-section is representative of locations along the stream reach where discharge, slope, and roughness characteristics are uniform. Calculated water surface elevations for each cross-section are then compared to the elevations of the slackwater deposits. A sequence of runs are made to determine the discharge which produces a water surface profile closest to that of the slackwater deposit.

Radiocarbon Dating Techniques In Determining Flood Chronologic Histories

New techniques in geochronology allow more accurate determinations of paleoflood ages. Thornes, et al. (1977), and Cullingford et al. (1980) review numerous dating methods applied to Quaternary sediments. The stratigraphic position of a deposit can be used in placing a series of events in chronologic order known as relative dating. Absolute dating places a time on the event, and typically, in younger geologic events is done by radiocarbon dating.

According to Baker (1987), radiocarbon dating is the standard tool employed for absolute dating in paleohydrologic analysis. A list of materials commonly used in radiocarbon dating are given in Table 2.3. Charcoal, if in place, is highly sought in radiocarbon dating in paleoflood reconstruction techniques, because it yields reliable dates. Charcoal preserved in slackwater deposits, however, can often yield erroneous dates, because it could be reworked from earlier flood events and redeposited in the younger stratigraphic deposit, thus, providing an older date than the flood event. Datable materials of this type are termed allochthonous, and they only provide maximum limiting ages (Baker, 1987).

The location of datable materials on discontinuity surfaces that separate individual flood events is the most useful stratigraphic association (Baker, 1987). According to Baker (1987) charcoal from burns on the paleoground surface and leaf litter falling on that surface are examples of autochthonous materials that may be buried by the slackwater sediments of a subsequent flood. Dates on the surfaces provide a precise minimum limiting date for

TABLE 2.3

MATERIALS USED FOR RADIOCARBON DATING OF SLACKWATER SEDIMENTS

Type of material	Interval dated*	Stratigraphic association	Possible error (yr)	Discussion
Buried trees	N	Growing on paleoground surface	0-1	Dendrochronology may be used for precise dating
Flood-transported fine-grained organics	F	Allochthonous at tops of individual flood layers	1-10	Leaves and twigs may be seasonal growth preceeding flood event
Burn layers (in situ charcoal)	N	Autochthonous	10	Wood for hearth may have a radiocarbon age when burned
Organic mats	N	Autochthonous accumulated debris	10	May accumulater over several years to decades
Organic paleosols	N	on paleoground Autochthonous	100	Involves mean residence time of organics in the soil profile
Flood-transported wood	F	Allochthonous	10-100+	May be eroded from older deposits
Flood-transported charcoal	F	Allochthonous	10-100+	May be eroded from older deposits

* F = flood intervals; N = non-flood intervals

From Baker (1987)

the flood emplacing the immediate underlying slackwater deposit, and a maximum limiting date for the flood depositing the immediate overlying deposit (Baker, 1987).

A layer of fine-grained organic detrital material found in the upper few centimeters of the slackwater unit yields a radiocarbon date synchronous with the flood event (Kochel, 1980). Such material may include seasonal ground litter of seeds, leaves, small twigs, and other debris (Baker, 1987). Baker et al. (1985) showed that such material will have a radiocarbon age within one year of the flood event.

The organic matter in soils (paleosols) buried by flood deposits is another datable material. Costa (1978) stated that radiocarbon dating of a buried soil can provide a minimum estimate of the total time between flood events whereas a date on a buried soil surface will yield the minimum time interval between floods. Dates from soil organic matter in buried soils reflect the mean residence time of the carbon and have little significance to the real age of the soil (Figure 2.3).

Radiocarbon dating of buried soils can sometimes lead to erroneous dates because of possible contamination. Contamination by modern plant roots and the leaching effect of humic acids are the major sources of dating problems associated with buried soils (Gilet-Blein et al., 1980; Ruhe, 1969; and Carter, 1990). Contamination is at a maximum in the upper fifteen centimeters of soil where biotur-

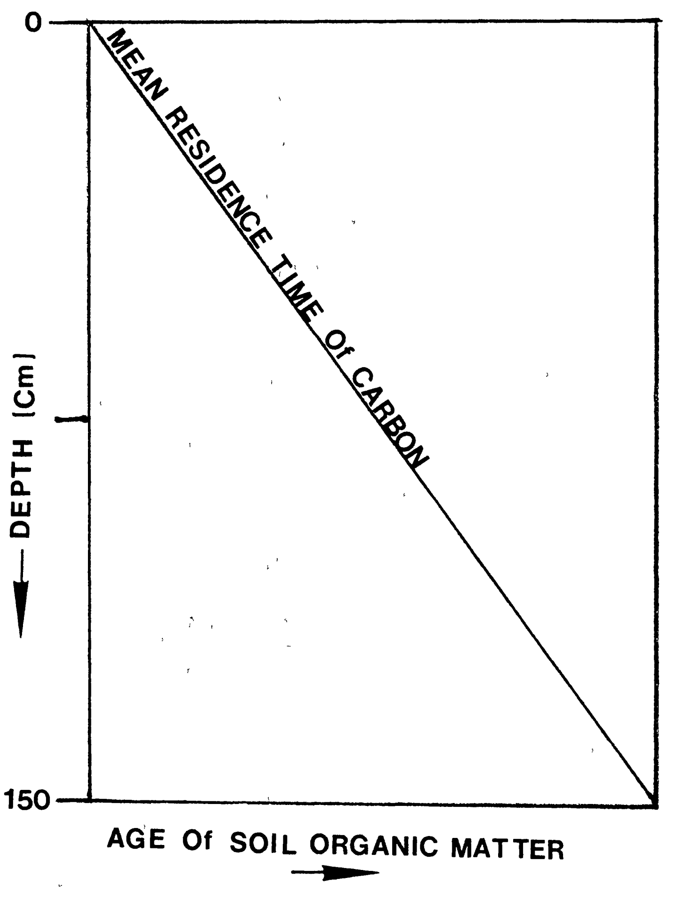

Figure 2.3. Depicts increasing age of the mean residence time of the carbon (soil organic matter) with increasing depth. After Scharpenseel (1971).

bation is common, and above seventy-five centimeters from plant roots.

Flood chronologic studies rely on accurate radiocarbon dates from alluvial deposits. Buried soils have a wider distribution in a floodplain, and are easier to locate than wood or charcoal (Brakenridge, 1988).

Flood Frequency Extension By Slackwater Deposits

Kochel (1980) noted that "a catastrophic flood is considered to be an event which either has a return interval of greater than 100 years or causes failure of flood protection features by exceeding project design criteria, and is of a magnitude great enough to exceed whatever threshold bounds the normal equilibrium state of a given fluvial system". Statistical errors result with the prediction of catastrophic floods because the approach is to predict the tail of the probability distribution from a small population sample which does not usually include the tail.

Flood frequency diagrams are developed from gaging station records of maximum annual discharge and probability of occurrence, and are based on the systematic record. A flood frequency graph is used to estimate the largest flood event that can occur within any given year, and the recurrence interval of a flood event with a given discharge.

Concerns for data adequacy have continued unabated in the United States to the present, because of the need for more detailed hydrologic data at gaged and especially at ungaged sites. The U.S. Geological Survey began its stream gaging program in 1888 (Kirby and Moss, 1987). Nationwide the systematic flood peak discharges and stages are available for about 21,000 sites, with an average record length of about 22 years per site (Kirby and Moss, 1987).

Fuller in 1914 made the first attempt to interpret flood flows in terms of probability. He stated "the mean annual flood was approximately proportional to the 0.8 power of the drainage area and that flood flows above the mean followed an exponential-tailed probability law". Foster in 1924 outlined a method using the sample mean, standard deviation, and skewness of the untransformed flows to fitting the flood flow data to a Pearson Type III distribution. Hazen in 1930 suggested the use of log normal probability plotting and the log normal probability distribution of the data which could make the data approximately free of skewness (Kirby and Moss, 1987).

The log Pearson Type III and Gumbel (Extreme Value Type I) distributions are the most commonly utilized in flood frequency analysis. Extremes of hydrologic phenomena, such as floods, do not follow a normal symmetrical distribution but are skewed. Gumbel, in analyzing floods, developed a standard skewed distribution based on the theory of largest values (Gumbel, 1958) (Figure 2.4). In the Gumbel method floods are ranked in order of magnitude

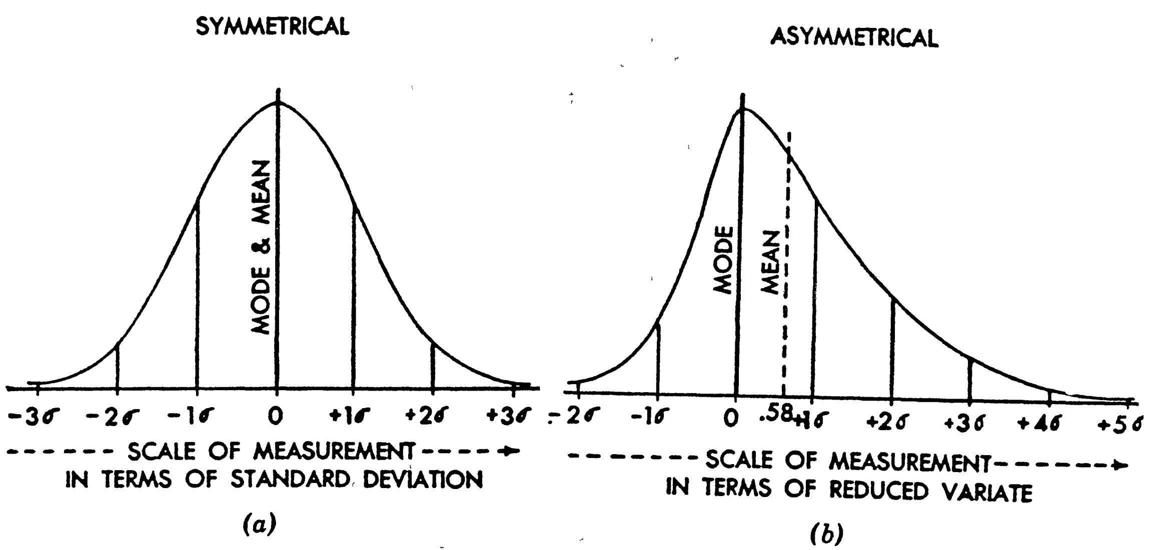

Figure 2.4. Comparison of (a) the normal probability curve and (b) Gumbel's standard skewed distribution of large values. From Velz (1970).

from lowest to highest from a successive sample group of the population where:

$$Tr = (n+1)/m$$

Where:

Tr = return or recurrence interval in years

m = rank order

n = number of years of data plus one

Large statistical errors are possible in this analysis because the precise mathematical form of the distribution can not be defined (Benson, 1962; and Kochel, 1980).

The log Pearson Type III distribution technique for determining flood flow frequencies is first to transform the natural data to logarithms, and then to compute the statistical parameters of mean, standard deviation, and skew coefficient of the distribution. The distribution is plotted on log probability paper because a distribution with zero skew will plot as a straight line. This technique has been recommended by the U.S. Water Resources Council, and provides a better assessment of low frequency, high magnitude events. Details of the log-Pearson Type III calculations are described in the Water Resources Council Bulletin 17B.

Many investigators have discussed the value of historical or paleoflood information for improving estimates of flood frequency distributions, (Benson, 1950; Leese, 1973; Stedinger and Cohn, 1986; and Hirsch, 1987).

According to Cohn and Stedinger (1987), Bulletin 17B from the U.S. Water Resources Council (1982) makes inefficient use of historical data. Cohn (1984; 1986) demonstrated the use of maximum likelihood estimators with historic records, and this procedure was found superior to that advocated by the U.S. Water Resources Council (Baker, 1987).

Hirsch (1985) showed that the standard plotting positions used in flood frequency analysis are strictly applicable only to systematic records, and the extension of the gage record with historic or paleoflood data are censored records. A statistical censored sample may be either a Type I or Type II. Type I censored samples are missing data above or below a known fixed threshold, whereas Type II samples have a fixed number of the smallest or largest observations removed, regardless of the magnitude (Hirsch, 1987; Stedinger and Cohn, 1986; and Wohl, 1988). Type I samples are usually applied to paleoflood records interpreted from slackwater deposits (Wohl, 1988). Once a flood deposits a layer of sediment on a slackwater deposit, only higher floods can add material to the top and the information is censored by a progressively rising censoring level (Pickup et al., 1988).

Hirsch (1987) stated that problems with evaluating a flood record are identifying the threshold, and determining which years are in the sample, and which are not. Baker (1987) noted that the length of record, parameter (n), may be uncertain in historic and paleohydrologic records. The interpreted probabilities of events may be biased toward higher probabilities because of too small an n factor, because there may be a unknown prior time period in which a flood event did not happen (Baker, 1987).

Hirsch (1987), for purposes of evaluating fitted flood frequency distributions or for purposes of estimating distributions directly from plots of flood peaks versus exceedance probabilities, suggested that a new probability plotting position method is needed which can be applied to all the flood data available: both systematic and historic/paleohydrologic floods. Instead of the utilization of traditional probability plotting positions where no historical floods are considered, one should use exceedence based rules where they are. Hirsch and Stedinger (1986) introduced a new plotting position formula which uses methods of maximum likelihood estimators and probability of weighted moments in combination with the Weibull concept. The formula is based on a recognition that the records are partially censored samples, and the frequency of flooding above the censored threshold is a key descriptor of the data set, and subdivides the range of probabilities between the above-threshold and below-threshold groups (Hirsch, 1987).

The incorporation of paleoflood records in the extension and accuracy of flood frequency analysis has been demonstrated by computer simulations conducted by Hosking and Wallis (1986) and Stedinger and Cohn (1986). They found significant improvements in estimates by the use of the number of largest floods for a specified pregage period.

In summary, this chapter reviewed previous investigations conducted in paleoflood hydrology using slackwater deposits as paleoflood indicators, and the application of slackwater deposits used in paleoflood reconstructions. Chapter 3 contains the purpose of the field investigations, methodology of sample collection, laboratory methods, coring procedures, and surveying techniques used in the study. Detailed stratigraphic descriptions of core sites and field sites are provided.

CHAPTER III

FIELD INVESTIGATIONS AND LABORATORY METHODS

Introduction

This chapter describes the field program and laboratory methods carried out to assess the development and preservation of slackwater deposits within the study area. The purpose of the field investigations is presented in this chapter along with the site selections and locations, and the core locations and soil stratigraphic descriptions. The laboratory procedure for total organic carbon and particle size distributions is discussed. The sample collection of buried soils used in radiocarbon dating is shown. The surveying techniques used in determining relative positions of the core sites, and the surveying methods used to generate detailed cross-sections for use in the HEC-2 computer model are examined.

Initial Field Investigations

Site Selection And Location

The drainage system and drainage pattern of Black Bear Creek was initially delineated on geologic maps, aerial photographs, and topographic maps. Eight tributary sites were chosen based on topographic maps as possible field sites. Reconnaissance work, begun in the summer of 1989, on these tributaries in the lower portion of Black Bear Creek, located recognizable slackwater deposits and associated paleosols. Turkey Creek, Pepper Creek, Skedee Creek, Camp Creek, and Crystal Creek were five sites chosen from the possible eight locations, because they had well preserved paleoflood indicators. All sites were chosen at or close to the intersection of the tributaries with Black Bear Creek, because maximum preservation of slackwater deposits was observed during field investigations at these sites in the summer of 1990 (Figures 3.1 through 3.5).

Type Section Descriptions

The five sites selected, designated as type sections, were described according to the soil taxonomic scheme of the U.S. Department of Agriculture, Soil Survey Staff (1975). Master horizons (Table 3.1) were identified as a result of changes in soil texture, soil structure, consistence, color, cutans, nodules or concretions, pH, boundary characteristics, voids, and horizon continuity. Each horizon indicates that the original material has been changed in certain ways. Subordinate distinctions within master horizons were described and shown with lower case letters (Table 3.2).

All site surfaces were cleaned approximately one-half meter into the bank to expose a fresh surface that could be

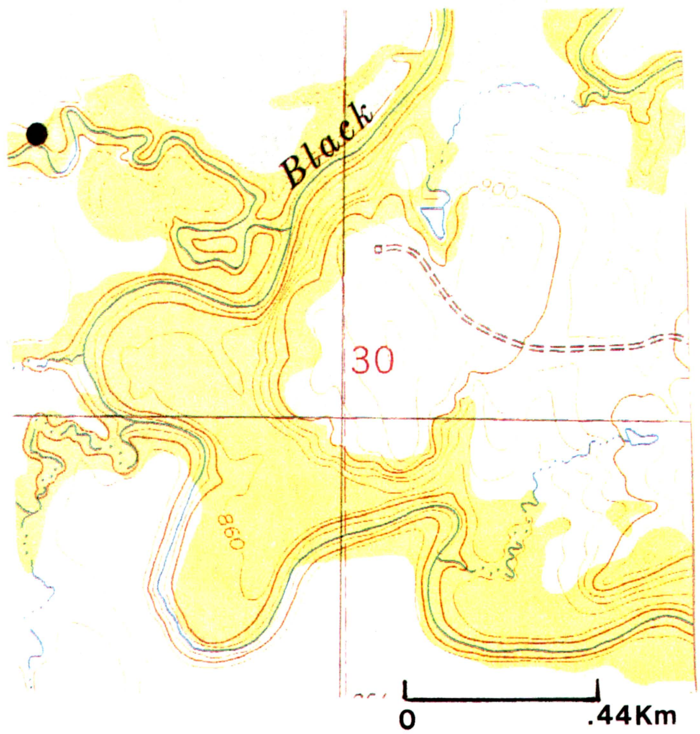

Figure 3.1. Location of Turkey Creek type section.
Legal: NW/4 of NW/4 Sec. 30, T.22N., R.4E.

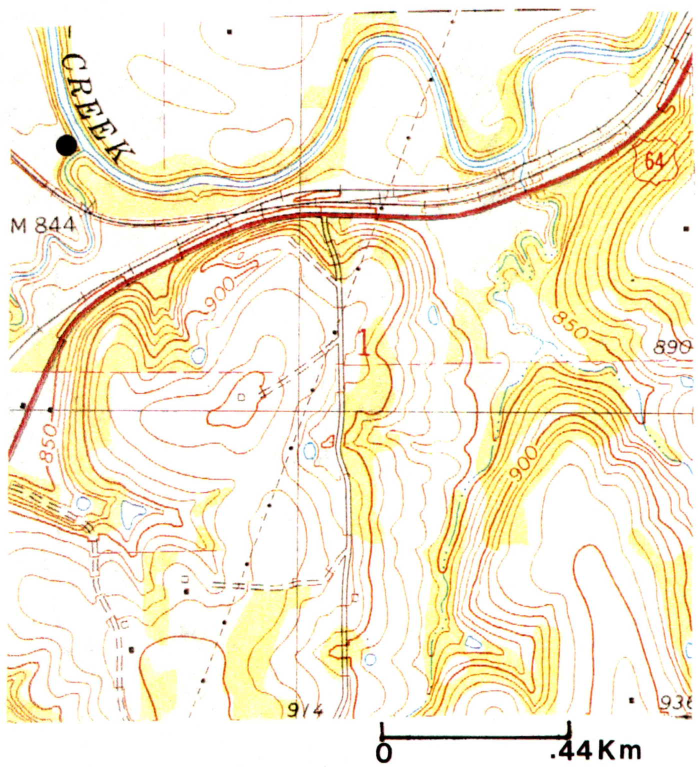

Figure 3.2. Location of Pepper Creek type section.
Legal: NW/4 of NW/4 Sec. 1, T.21N., R.4E.

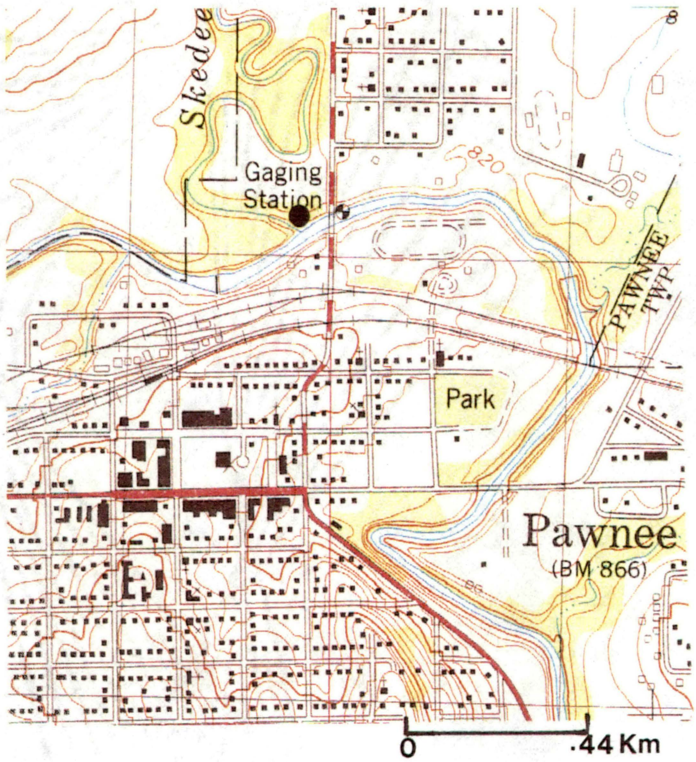

Figure 3.3. Location of Skedee Creek type section.
Legal: SE/4 of NE/4 Sec. 31, T.22N., R.5E.

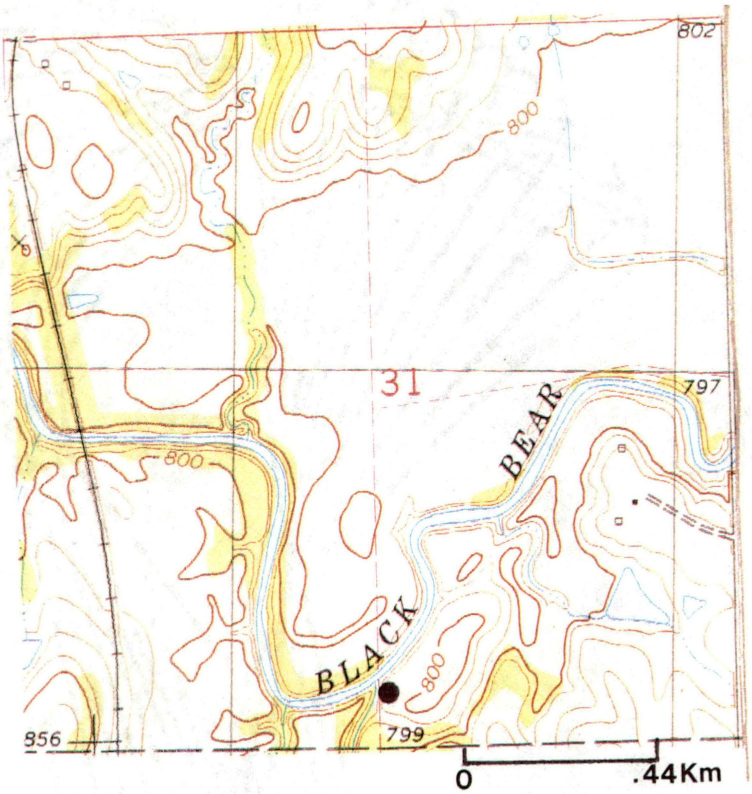

Figure 3.4. Location of Camp Creek type section.
Legal: SE/4 of SW/4 Sec.31, T. 22N.,R.6E

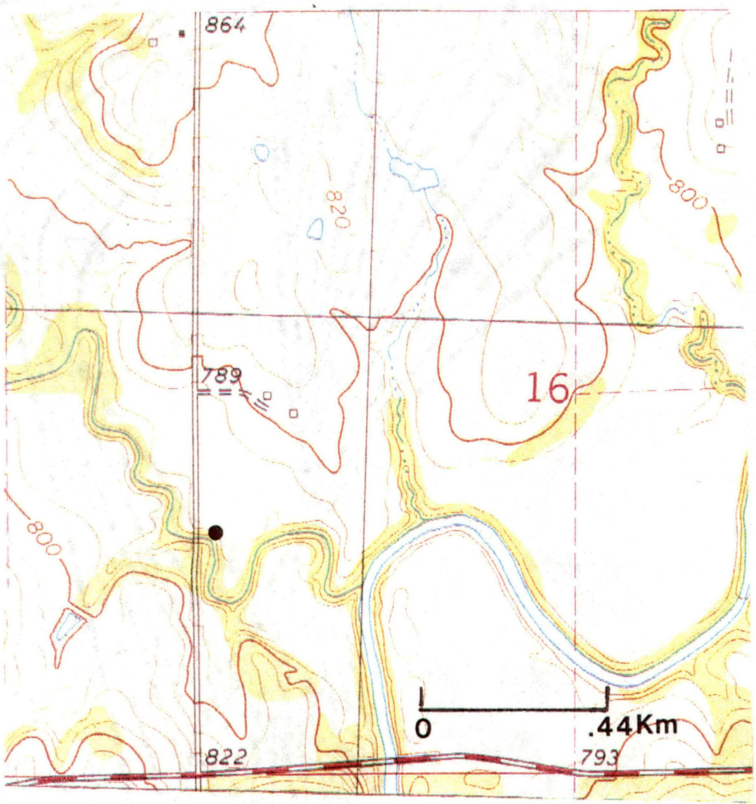

Figure 3.5. Location of Crystal Creek type section.
Legal: NW/4 of SW/4 Sec. 16, T.22N.,R.6E.

TABLE 3.1

MASTER HORIZONS AND LAYERS

Master Horizon	Description
O	Layers dominated by organic material, except limnic layers (coporogenous earth, diatomaceous earth, marl) that are organic. Some are saturated with water for long periods or were once saturated but are now artifically drained; others have never been saturated.
A	Mineral horizons that formed at the surface or below an O horizon and (1) are characterized by an accumulation of humified organic matter intimately mixed with the mineral fraction and not dominated by properties charactistic of E or B horizons or (2) have properties resulting from cultivation, pasturing, or similar kinds of disturbance.
E	Mineral horizons in which the main feature is loss of silicate clay, iron, aluminum, or some combination of these, leaving a concentration of sand and silt particles of quartz or other resistant minerals.
B	Horizons that formed below an A, E, or O horizon are dominated by obliteration of all or much of the original rock structure and by (1) illuvial concentration of silicate clay, iron, aluminum, humus, carbonates, gypsum, or silica, alone or in combination; (2) evidence of removal of carbonates; (3) residual concentration of sesquioxides; (4) coatings of sesquioxides that make the horizon conspicuously lower in value, higher in chroma, or redder in hue than overlying and underlying horizons without apparent illuvi-ation of iron (5) alteration that forms silicate clay or liberates oxides or both and that forms granular, blocky, or prismatic structure if volume changes accompany changes in moisture content; or (6) any combination of these.
C	Horizons or layers, excluding hard bedrock, that are little affected by pedogenic processes and lack properties of O, A, E, or B horizons. Most are mineral layers, but limnic layers layers, whether organic or inorganic, are included. The material of C layers may be either like or unlike that from which the solum presumably formed, A C horizon may have been modified even if there is no evidence of pedogenesis.
R	Layers: Hard Bedrock.

From Department of Agriculture Soil Survey Staff (1975)

TABLE 3.2

SUBORDINATE DISTINCTIONS WITHIN MASTER HORIZONS AND LAYERS

Symbol	Description
a	Highly decomposed organic material
b	Buried genetic horizon
c	Concretions or hard nonconcretionary nodules
e	Organic material of intermediate decomposition
f	Frozen soil
g	Strong gleying
h	Illuvial accumulation of organic matter
i	Slightly decomposed organic matter
k	Accumulation of carbonates
m	Cementation or induration
n	Accumulation of sodium
o	Residual accumulation of sesquioxides
p	Plowing or other disturbance
q	Accumulation of silica
r	Weathered or soft bedrock
s	Illuvial accumulation of sesquioxides and organic matter
t	Accumulation of silicate clay
v	Plinthite
w	Development of color or structure
x	Fragipan character
y	Accumulation of gypsum
z	Accumulation of salts more soluble than gypsum

From Department of Agriculture Soil Survey Staff (1975) investigated. Thickness and depth of each horizon below the soil surface were measured and recorded. A key to the soil descriptions is shown in Table 3.3. Photographs of the type sections are shown in Figures 3.6 through 3.10, and detailed descriptions are given in Tables 3.4 through 3.8.

Sample Collection And Radiocarbon Dating Methods

Samples (approximately 200 grams) were obtained from the top of A-horizons of all prominent paleosols which underlie recognizable slackwater deposits at the type sections. The samples were air dried, crushed, and all visible rootlets removed. The samples were sent to Beta Analytic Inc., in Coral Gables, Florida, to radiocarbon date the soil organic matter. The Beta Analytic procedure involved the examination and removal of any visible rootlets. After being soaked in a hot bath of hydrochloric acid to remove carbonates, the soil material is allowed to settle from solution for several days. The acid is decanted, and the sample is repeatedly rinsed with deionized water to neutrality, and allowed to dry overnight in a convection oven at 110 degrees Centigrade. The soil samples are divided into ten 20-gram batches, and are given multiple combustions to extract the carbon in an enclosed vacuum line. The dates obtained are RCYBP (radiocarbon years before 1950 A.D.). The radiocarbon dates obtained

TABLE 3.3

KEY TO SOIL DESCRIPTIONS

H.# = horizon number. Depths are given in centimeters. Colors are based on Munsell color system.

Mottling degree symbols are: F = few, C = common, M = many, f = fine, m = medium, c = coarse, ft = faint, d = distinct, p = prominent.

Texture symbols are: S = sand, Si = silt, C = clay, L = loam, vf = very fine, f = fine, g = gravelly, and qtz peb = quartz pebbles.

Structure symbols are: 1 = weak, 2 = moderate, 3 = strong, f = fine, m = medium, c = coarse, and PR = prismatic, SBK = subangular blocky, ABK = angular blocky, G = granular, M = massive, and SG = single grain.

Consis. = Consistence and symbols are: s = soft, h = hard, vfr = very friable, fr = friable, and fi = firm.

B. = Boundary symbols are: A = abrupt, C = clear, G = gradual, D = diffuse, S = smooth.

Symbols for roots and pores are: F = few, C = common, M = many, vf = very fine, f = fine, m = medium, and c = coarse.

Ped surface = Ped surface feature and Por surface = Pore surface feature symbols are: vf = very few, F = few, C = common, M = many, ft = faint, d = distinct, p = prominent, Fe = iron, Mn = manganese, and OM = organic matter.

Eff matrix = effervescence within matrix. Symbols are: Rx = reaction to hydrochloric acid, vsle = very slightly effervescent, sle = slightly effervescent, and ste = strongly effervescent.

(From Soil Survey Manual, 1981).

Figure 3.6. Photograph of Turkey Creek type section.

TABLE 3.4

SOIL DESCRIPTION AT TURKEY CREEK TYPE SECTION

H.#	Horizon Name	Depth (cm)	Dominant Color	Texture	Structure	Consis.	B.
1	O	0 - 3		Leaf litter			
2	A1	3 - 58	5YR 3/3	SiCL	2mSBK	fr	AS
3	A2	58 - 84	5YR 3/4	SiCL	3mSBK	fr	AS
4	Bt1	84 - 142	5YR 4/4	CL	3mSBK	fi	CS
5	Bt2	142 - 173	5YR 4/6	SCL	3mSBK	fi	CS
6	Bt3	173 - 201	5YR 5/5	SiL	2mSBK	fi	CS
7	BC	201 - 221	5YR 4/4	vfSL	1mSBK	fr	CS
8	CB	221 - 249	5YR 4/4	fSL	1mSBK	fr	CS
9	C1	249 - 353	5YR 4/6	fSL	1mSBK	vfr	GS
10	C2	353 - 373	5YR 4/4	SL	SG	vfr	AS
11	C3	373 - 391	5YR 4/6	cS	SG	vfr	AS
12	A,b1	391 - 427	5YR 3/2	C	2mABK	fr	AS

* See Key

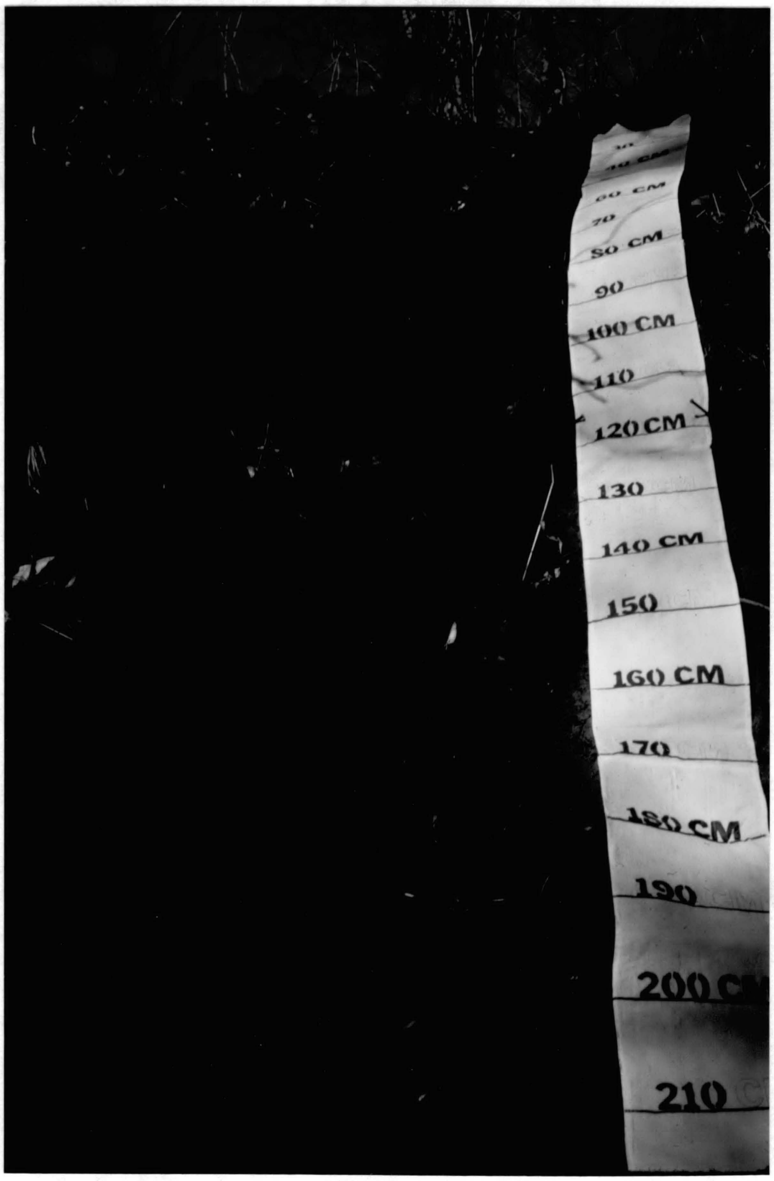

Figure 3.7. Photograph of Pepper Creek type section.

TABLE 3.5

SOIL DESCRIPTION AT PEPPER CREEK TYPE SECTION

H.#	Horizon Name	Depth (cm)	Dominant Color	Texture	Structure	Consis.	B.
1	A	0 - 43	5YR 4/2	fSL	3mG	fr	CS
2	Bt1	43 - 98	5YR 4/6	vfSL	3mSBK	fr	GS
3	Bt2	98 -147	5YR 4/5	SiL	2mSBK	fr	GS
4	A,b1	147-158	5YR 4/2	SL	2mSBK	fr	GS
5	Bw,b1	158-236	5YR 4/3	vfSL	2mABK	fr	GS
6	Bt1,b1	236-252	5YR 4/4	SiC	1mSBK	fr	CS
8	Bt2,b1	252-263	5YR 5/6	C	1mSBK	fr	CS
7	A,b2	263-276	5YR 4/3	SiL	2mSBK	fr	CS
8	Bt,b2	276-318	5YR 4/4	SiCL	3mABK	fr	GS
9	AB,b2	318-340?	5YR 4/6	vfSL	2mABK	fr	

* See Key

Figure 3.8. Photograph of Skedee Creek type section.

TABLE 3.6

SOIL DESCRIPTION AT SKEDEE CREEK TYPE SECTION

H.#	Horizon Name	Depth (cm)	Dominant Color	Texture	Structure	Consis.	B.
1	A	0 - 18	5YR 4/6	fSL	1mSBK	vfr	CS
2	C1	18 - 61	5YR 4/3	LS	M	vfr	CS
3	C2	61 - 89	5YR 4/4	vfSL	M	fr	CS
4	C3	89 - 114	5YR 4/6	fLS	M	fr	CS
5	A,b1	114 - 178	5YR 4/3	L	2mSBK	fr	CS
6	C1,b1	178 - 188	5YR 5/4	fS	M	vfr	AS
7	C2,b2	188 - 239	5YR 4/4	SiL	M	fr	CS
8	A,b2	239 - 254	5YR 3/3	SiL	2fSBK	fr	AS
9	BC,b2	254 - 320	5YR 4/6	SiL	1mSBK	fr	CS
10	A,b3	320 - 333	5YR 2.5/2	SiL	2fSBK	fr	AS
11	C,b3	333 - 348	5YR 4/4	vfSL	M	fr	AS
12	A,b4	348 - 396?	5YR 3/2	SiL	2mSBK	fr	

* See Key

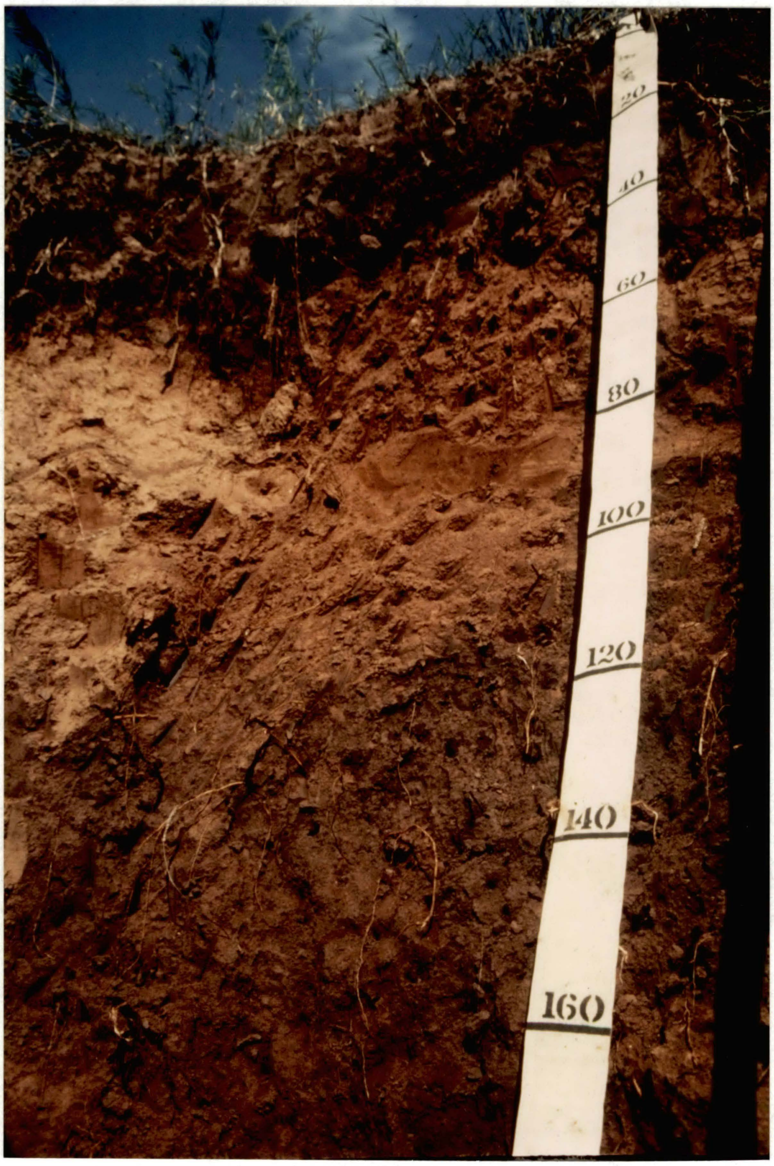

Figure 3.9. Photograph of Camp Creek type section.

TABLE 3.7

SOIL DESCRIPTION AT CAMP CREEK TYPE SECTION

H.#	Horizon Name	Depth (cm)	Dominant Color	Texture	Structure	Consis.	B.
1	A	0 - 27	7.5YR 3/2	vfSL	2mG	fr	CS
2	Bw	27 - 55	5YR 4/4	vfSL	2mSBK	fr	GS
3	Bc	55 - 100	5YR 4/3	L	1cSBK	fr	CS
4	A,b1	100 - 137	7.5YR 3/2	SiL	2fSBK	fr	GS
5	Bt1,b1	137 - 181	5YR 3/4	SiCL	2mG	fr	GS
6	Bt2,b1	181 - 217	5YR 4/4	SiCL	2mSBK	fr	GS
7	Bw,b1	217 - 294	5YR 4/3	L	2mP	fr	CS
8	AB,b2	294 - 344	5YR 3/4	C	3mABK	fr	GS
9	Bw,b2	344 - 394	5YR 4/4	SiL	2mSBK	fr	CS
10	AB,b3	394 - 436	5YR 3/4	C	2mABK	fr	GS
11	Bw,b3	436 - 518?	5YR 4/4	SiCL	1cPr	fr	

* See Key

Figure 3.10. Photograph of Crystal Creek type section.

TABLE 3.8

SOIL DESCRIPTION AT CRYSTAL CREEK TYPE SECTION

H.#	Horizon Name	Depth (cm)	Dominant Color	Texture	Structure	Consis.	B.
1	A	0 - 48	5YR 2.5/2	vfSL	2mABK	fr	CS
2	Bt1	48 - 121	5YR 4/6	SiCL	1mBK	fr	CS
3	Bt2	121 - 138	5YR 4/2	SiCL	2mBK	fi	CS
4	A,b1	138 - 335	5YR 3/2	L	2mABK	fr	GS
5	Bt,b1	335 - 457?	5YR 3/4	SiL	2mSBK	fr	CS

* See Key

for selected type sections are shown in Table 3.9.

Coring Procedure And Core Descriptions

Stratigraphic analysis of the type sections in conjunction with aerial photographs and topographic maps helped to determine sites where cores would be obtained during the summer of 1990. Cores were to be taken up-the-tributaries to determine the elevation where individual slackwater units pinched out. This procedure was done, because suspended sediment deposited in slackwater locations records stages equal to or less than the maximum stages of previous floods.

Cores were obtained in the summer of 1990 along Turkey and Crystal Creeks because the most easily recognizable slackwater units and associated paleosols were located on them. They also were representative of the upper and lower portions of the study area. Seven cores, four along Crystal Creek and three along Turkey Creek, were obtained with a truck-mounted Giddings Probe (model GSRP-S) Giddings Machine Company, Ft. Collins, CO. All cores, taken to the deepest penetratable zone by the probe, had an average depth of 7.8 meters with a diameter of five centimeters. Core site locations and depths of penetration are shown in Figures 3.11 and 3.12. The seven cores were taken to the Oklahoma State University Soil Genesis And Morphology laboratory where detailed descriptions were measured and recorded in Appendix A.

TABLE 3.9

RADIOCARBON DATES OBTAINED FROM PALEOSOLS OVERLAIN BY DISTINCT SLACKWATER DEPOSITS AT TYPE SECTION LOCALITIES

Type Section Location *	Sample Depth (cm)	C-14 Years BP Soil Organic Date
Turkey Creek	358 - 363	3590 +/- 80 BP, Beta - 35497
Pepper Creek	147 - 152	390 +/- 60 BP, Beta - 35496
Camp Creek	110 - 114	760 +/- 80 BP, Beta - 33073
Crystal Creek	138 - 145	1150 +/- 100 BP, Beta - 35495

* See Figure 3.1 through 3.5 for legal locations.

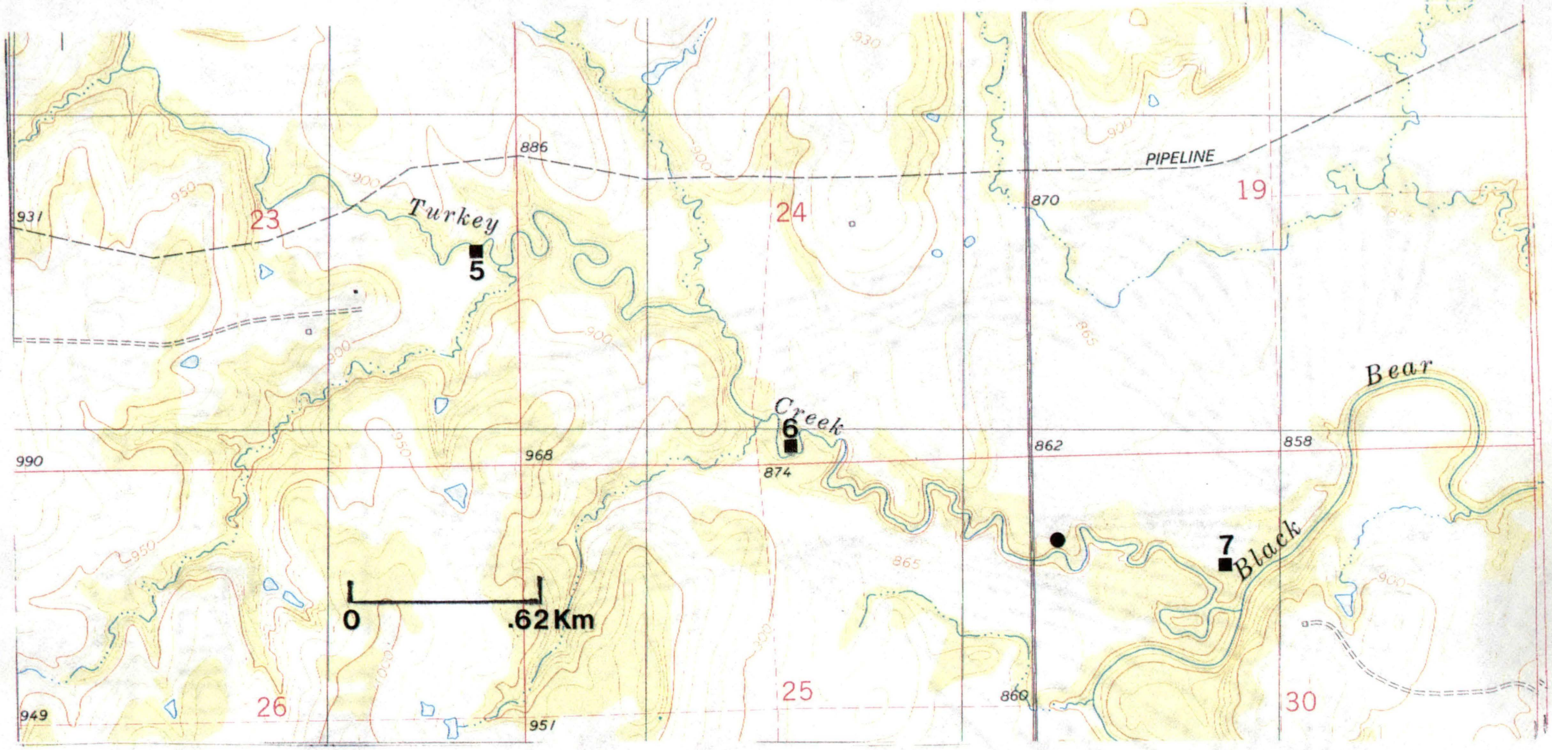

Figure 3.11. Core site locations and depths - Turkey Creek.

Core Number	Core Depths (meters)
5 ■	9.3
6	9.2
7	7.6
●	Type Section

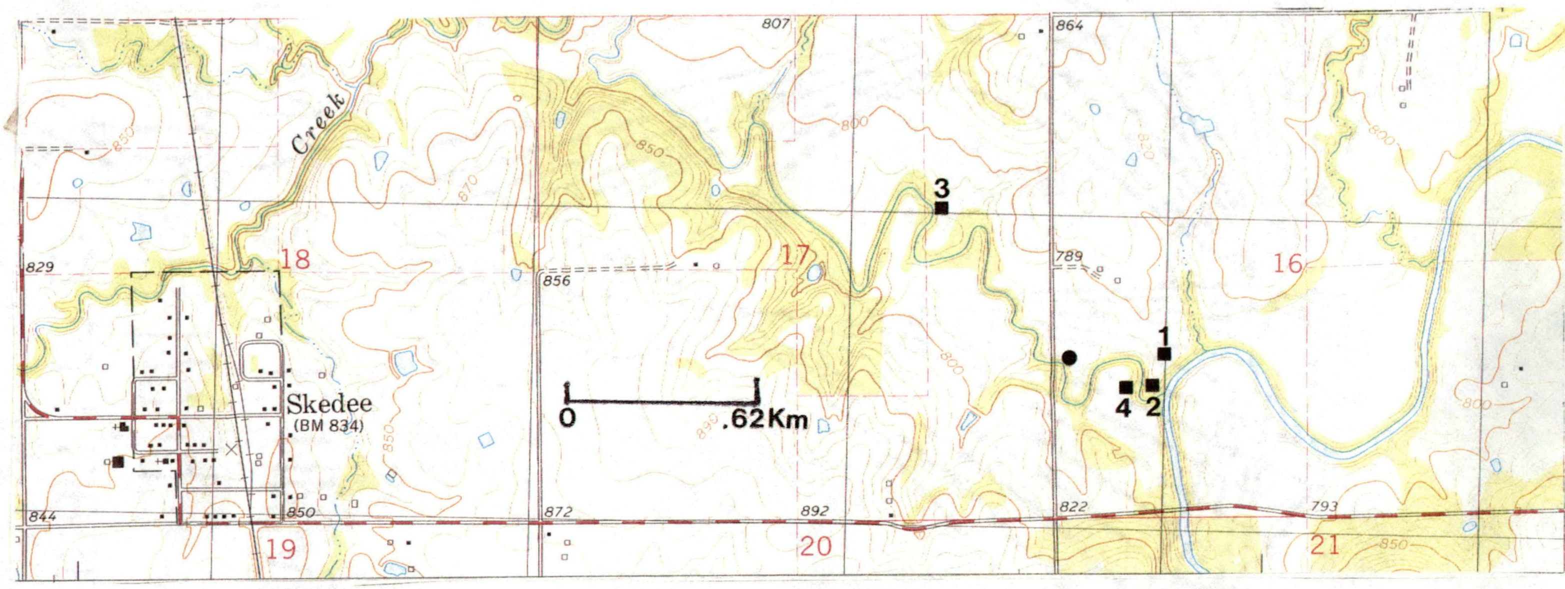

Figure 3.12. Core site locations and depths - Crystal Creek.

Core Number	Core Depths (meters)
1■	9.3
2	6.3
3	5.7
4	7.2
●	Type Section

Laboratory Methods

Total Organic Carbon Procedure

Each core was sampled for total organic carbon every ten centimeters in the upper four and a half meters of the core and across all buried soils, and approximately every twenty-five centimeters in the lower portion. Samples from bank and terrace locations were also tested for total organic carbon. This procedure was conducted to support field observations in the identification of buried soils. The laboratory procedure followed the methods outlined in "Methods of Soil Analysis" by the Soil Science Society of America, Inc.

Samples selected for organic carbon content were air dried and crushed to a medium sand size fraction (500 microns). Approximately one gram of sample was weighed to the third decimal place on the Mettler PC 440 top-loading digital balance, and the mass was recorded. Each sample was placed in a ceramic crucible, mixed with one scoop of iron accelerator, and one scoop of tin accelerator was sprinkled on top, then each was covered with a perforated ceramic lid.

Sample preparation is followed by weighing the Ascarite absorption bottle to the fourth decimal place on the Digital Sartorius B 120 S balance. The Ascarite containing bottle, after weighing, is attached to the LECO high-frequency induction furnace, and the crucible placed on the ceramic pedestal. The LECO furnace uses the heat generated by the coupling of the metallic accelerators to oxidize the ceramic pedestal. The LECO furnace uses the heat generated by the coupling of the metallic accelerators to oxidize the carbon in soils, and therefore, is used to determine the percent organic carbon present.

A sample set consists typically of two standards and ten samples. Carbon dioxide, produced as the carbon burns, is collected in the Ascarite (a carbon dioxide absorbing compound). The Ascarite bottle is weighed after each sample burn on the digital Sartorius balance. The weight of the carbon dioxide and the weight of the sample are used to calculate the percent carbon in the wet sample.

Because percent organic carbon is reported on a dry basis, the moisture content of each sample had to be determined. Each sample was adjusted for the moisture amount determined from a subsample measurement. Subsamples of 25 grams were weighed to the third decimal point on the Mettler PC 440 digital balance, recorded, and placed in tared tins. Each tin was dried overnight in a forced convection oven at 106 degree Centrigrade. Each sample was weighed on the Mettler balance, and each weight was recorded. The formula used to determine percent organic carbon (dry weight), and the results are given in Appendix B (Nelson and Sommers, 1982).

Particle Size Distribution Procedure

Particle size distribution tests, for selected horizons, were conducted to support field determined soil textures. The tests conducted followed the methods outlined in "Methods of Soil Analysis" set forth by the American Society of Agronomy, Inc. The laboratory procedure and results of the particle size distribution for selected horizons are given in Appendix C (Gee and Bauder, 1986).

Field Investigations And Site Analysis

Surveying Of Core Locality Sites

Each core site was surveyed with a theodolite and stadia rod in the summer of 1990. The survey determined the relative elevation of the drill site surfaces above the stream bed. The data generated was used in the paleoflood reconstruction of lower Black Bear Creek which is described in Chapter 5.

Field Investigations Of Core Site/Bank Exposure

Detailed stratigraphic descriptions of core site/bank localities along Turkey and Crystal Creeks were completed in the winter of 1991. This procedure was used to correlate the bank exposures and core sites. Photographs of the sites, shown in Figures 3.13 through 3.18, and detailed soil descriptions are given in Tables 3.10 through 3.15.

Figure 3.13. Crystal Creek bank site adjacent to core site 2.

TABLE 3.10

STRATIGRAPHIC DESCRIPTION OF BANK SITE ADJACENT TO CORE SITE 2 - CRYSTAL CREEK

H.#	Horizon Name	Depth (cm)	Dominant Color	Texture	Structure	Consis.	B.
1	Ap	0-5	7.5YR 4/2	vfSL	1fG	fr	CS
2	A1	5-46	5YR 3/2	fSL	2mBK	fr	CS
3	Bt1	46-74	5YR 4/4	SiL	2mSBK	fr	GS
4	Bt2	74-109	5YR 5/4	SiCL	2mSBK	fi	CS
5	A,b1	109-122	5YR 4/5	vfSL	2mSBK	fr	AS
6	C1,b1	122-142	7.5YR 6/4	fS	SG	vfr	CS
7	C2,b1	142-193	7.5YR 5/4	cS	SG	vfr	AS
8	A,b2	193-224	5YR 3/2	SiL	2mSBK	fr	CS
9	Bt,b2	224-242?	5YR 4/4	SiC	2mSBK	fi	

* See Key

Figure 3.14. Crystal Creek bank site adjacent to core site 3.

TABLE 3.11

STRATIGRAPHIC DESCRIPTION OF BANK SITE ADJACENT TO CORE SITE 3 - CRYSTAL CREEK

H.#	Horizon Name	Depth (cm)	Dominant Color	Texture	Structure	Consis.	B.
1	Ap	0 - 10	5YR 3/2	SL	2mSBK	fr	GS
2	A1	10 - 53	10YR 3/2	vfSL	2mSBK	fr	CS
3	A,b1	53 - 122	7.5YR 4/2	SiL	1fSBK	fr	AS
4	AB,b1	122 - 160	7.5YR 4/4	vfSL	2mSBK	fr	CS
5	A1,b2	160 - 231	7.5YR 3/2	SiL	2mSBK	fr	CS
6	A2,b2	231 - 305	7.5YR 4/4	fSL	2mSBK	fr	CS
7	Bt,b2	305 - 361?	5YR 3/4	SiL	2mSBK	fr	

* See Key

Figure 3.15. Crystal Creek bank site adjacent to core site 4.

TABLE 3.12

STRATIGRAPHIC DESCRIPTION OF BANK SITE ADJACENT TO CORE SITE 4 - CRYSTAL CREEK

H.#	Horizon Name	Depth (cm)	Dominant Color	Texture	Structure	Consis.	B.
1	Ap	0 - 18	5YR 3/2	vfSL	1fSBK	fr	CS
2	A	18 - 46	7.5YR 4/2	SiL	2mSBK	fr	CS
3	Bt1	46 - 79	7.5YR 4/4	SiL	2mSBK	fr	CS
4	A,b1	79 - 277	5YR 3/2	SiL	2mSBK	fr	CS
5	Bt,b1	277 - 368	5YR 4/6	vfSL	2mSBk	fr	

* See Key

Figure 3.16. Turkey Creek bank site adjacent to core site 5.

TABLE 3.13

STRATIGRAPHIC DESCRIPTION OF BANK SITE ADJACENT TO CORE SITE 5 - TURKEY CREEK

H.#	Horizon Name	Depth (cm)	Dominant Color	Texture	Structure	Consis.	B.
1	Ap	0 - 10	5YR 4/3	vfSL	1fSBK	fr	CS
2	BA	10 - 43	5YR 4/2	fSL	2mBK	fi	CS
3	A,b1	43 - 117	5YR 3/2	SiL	2mSBK	fr	CS
4	AB,b1	117 - 145	5YR 3/3	SCL	2mSBK	fr	CS
5	Bt1,b1	145 - 191	5YR 4/4	SCL	2mSBK	fr	CS
6	Bt2,b1	191 - 212	5YR 4/3	SCL	1mSBK	fr	CS
7	Bt3,b1	212 - 270	5YR 4/4	SCL	2mSBK	fr	

* See Key

Figure 3.17. Turkey Creek bank site adjacent to core site 6.

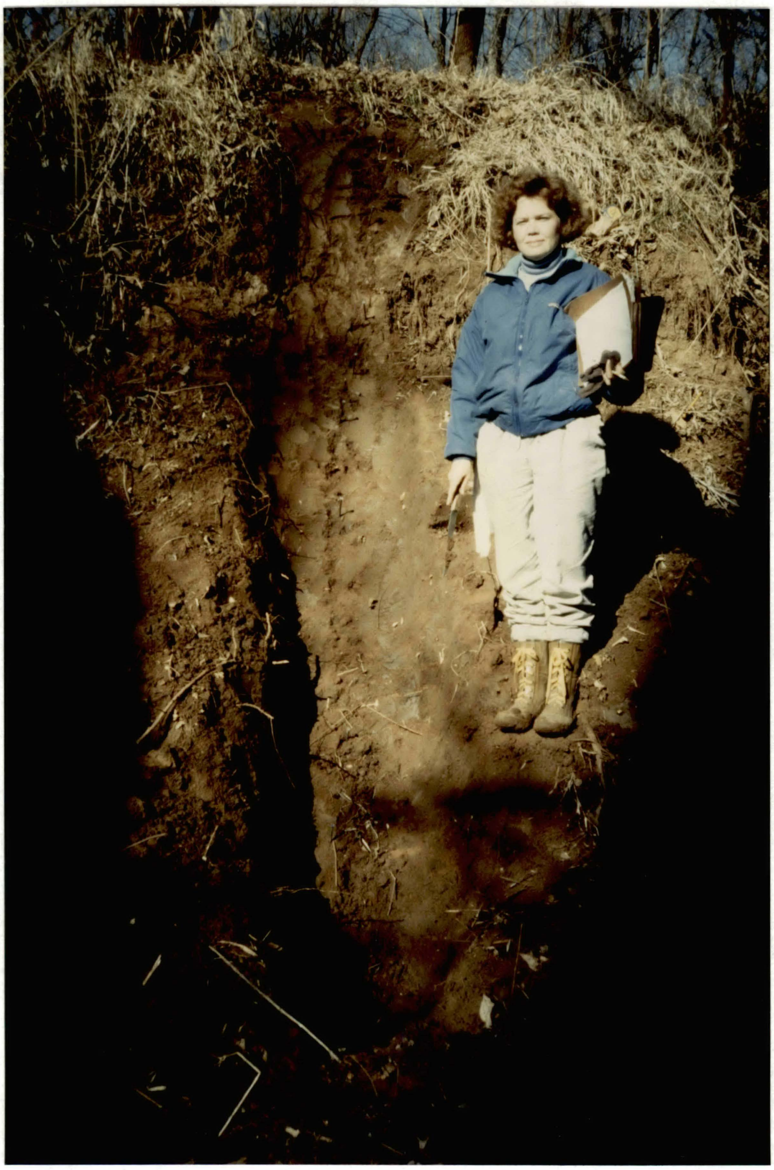

Figure 3.18. Bank site at Turkey Creek - Black Bear junction.

TABLE 3.15

STRATIGRAPHIC DESCRIPTION OF TURKEY CREEK BANK MOUTH SITE

H.#	Horizon Name	Depth (cm)	Dominant Color	Texture	Structure	Consis.	B.
1	O	0 - 3					
2	A1	3 - 23	5YR 3/4	SL	2mGR	fr	CS
3	A2	23 - 46	5YR 3/3	SiL	2mSBK	fr	CS
4	Bt1	46 - 79	5YR 4/4	CL	2mSBK	fi	CD
5	BW1	79 - 122	5YR 3/3	vfSL	2mBK	fr	CS
6	BW2	122 - 145	5YR 4/4	vfSL	2mSBK	fr	CS
7	BW3	145 - 168	5YR 4/6	mSL	2mSBK	fr	CS
8	A,b1	168 - 208	5YR 3/2	CL	2mSBK	fr	CS
9	AC,b1	208 - 302	5YR 4/4	SL	1fGR	fr	CS
10	A,b2	302 - 338?	5YR 3/3	SiL	2mSBK	fr	

* See Key

Physical Tracing Of Slackwater Deposits-Up-Slope Procedure

During the winter of 1991, individual slackwater deposits were physically traced upstream from the type sections and core localities along Turkey and Crystal Creeks. This procedure was done to help identify the pinch-out of the individual slackwater deposits, and to correlate the individual slackwater deposits and associated paleosols from site-to-site.

Physical Tracing Of Slackwater Deposits-Up-Slope Procedure

Physical tracing of individual slackwater units up-slope perpendicular to Turkey and Crystal Creeks was completed in the fall of 1990 and the winter of 1991, respectively. This was accomplished to determine elevations where individual slackwater units pinched out up-slope. The elevation where the slackwater deposit pinches out up-slope is also representative of the minimum stage of the flood emplacing the slackwater deposit. Information obtained was used in generating water surface profiles in the computer modelling phase.

Turkey Creek.

The Soil Conservation Service was in the early stages of constructing a flood control structure along Turkey Creek in the fall of 1990, 105 meters north of my core site

6. A total of 14 test holes were drilled up-slope by the Soil Conservation Service (SCS). The SCS provided detailed stratigraphic descriptions, elevations of all test holes, and the entire cores for test holes 5 and 10. The cross-section made by the Soil Conservation Service of the study area is shown in Figure 3.19.

The tracing of slackwater deposits up-slope perpendicular to Turkey Creek was accomplished by the following method. Bank exposures adjacent to the test holes 301 and 302 (SCS) were stratigraphically described (Tables 3.16 and 3.17), and are shown in Figures 3.20 and 3.21. The SCS bank exposure localities were stratigraphically and physically correlated with the bank exposure adjacent to core 6. The slackwater unit and associated paleosol present in the bank exposure adjacent to core 6 had been physically traced upstream from the Turkey Creek type section. The elevation where the slackwater deposit pinches out up-slope was determined from the stratigraphic descriptions of wells 302, 11, and 301. The documented elevation was used to generate the water surface profile in the HEC-2 program.

<u>Crystal Creek.</u>

The slackwater deposit present at the Crystal Creek type section is within 140 cm of the surface. The slackwater unit was physically traced up-slope from the type section by digging to expose the unit. Digging was repeated until the slackwater unit pinched out above a well

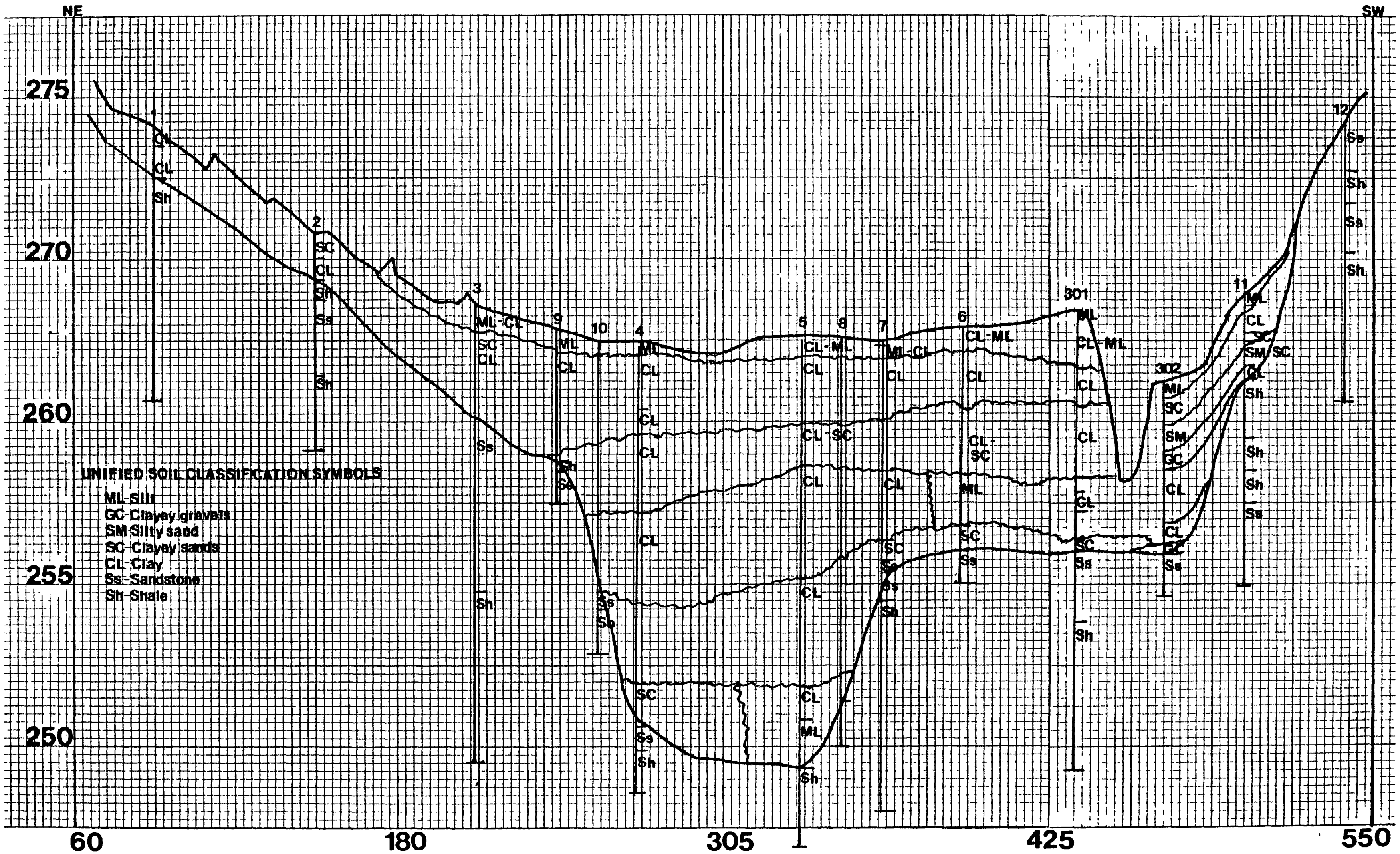

Figure 3.19. Cross-section of up-slope site along Turkey Creek From Soil Conservation Service, (1962).

Figure 3.20. Bank site adjacent to Soil Conservation Service well 301.

TABLE 3.16

SOIL DESCRIPTION OF BANK SITE ADJACENT TO SCS-301

H.#	Horizon Name	Depth (cm)	Dominant Color	Texture	Structure	Consis.	B.
1	A	0 - 74	5YR 3/4	vfSL	2mSBK	fr	CS
2	Bt1	74 - 119	5YR 5/4	SiL	2mSBK	fi	CS
3	Bt2	119 - 155	5YR 5/6	SiL	2mBK	fr	CS
4	Bt3	155 - 180	5YR 4/6	SiL	2mSBK	fr	CS
5	Bt4	180 - 231	5YR 4/4	fSL	2mSBK	fr	GS
6	C1	231 - 246	5YR 5/4	SiL	2mSBK	fr	CS
7	C2	246 - 264	5YR 4/6	vfSL	1mSBK	fr	GS
8	C3	264 - 307	5YR 4/4	fSL	2mSBK	fr	GS
9	C4	307 - 345	5YR 4/6	mSL	2mSBK	fr	CS
10	A,b1	424 - 485?	5YR 4/4	CL	2mSBK	fr	

*See Key

Figure 3.21. Bank site adjacent to Soil Conservation Service well 302.

TABLE 3.17

SOIL DESCRIPTION OF BANK SITE ADJACENT TO SCS-302

H.#	Horizon Name	Depth (cm)	Dominant Color	Texture	Structure	Consis.	B.
1	A	0 - 48	5YR 3/3	fSL	2mSBK	fr	CS
2	Bt1	48 - 79	5YR 5/4	SiL	2mSBK	fi	CS
3	Bt2	79 - 97	5YR 5/6	SiL	2mSBK	fi	CS
4	Bt3	97 - 114	5YR 5/4	SiL	2mSBK	fr	CS
5	C1	114 - 201	5YR 4/6	fSL	2mSBK	fr	CS
6	C2	201 - 267	5YR 4/4	vfSL	2mSBK	fr	CS
7	C3	267 - 290	5YR 4/4	SL	SG	fr	CS
8	C4	290 - 302	5YR 3/4	cSL	SG	fr	CS
9	A,b1	302 - 335?	5YR 4/2	CL	1mBK	fr	

*See Key

defined paleosol (Figure 3.22). Surveying was conducted from the type section to the up-slope location where the pinchout occurred, and the elevation determined. The information was used to generate a water surface profile in the computer modelling phase. Up-slope digging locations are shown in Figure 3.23.

Surveying Of The Study Reach For The HEC-2 Water Surface Profile Program

A detailed survey of the study reach along Black Bear Creek, Turkey Creek, and Crystal Creek was completed in the winter of 1991. The majority of the detailed surveys and cross-sections of the study reach were provided by the Soil Conservation Service. The cross-sections selected were those which best described the geometry and hydraulics of the reach, and all were made perpendicular to the high-flow channel. A total of fifteen cross-sections, used in the HEC-2 program, are included in Appendix D.

Summary

In summary, this chapter contains all the data generated from the field investigations and laboratory methods. The laboratory methods are essential in supporting the field investigations, especially in the recognition of buried soils, and to confirm the preservation of slackwater units. A detailed discussion of the findings from the laboratory methods and field investigations will be pre-

Figure 3.22. An up-slope site along Crystal Creek exposing slackwater unit deposited on a well-defined buried soil. Site was physically correlated from Crystal Creek type section and the elevation was recorded.

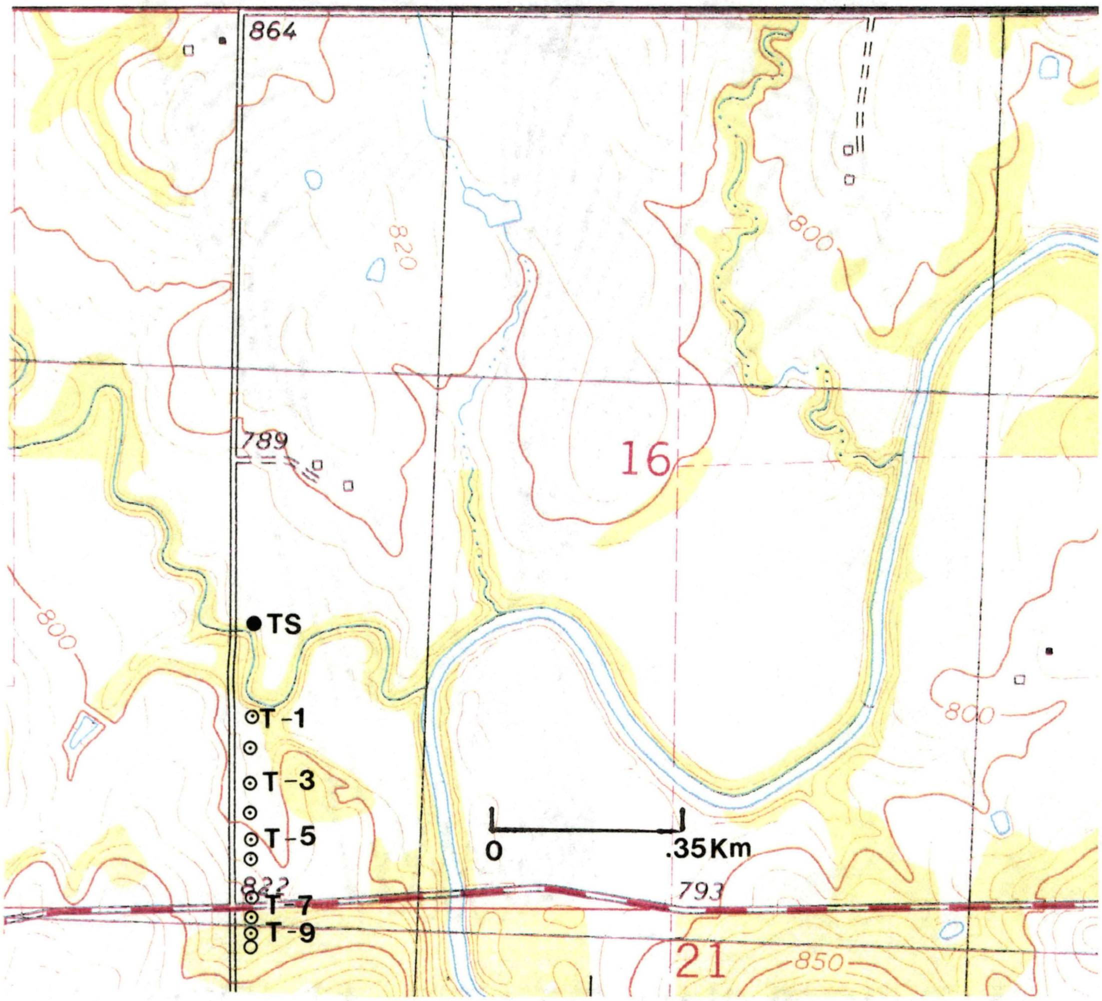

Figure 3.23. Locations of up-slope sites along Crystal Creek. T = up-slope site and TS = type section.

sented in chapter 4.

The information obtained from the field investigations is input for the HEC-2 Water Surface Profile which will be examined in chapter 5. The statistical extension of the flood frequency record of lower Black Bear Creek also required field data, and is discussed in chapter 6.

CHAPTER IV

SLACKWATER DEPOSITS USED AS PALEOSTAGE INDICATORS ALONG BLACK BEAR CREEK

Introduction

The purpose of this chapter is to assess the preservation and accumulation of slackwater deposits along the study reach and to establish paleo-floodstages. The stratigraphy, structure, preservation, and sites of accumulation of slackwater deposits along Black Bear Creek tributaries are described in this chapter. The methods used in the correlation of the units from site-to-site are discussed. Procedures to determine maximum slackwater elevations are examined, and examples of how these elevations are used in the HEC-2 program are presented. Assumptions in utilizing slackwater deposits as paleo-floodstage indicators in an alluvial setting are stated and compared to those in a bedrock setting.

Reconstruction of past floods in the lower Black Bear Creek drainage basin was established with slackwater deposits. Slackwater deposits, found preserved at five tributary localities within the study area, are pictured and stratigraphically described in chapter 3. Maximum preservation of a slackwater deposit above a well-defined paleosol, however, was clearly recognized on Turkey and Crystal Creeks. Deposits on these creeks, representative of the upper and lower ends of the study reach, were used to reconstruct the late Holocene history of lower Black Bear Creek.

Sediment Properties Of Black Bear Creek Slackwater Deposits

Mean slackwater sediment size is partially inherited from the lithology of the mainstream upstream from the depositional site. Grain size is also controlled by the fluvial regime of the river ie., the current velocity. Slackwater deposits of the Lake Missoula floods which include coarse gravel were limited by the competence of the backwater flows where tractive processes transported gravels up to tens of meters in diameter in the main Scabland channels (Baker, 1973). In contrast, the size of lower Black Bear Creek slackwater sediments is limited less by competence than by the maximum size of sediments available in the mainstream.

Sieve analyses were conducted on thirty-four slackwater deposits from cores, up-terrace, and bank sites along lower Black Bear Creek. Sediment properties were determined by graphical statistical parameters of Folk (1968), and are given in Table 4.1. The mean grain size along the study reach was 4.7 phi (very coarse silt). A t-test was conducted to test the null hypothesis that the slackwater

TABLE 4.1

GRAIN SIZE PARAMETERS OF SLACKWATER DEPOSITS

	5	16	25	50 (Phi Units)	75	84	95	Mean Size	1 Std. Dev.
Turkey Creek									
Core 5	2.7	3.4	4.0	4.9	7.0	7.2	7.7	5.2	1.7
Core 6	2.0	2.5	3.0	4.0	5.8	7.1	7.5	4.5	1.9
Bank Exposure 2	2.1	2.4	2.7	3.9	5.0	6.1	6.8	4.3	1.7
Type Section	2.6	3.2	3.9	4.7	6.5	6.8	7.8	4.9	1.8
Bank Exposure 6	1.8	2.3	2.6	4.0	5.2	6.0	7.3	4.1	1.8
Core 7	2.4	2.8	3.0	3.8	4.9	6.0	7.3	4.2	1.5
Crystal Creek									
Core 3	3.0	3.8	4.0	4.7	6.3	6.5	6.9	5.0	1.3
Type Section	2.6	3.4	3.6	4.8	7.0	7.2	7.6	5.1	1.7
Core 4	2.6	3.5	3.8	4.6	6.0	6.5	7.4	4.9	1.5
Bank Exposure 4	2.8	3.4	4.0	4.6	6.1	6.7	8.1	4.9	0.0
Core 2	2.3	3.1	3.6	4.6	6.5	7.2	7.6	4.9	1.8
Core 1	2.1	2.4	2.6	2.9	3.8	4.6	7.1	3.3	1.3
Terrace 1	2.7	3.7	3.6	4.6	6.9	6.7	7.1	5.0	1.5
Terrace 2	2.6	3.7	3.8	4.7	6.2	6.8	7.9	4.9	1.6
Terrace 5	2.1	3.3	3.7	4.6	6.1	6.9	7.8	4.7	1.8
Terrace 7	2.3	3.5	3.6	4.4	6.4	6.9	7.7	4.9	1.7

deposits present in the study reach are all from the same lithologic source along Black Bear Creek. The probability that the deposits are significantly different from zero is indicated by the probability value, P, at the .05 significance level. The null hypothesis to be tested is that no significant difference exists between mean sizes of slackwater deposits from the upper and lower portion of the study area. Table 4.2 shows the t-test, and the result that no significant difference exists between the mean size.

TABLE 4.2

T-TEST OF MEAN SIZE FOR SLACKWATER DEPOSITS

Turkey (Phi Units)	Crystal (Phi Units)
5.2	5.0
4.5	5.1
4.3	4.9
4.9	4.9
4.1	4.9
4.2	3.3
	5.0
	4.9
	4.7
	4.8
$\bar{x} = 4.5$	$\bar{x} = 4.8$
$\sum x^2 = 124.2$	$\sum x^2 = 228.1$

$s = 0.57$
t calc. $= 1.1$
$t_{14,\ .05} = 2.145$

The availability of certain grain sizes, ie., very coarse silt, for suspended transport to slackwater sedimentation sites has been the same for at least the last 3,000 years in the lower Black Bear Creek study reach.

Sorting is strongly dependent upon grain size (Folk, 1968). Sorting in sediment with mean sizes of 2 to 3 phi (fine sand) tends to be well-sorted, and the degree of sorting decreases as the phi size increases toward 8 phi (Folk, 1968). According to Folk (1968), a fine sand-coarse silt population, as found at Black Bear Creek, represents the stable residual products liberated from the weathering of granular rocks such as granite, phyllite, metaquartzite, or older sandstones whose grains were ultimately derived from one of these sources. Sandstone outcrops are present throughout the Black Bear Creek drainage basin as discussed in the geology section of chapter 1.

The inclusive graphic standard deviation which includes 90% of the distribution, and is a good overall estimator of sorting, was applied to the slackwater deposits in Black Bear Creek. The slackwater sediments were determined to be poorly sorted because the phi size range was 1.6. Folk (1968) noted that sorting attained for dune and beach sands, is between .25 to .35 phi. River sediments range between .40 and 2.5 phi. The average standard deviation of the slackwater deposits of 1.6 phi, suggests that Black Bear Creek slackwater sediments were deposited by fluvial processes, not eolian processes.

In summary, grain size data ie., the sorting parameter and standard deviation, did establish that the slackwater units identified in the field were fluvial in origin, and not eolian. Comparing the statistical parameters of grain size from the upper and lower end of the study area indicated no difference between mean size. The slackwater sediments preserved in the tributaries are derived mainly from the same slackwater sediment source which is the older sandstone rocks outcropping along Black Bear Creek. Soil Surveys have identified loess as possible source materials, however, these parent materials are not substantiated by laboratory findings.

<u>Primary Sedimentary Structure Of Black Bear Creek Slackwater Deposits</u>

Previous investigators, working on the sedimentology of slackwater units, noted that with the exception of the Lake Missoula slackwater deposits, the majority of slackwater units displaying primary structure are those with horizontal laminations. Many slackwater deposits lack primary structure, however, and are considered to be structureless which indicated rapid deposition of the sediments from suspension. Primary sedimentary structure of the slackwater deposits at the type sections varied from the upper-end of the Black Bear Creek basin at Turkey Creek to the lower-end at Crystal Creek.

The Turkey Creek slackwater unit observed at the type section contains cross-beds near the base of a thick sandy unit which overlies a gleyed paleosol. The cross-beds indicate a paleoflow direction up-tributary. The sand fines upward into a silty unit which is structureless. The slackwater unit is approximately 2 meters thick, the mean grain size is 4.9 phi, and coarse silt represents the majority of the unit (Figure 4.1).

The slackwater unit present at the Crystal Creek type section lacks primary structure and is structureless. The unit is approximately 1 meter in thickness with a mean grain size of 4.7 phi. The slackwater deposit is comprised of approximately 50 percent silt size particles, and 25 percent sand size and 25 percent clay size. The predominance is coarse silt with fine sand (Figure 4.2).

Sites Of Maximum Slackwater Accumulation Along Black Bear Creek

Flume studies conducted by Kochel and Ritter (1986) to model steep, bedrock settings indicate that optimal preservation of slackwater deposits occurs at tributary mouth sites where the junction angles are close to 90 degrees, and where mainstems are not prone to flashy hydrographs. Field investigations along the study reach showed the junction angles of Turkey and Crystal Creeks were approximately 90 degrees with Black Bear Creek. Based on previous studies by Kochel and Ritter (1986), the junction angles of these two tributaries would allow Black Bear Creek to back-

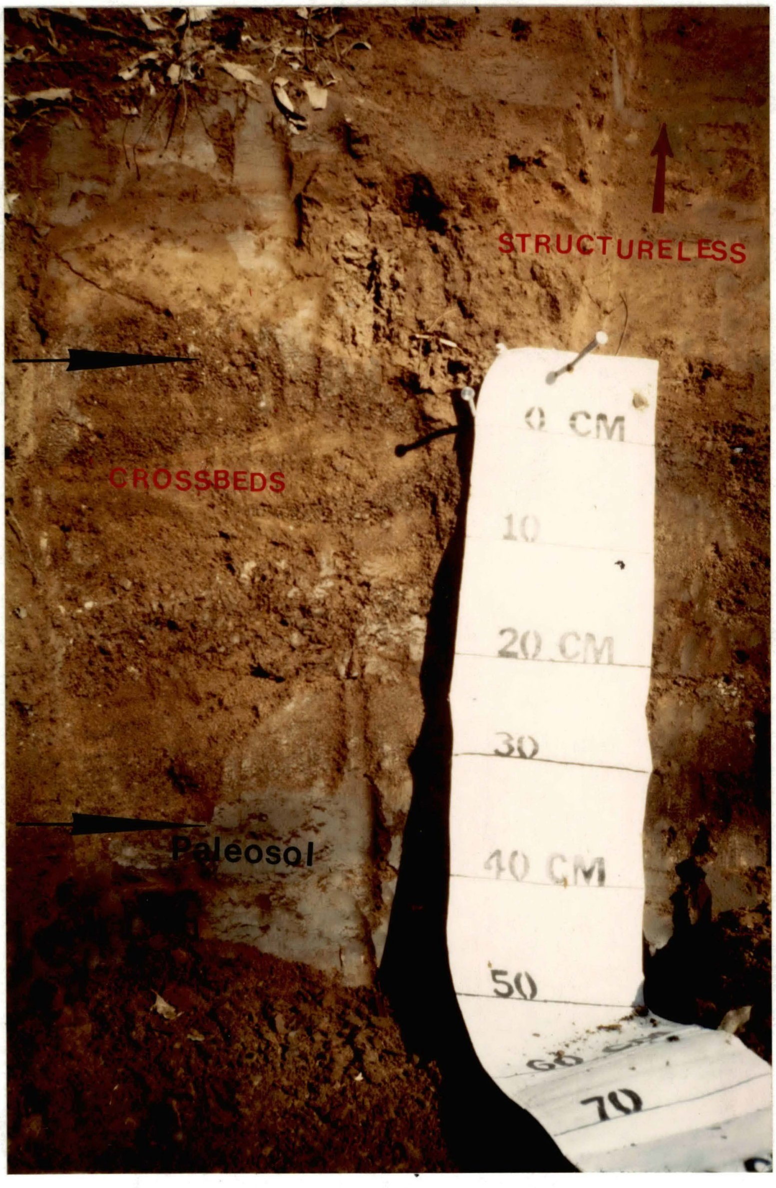

Figure 4.1. Turkey Creek type section. Slackwater unit exhibits small-scale crossbedding in the basal sands. Sequence fines upwards into structureless silty-clay horizons.

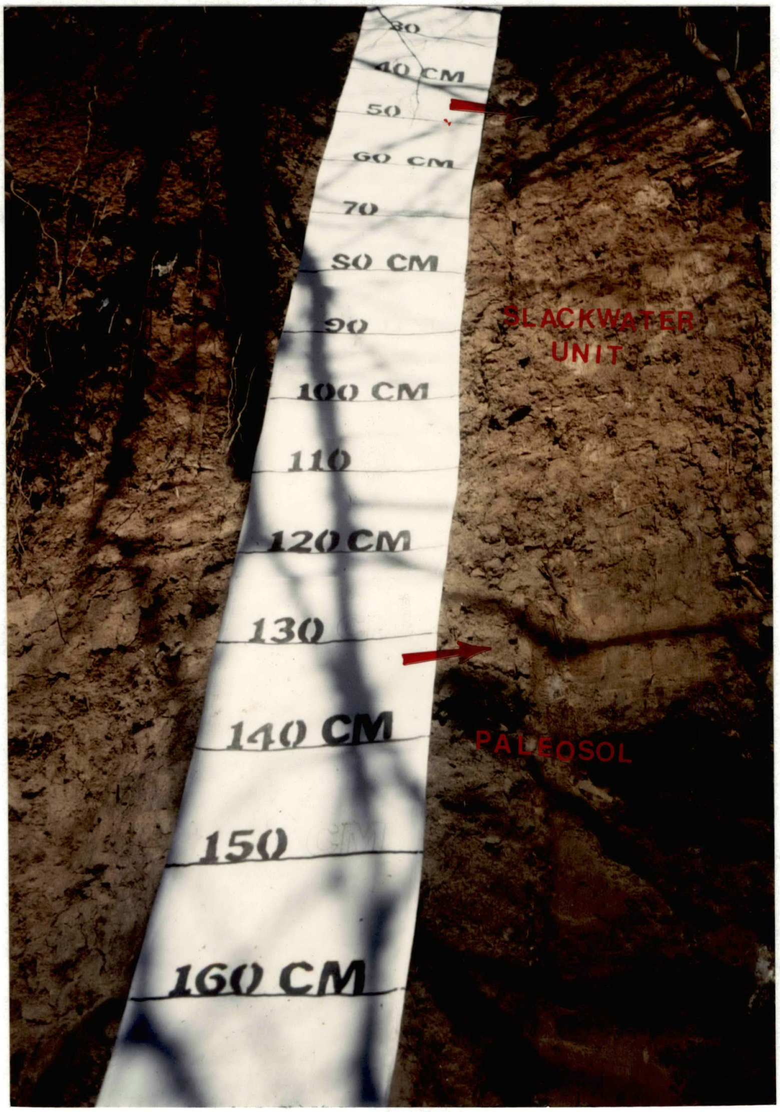

Figure 4.2. Crystal Creek type section. Slackwater deposit is a structureless unit consisting predominantly of silt overlying a distinct paleosol. Paleosol is equivalent to the regionally expressed Copan Soil.

flood efficiently into the tributary mouths for maximum slackwater accumulations.

Kochel (1980) showed that mainstreams prone to flashy hydrographs were most likely to destroy previous accumulations of slackwater deposits located at the mouths of the tributaries in steep, bedrock canyons. Beard (1975) developed a measure of flash flood potential known as the Flash Flood Magnitude Index (FFMI) for the United States. The FFMI is calculated from the standard deviation of the logarithms of annual maximum discharge, and is presented in generalized form in Figure 4.3. The FFMI is based on gauging records from 2,900 stations that had records exceeding 20 years which represented basins less than 2,590 square kilometers.

North-central Oklahoma has a low FFMI (.3), which indicates that streams in the area are not prone to extreme flash floods. The geology and physiography of north-central Oklahoma does provide conditions for flash floods, however, these floods have minor geomorphic effectiveness unless they are rare flood events. Lower Black Bear Creek should be favorable to the development and preservation of slackwater sequences as shown from this single indicator.

Field investigations along Turkey and Crystal Creeks indicated no discernable slackwater deposits above well-defined paleosols at the junction sites. Walking up-the-tributaries, from the tributary mouth sites, well-preserved slackwater deposits were located overlying distinct paleo-

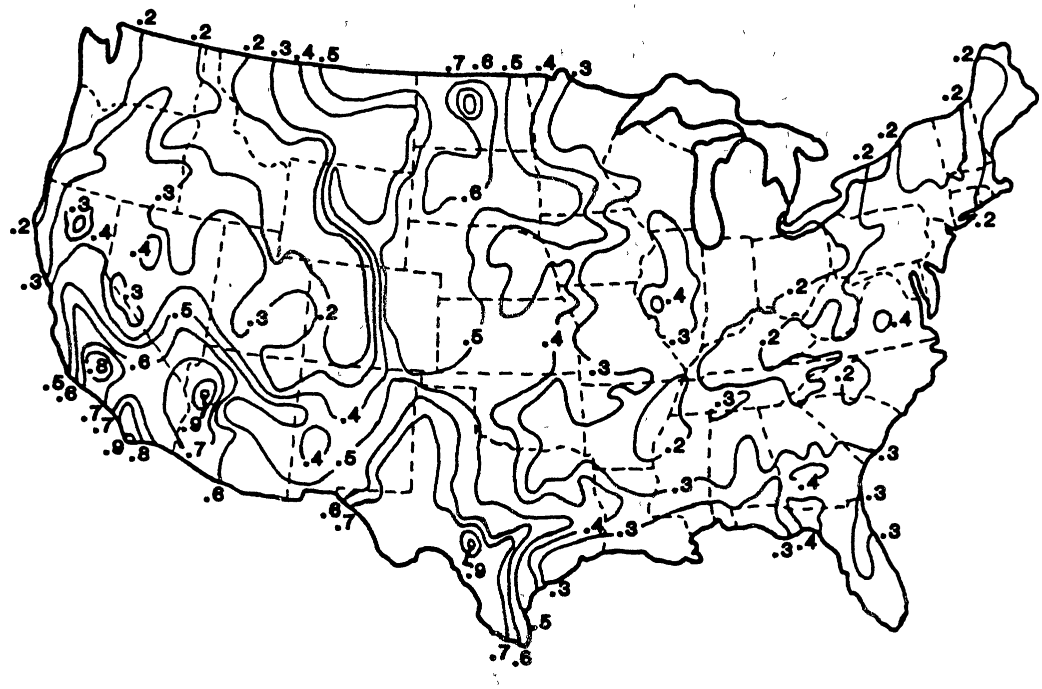

Figure 4.3. Regional variation of the Flash-Flood Magnitude Index for the United States (after Beard, 1975).

ols approximately 325 meters upstream from Black Bear Creek. These sites were designated as type sections. Stratigraphic descriptions and radiocarbon dates for the type sections are discussed in chapter 3.

Baker and Kochel (1988) state that maximum accumulation of slackwater deposits are found at the mouths of the tributaries. Why this does not occur on Black Bear Creek may be directly related to the alluvial setting of Black Bear Creek and the size of its floodplain. During floods, large flows go overbank onto the broad floodplain. Because of floodplain storage, large increases in flood discharge produce only small increases in stage for overbank flow. During rare flood events as are documented in the Black Bear Creek basin, however, floodplain storage is diminished and large increases in stage from overbank flows are possible. The floodplain becomes the extended channel, and the flood waters would encroach upon the present-day floodplains of Crystal and Turkey Creeks. During rare floods the mouths of Crystal and Turkey Creeks would be located farther upstream dependent upon the magnitude of the flood event along Black Bear Creek. This concept may be extended to explain why slackwater deposits are missing at the mouths of the present-day tributaries, and are found three-hundred meters up-the-tributaries.

Slackwater preservation does exist at the Crystal Creek mouth, but the deposits rest stratigraphically on a paleosol which are not correlatable to the type section and are higher in the soil profile. More radiocarbon dates of the various paleosols with overlying slackwater deposits are needed to aid in the chronostratigraphic correlation of these flood units.

Slackwater Preservation

The preservation of slackwater deposits is an important factor in the reconstruction of paleoflood events within the Black Bear Creek basin. The stage of a paleoflood event is estimated from the elevation of where the slackwater unit pinches out. The accuracy of this elevation is related to an assumption that the deposits have not been emplaced by different floods, or that the top of the slackwater deposit has not been eroded by subsequent flood events.

Slackwater samples from the Turkey and Crystal Creek banks, cores, and up-slope sites were subjected to particle size distribution tests. The tests were conducted to determine if adequate preservation of slackwater deposits exist at the two tributaries which are representative of paleoflood events occurring along Black Bear Creek. Two depositional events may be indicated, if grain size trends change abruptly within a unit where a younger flood event has partially eroded the sediments from an older event.

The results of the particle size distribution tests, in Appendix C, indicated no abrupt particle size differences of the slackwater deposits preserved at the Turkey and Crystal Creek type sections, selected bank and core sites and up-slope locations. Based upon the observations of particle size, adequate preservation at these localities was assumed for paleostage determinations.

Correlation Of Slackwater Deposits

Correlation of the slackwater deposits present at the type sections of Crystal Creek and Turkey Creek was based upon physically tracing the units from the type section to as many bank and well sites as possible. Buried soil horizons were the key marker beds with a distinct paleosol being present at each of the type sections.

The assumption that different sites could preserve different flood units presented problems in correlation. Up-tributary cores exhibited wide variability only within a few meters. Detailed and more complete radiocarbon dating of the bank and core sites could make possible more definitive correlations.

Assumptions Used In Paleoflood Reconstruction

Several assumptions are necessary to use slackwater deposits as paleostage indicators in semi-arid to arid, steep bedrock channels. These assumptions, however, are not as applicable in a humid, alluvial channel setting.

Channel Stability

The first assumption is that the channel cross-sections of the mainstream and tributaries have remained relatively stable during flood events with minor scour and fill of the channel. Channel cross-sections used in the HEC-2 model were made where constrictions along the Black Bear Creek reach occurred. The majority of the constrictions had bedrock control ie., outcrops along the bank (Figure 4.4). It is assumed that the channel configuration of Black Bear Creek has remained relatively stable over the time period covered by the paleoflood reconstruction. Aerial photographs of 1963, 1978, topographic maps of 1929 and 1978, and Landsat imagery of the area show no channel avulsion features on the floodplain along the study reach.

Costa (1974) and Knox (1985), working in humid, alluvial channel settings, found that channel adjustment to changes in flood hydrology occurs rapidly. Both investigators observed that channel recovery to major widening and scouring was very rapid even with floods with a greater than 100-year return periods. This "healing" process may obscure paleo-remnants of flood scar surface features on the Black Bear Creek floodplain.

Channel Aggradation And Degradation

A second assumption is minor channel aggradation or degradation has occurred over the time period since the slackwater unit was deposited. The possibility that the

Figure 4.4. Photograph of a portion of the study reach showing channel stability. Cross-sections were measured where channel stability has been maintained by outcrops along the study reach. Photograph taken in October, 1989, along lower Black Bear Creek, T.22N., R.6E.

Black Bear Creek channel has aggraded or degraded is not as a significant assumption as it is in steep, bedrock channels where the channel represents the majority of the landscape surface impacted by outstanding flood events. Black Bear Creek is situated in a broad, gentle, sloping floodplain where large flood events spread over a large area. The floodplain, in comparison to the channel, occupies the majority of the landscape, and in the case of large floods is the most impacted geomorphic feature.

Aggradation In The Black Bear Creek Floodplain

This study has found that aggradation across the floodplain has taken place along the study reach; however, it is shown that the discharges obtained from the HEC-2 model can still be valid in such a setting.

The type sections at Turkey and Crystal Creeks were used to determine the amount of alluvium fill which had been deposited on the top of the radiocarbon dated paleosols. The paleosols represented the old landscape surfaces drowned by the paleoflood events which deposited the overlying slackwater units. A procedure was developed to simulate the preflood landscape surface both in the Crystal and Turkey Creek basins.

Figure 4.5 depicts the procedure. The paleoland surface elevation was calculated for each side of a cross-

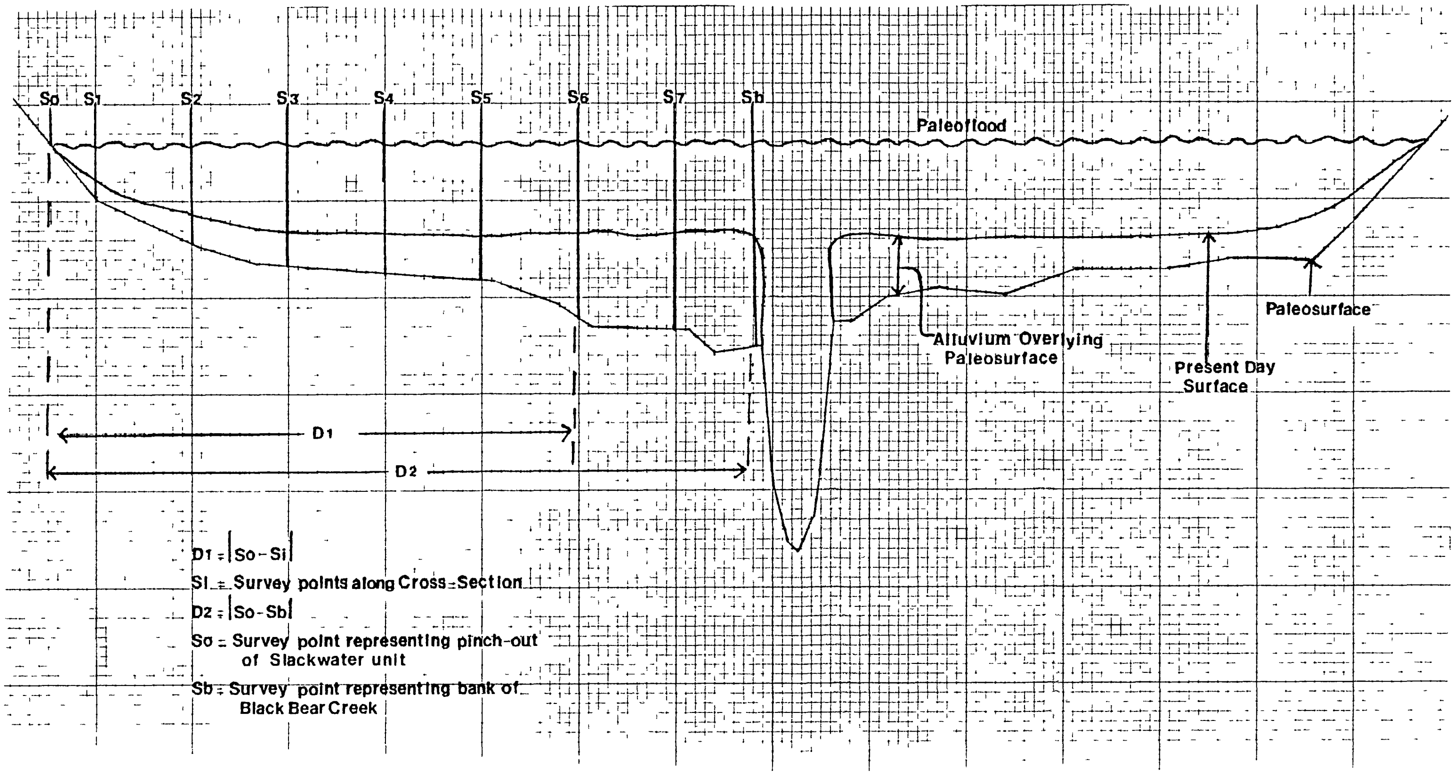

Figure 4.5. A procedure was developed to simulate the preflood landscape surface of the study reach. This figure is as an example of the procedure utilized.

section using the following equation:

$$P_2SE = P_1SE - (D_1/D_2 * OATS)$$

where:

P_1SE = Present surface elevation

P_2SE = Paleosurface elevation

D_1 = Distance from the survey station representing the point where the slackwater unit pinches-out (S_0) to each survey station (S_i). Procedure completed for both sides of bank along mainstream.

D_2 = Distance along the cross-section from S_0 to the survey station representing the bank of Black Bear Creek (S_b). Procedure completed for both sides of bank along mainstream.

OATS = Depth of overlying alluvium at type section

A proportion was determined by using the distance from the type section ie., representing the greatest accumulation, to the point where the slackwater deposit pinched out up-terrace ie., the thickness was zero. D_2 is held constant for all stations calculations for each cross-section on both sides of Black Bear Creek. The OATS variable is held constant for all cross-sections along the Turkey Creek portion of the study reach, and is held constant for those along the Crystal Creek portion. The percent adjustment of removal of the sediment was applied to each cross-section in the HEC-2 model.

This method is based upon several assumptions:

1. The current surface is representative of the paleolandscape but at a higher elevation.
2. The thickness of the alluvial fill at the type section is the maximum depth of the deposit.

3. The alluvial fill is deposited at a decreasing rate up-slope.
4. The alluvial fill is uniform throughout the study reach simulated by the HEC-2 model.

The cross-sections were adjusted to represent the paleoland surfaces according to the method described.

The Determination Of The Maximum Elevation Of Slackwater Deposits Along The Study Reach

Up-Tributary Method

The maximum height of a slackwater deposit provides an estimate of the minimum paleostage level of a flood event. This elevation is used to estimate paleodischarge. Previous investigations had been conducted in steep, bedrock channels up-tributaries which allow the slackwater unit to pinch-out over a very short distance. This study reach is characterized by a landscape of moderate to gently sloping, uplands separating broad flat bottomlands.

Physically tracing slackwater units up-tributaries was possible for many kilometers, and in some cases up to 8 km. However, the physical continuity of the slackwater deposit became questionable the farther it occurred from Black Bear Creek, and the type section. The variability of slackwater deposit preservation up-tributaries made the correlation of the units in the cores an impossible task. Extensive radiocarbon dating control is needed with such variability to be certain the slackwater unit is the same flood event and the associated paleosol is the same landscape.

A second problem encountered was tracing slackwater units large distances from the mouth of the tributaries over gentle slopes. Inability to trace units negates the objective of the entire study which is to identify large flood events of Black Bear Creek. The farther the distance up-tributary the more likely the large flood events of Black Bear Creek are masked by tributary flood events. Recognizing the impact of Black Bear Creek floods becomes difficult to interpret. Coring up-tributaries was not an adequate procedure in determining the maximum elevation of slackwater pinchout within the study reach.

Up-Slope Method

Slackwater units and associated paleosols were traced up-slope to determine the maximum elevation of the slack-water deposit pinchout and estimate the minimum paleostage. On the two study reach tributaries, preserved slackwater deposits were representative of two flood events based upon the different ages of the paleosols preserved at the type sections. The paleosol at Turkey Creek was radiocarbon dated at 3,580 +/- 80 years B.P., and the paleosol at Crystal Creek was dated at 1,150 +/- 100 years B.P. The up-slope procedure for the two tributaries will be discussed separately.

Up-Slope Procedure Along Turkey Creek.

The slackwater unit and associated paleosol present at the type section were physically traced upstream approximately 950 meters to bank sites adjacent to well site 6, Soil Conservation Service wells 301, and 302. The Soil Conservation Service had cored up-slope from bank site SCS-302, and provided this study with stratigraphic descriptions of all the cores as outlined in chapter 3. The SCS cores 302 and 11, based upon stratigraphic descriptions, were correlated with the bank exposure SCS 302, and were physically correlated with the Turkey Creek type section. The slackwater unit pinched out up-slope at an elevation of 269.8 meters. This elevation was used to estimate the paleostage of the flood waters emplacing the slackwater deposit.

Cores obtained from wells 5 and 6 do not correlate stratigraphically with the bank sites, nor does the SCS bank exposure at 301 correlate with well core SCS 301. The lack of correlation may result from the impact of agricultural practices removing the flood unit or human error in stratigraphic identification of the units. Figure 3.19 is a cross-section made by the Soil Conservation Service from core data showing a buried channel directly east of well sites 5, 6, and SCS 301.

Up-Slope Procedure Along

Crystal Creek.

At the Crystal Creek type section, a slackwater unit over a well-defined paleosol is 1.4 meters below the present-day landscape surface. Digging at 90 meter intervals, the slackwater unit and associated paleosol were traced up-slope (Figure 3.23). The slackwater unit pinched out at 250.3 meters, and was the elevation utilized in the HEC-2 program to represent the paleostage of the flood which deposited the slackwater unit.

In summary, this chapter discussed the findings of the field investigations and laboratory methods. Slackwater deposits preserved along the study reach, represent major flood events. The paleostages of two separate rare flood events along Black Bear Creek were determined, and are input data for the HEC-2 model presented in chapter 5.

CHAPTER V

ESTIMATION OF FLOOD DISCHARGES FROM THE APPLICATION OF THE HEC-2 WATER SURFACE PROFILE COMPUTER MODEL

Introduction

The HEC-2 Water Surface Profile model was employed to ascertain the discharges needed to emplace the slackwater deposits at the Turkey Creek and Crystal Creek type sections. These deposits represent two different paleoflood events in the late Holocene, and were modelled separately. The computer flow program determined the discharge that would emplace a slackwater unit on the Turkey preflood landscape surface dated at 3,590 years B.P., at the 270 meter elevation, and at the 250 meter elevation on the Crystal preflood landscape surface dated at 1,150 years B.P.

HEC-2 Model Requirements

The HEC-2 program utilizes detailed surveyed cross-sections of the channel and floodplain; distances between cross-sections; estimates of channel and floodplain roughness; and the elevation of the maximum height of a selected slackwater deposit. Locations of the cross-sections are shown in Figure 5.1, and Figure 5.2. The cross-sections are shown in Appendix D. The water surface profile is most influenced by changes in Manning roughness coefficients, starting water surface elevations, and designated discharge. In addition to initial stage and discharge conditions, flow regime must also be specified. The flow regime along the study reach was assumed to be subcritical. Numeric stability in the solution procedure requires that subcritical flows are calculated in the upstream direction. As a result, subcritical flow data were put into the model starting at the downstream end of the reach.

The Manning roughness coefficient values (estimated by the analyst) are used to compute friction losses of each cross-sectional component (left overbank areas, channel, right overbank areas). Roughness values for floodplains, typically very different from channel Manning numbers, are determined independently in this study. The surveyed cross-sections were divided into subsections at points where major roughness changes occur ie., the edge of dense woods, pasture, or channel bank, and n values were determined for each subsection. Varying climatic conditions of the late Holocene made the need for Manning roughness coefficients to change according to the vegetational type present at the time of the flood event. The method used to determine roughness coefficients for each subsection is based upon research by Acrement and Schneider (1989) who determined Manning roughness coefficient values (n) on

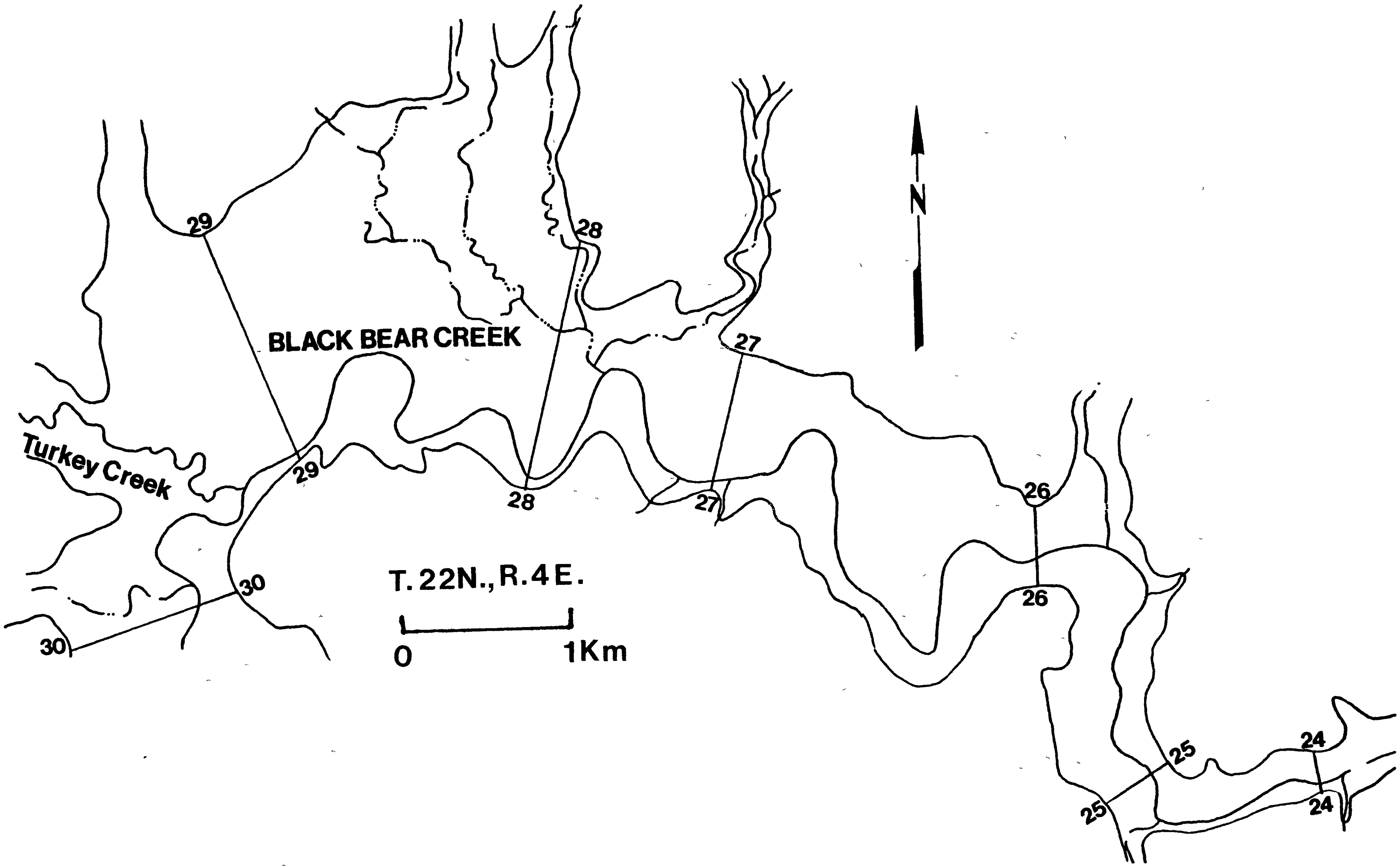

Figure 5.1. Location of cross-sections along Black Bear Creek utilized in the HEC-2 program for Turkey Creek.

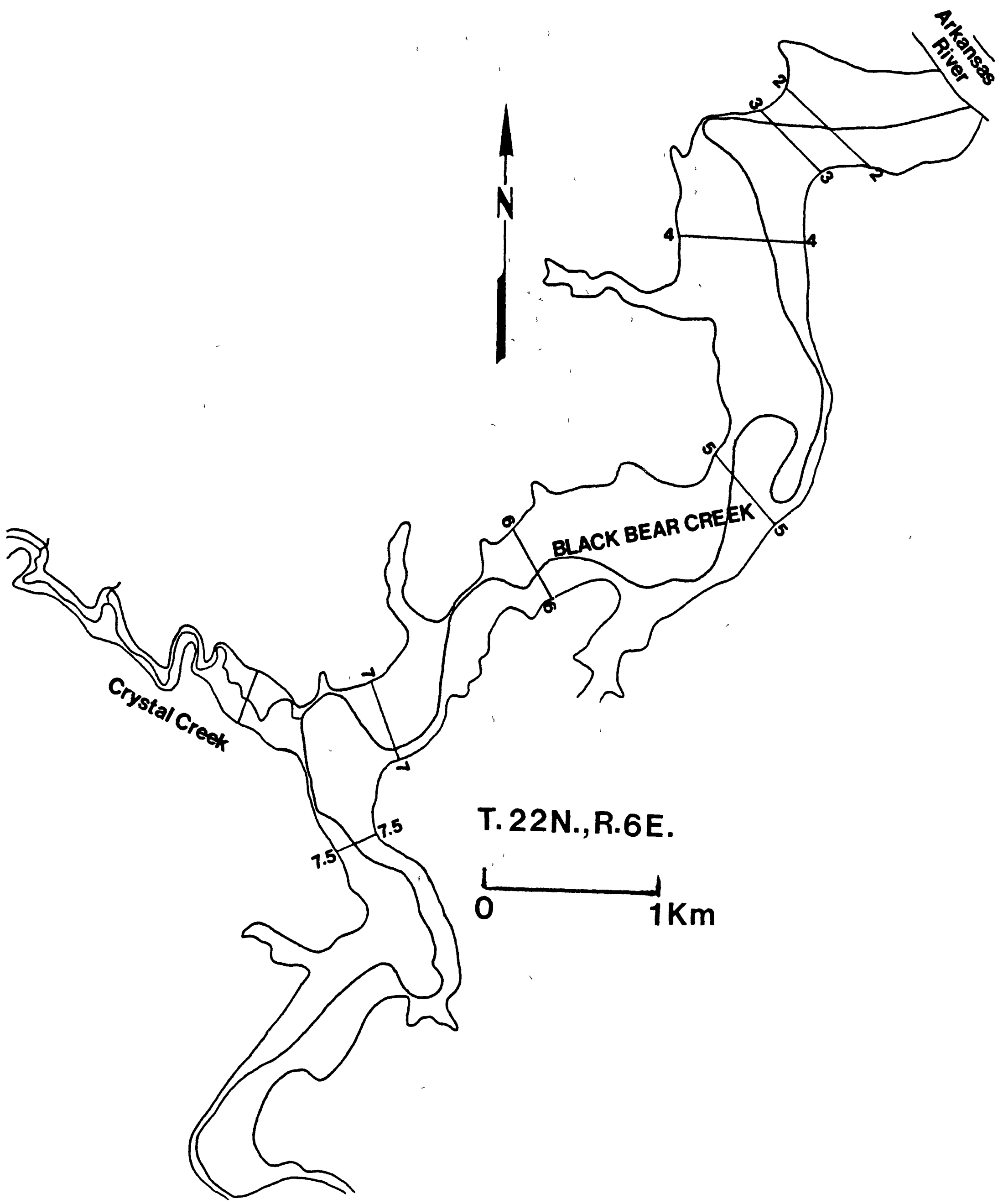

Figure 5.2. Location of cross-sections utilized in the HEC-2 program for Crystal Creek.

factors that would affect the roughness of channels and floodplains.

The channel n values were computed by:

$$n = (nb+n1+n2+n3+n4)m$$

where:

nb = a base value of n for a straight, uniform, smooth channel in natural materials.
n1 = a correction factor for the effect of surface irregularities.
n2 = a value for variations in shape and size of the channel cross-section.
n3 = a value for obstructions
n4 = a value for vegetation and flow conditions
m = a correction factor for meandering of the channel.

Floodplain n values were calculated by the equation:

$$n = (nb+n1+n2+n3+n4)m$$

where:

nb = a base value of n for the floodplain's natural bare soil.
n1 = a correction factor for the effect of surface irregularities on the floodplain.
n2 = a value for variations in shape and size of the floodplain cross-section, assumed to equal 0.0.
n3 = a value for obstructions on the floodplain.
n4 = a value for vegetation on the floodplain.
m = a correction factor for sinuosity of the floodplain, equal to 1.0.

Roughness values used in this study for present day are shown in Table 5.1. Increasing and decreasing the Manning numbers had a significant impact on the water surface profiles as the discharge increased. Water surface profiles were generated which represented the two paleofloods that emplaced the slackwater deposits at Turkey and Crystal Creeks. Simulations were also generated on the present land surface. Paleodischarges were utilized to

TABLE 5.1

MANNING ROUGHNESS COEFFICIENTS DETERMINED
FOR PRESENT DAY SURFACE

Channel

nb = .025	nb = .032	
n1 = .001	n1 = .005	Manning n values = .03 - .08
n2 = .001	n2 = .005	
n3 = .005	n3 = .015	
n4 = .002	n4 = .010	
m = 1.0	m = 1.15	

Floodplain

nb = .20	nb = .20	
n1 = .001	n1 = .005	
n2 = 0	n2 = 0	Manning n values = .22 - .23
n3 = .005	n3 = .0019	
n4 = .011	n4 = .025	
m = 1.0	m = 1.0	

determine the areal extent which would be impacted by such a rare flood event happening today.

HEC-2 Model Of Crystal Creek

Paleosol Radiocarbon Date = 1150 +/- 100 years B.P.
Slackwater Thickness = 1 meter
Depth of Paleosol below present-day surface = 1.4 meters
Maximum Elevation of Slackwater Unit = 250.3 meters
Cross-sections = 2, 3, 4, 5, 6, 7, 8

The HEC-2 model determined the effects of varying the Manning n values, starting water surface elevations, and discharges which could emplace the slackwater unit at an elevation of 250.3 meters at cross-section 7. Cross-section 7 represents the first downstream constriction of the floodplain below the confluence of Crystal Creek with Black Bear Creek. The constriction allows water from Black Bear to backflood into the Crystal Creek tributary. Simulations were generated to represent the prepaleoflood land surface and the present-day surface.

Water Surface Profile Determination Of The Paleolandscape For Crystal Creek

The HEC-2 model determined the effects of varying Manning n input values for the floodplain (left and right overbank) which would vary with the vegetational cover, ie., a response to climatic changes. Pollen and molluscan studies in north-central Oklahoma by Henry (1978) and Hall (1977; 1982; and 1990), indicate that between 2,000 to 1,000 years B.P., the climate was wetter than present-day conditions. The floodplain of Black Bear Creek would be covered with a hickory/oak forest (riparian to uplands) because of increased precipitation (D. Henry, 1991, personal communication).

Around 1,000 years B.P., the climate was drier, and semi-arid conditions prevailed. Floodplain vegetation was mainly grasses and shrubs. The Manning n number was selected to be .16, for the left and right overbank in this simulation, and the channel roughness coefficient at 0.05. The starting water surface elevation of 239.3 meters at cross-section 2, was chosen because it represents the 500-year flood event for the Arkansas River. A discharge of 11,048 cms was required to emplace the slackwater deposit at an elevation of 250.3 meters at cross-section 7 as determined by the HEC-2 model (Table 5.2).

The paleoenvironmental conditions existing at this time are not totally verifiable, however, pollen analyses do provide strong evidence of vegetation types. Various tests were generated using different Manning roughness coefficients to simulate various vegetation types on the floodplain (left and right overbank areas). Table 5.3 shows the discharges that would be obtained if the floodplain had vegetation similar to that of today, and a Manning number of .22 n.

Wetter conditions than today, represented by large tree stands and shrubs in a riparian-upland setting, were represented by a roughness coefficient of .28 n. The dis-

TABLE 5.2

HEC-2 PROGRAM DISCHARGE CALCULATION NEEDED TO EMPLACE SLACKWATER UNIT AT CROSS-SECTION 7 ON PALEOLANDSCAPE AT CRYSTAL CREEK

Cross-section	Lowest Elevation In Channel (meters)	Discharge cms	Calculated Water Surface Elevation at Cross-section (meters)
2	226.5	11,048	240.1
3	228.0	11,048	242.6
4	227.7	11,048	245.6
5	228.7	11,048	247.4
6	229.3	11,048	248.9
7	230.2	11,048	250.3
7.5	230.5	11,048	251.1

TABLE 5.3

DISCHARGES CALCULATED BY HEC-2 COMPUTER MODEL TO REACH HEIGHT OF SLACKWATER PINCHOUT WITH VARIOUS MANNING ROUGHNESS COEFFICIENTS ON THE PALEOLANDSCAPE SURFACE

	Crystal Creek	
Manning "n" Number	Cross-section 7 Elevation (m)	Discharge (cms)
.16	250.3	11,048
.22	250.3	8,782
.28	250.3	7,224

charges required to obtain a slackwater emplacement elevation of 250.3 meters with the various Manning numbers are 8,782 cms and 7,226 cms, respectively.

Water Surface Profile Determination Of The Present Landscape At Crystal Creek

The elevations obtained from the cross-sections along Black Bear Creek represented the present landscape surface, and were entered into the HEC-2 model. Manning n roughness coefficients, representing present-day vegetation at .22 n, were also utilized. In the first simulation, values used were a starting water surface elevation at cross-section 2 of 239.3 meters, right and left overbank areas at .22 n, the channel at .05 n, and a discharge of 11,048 cms. A discharge of 11,048 cms was used to determine what the water surface elevation would be on the present land surface at cross-section 7. The water surface profile reached 253 meters. This showed that a flood event with a discharge of 11,048 cms today would cover a larger areal extent than the 1,150 years B.P. event.

Varying the Manning numbers on the present-day landscape was also conducted to determine the impact that different types of vegetation would have on the areal extent of flood waters with a discharge of 11,048 cms. Tests were conducted with Manning n values of .28 and .16 for the floodplain. The elevations impacted by such variations were 254.4 meters and 251.4 meters, respectively. Figure

5.3 shows the water surface profile on the present-day landscape with various Manning values at a discharge of 11,048 cms.

Results:

A discharge of 11,048 cms was required to emplace the slackwater deposit at an elevation of 250.3 meters by Black Bear Creek in approximately 1,150 years B.P. A flood of this magnitude occurring today would impact a larger surface area because of aggradation in the floodplain. The flood event determined in this section will be used to statistically extend the flood frequency of Black Bear Creek in chapter 6.

HEC-2 Model Of Turkey Creek

Paleosol Radiocarbon Date = 3590 +/- 80 years B.P.
Slackwater Thickness = 2 meters
Depth of Paleosol below present-day surface = 3.9 meters
Maximum Elevation of Slackwater Deposit = 269.8 meters
Cross-Sections = 24, 25, 26, 27, 28, 29, 30

Water Surface Simulations On The Turkey Creek Paleolandscape

Cross-section elevations had been adjusted to remove alluvium fill from the Black Bear Creek basin to represent the preflood surface upon which the slackwater unit at the type section was emplaced.

Paleoenvironmental studies of this area indicate a drier climate than today (Henry 1978; and Hall, 1977; 1982;

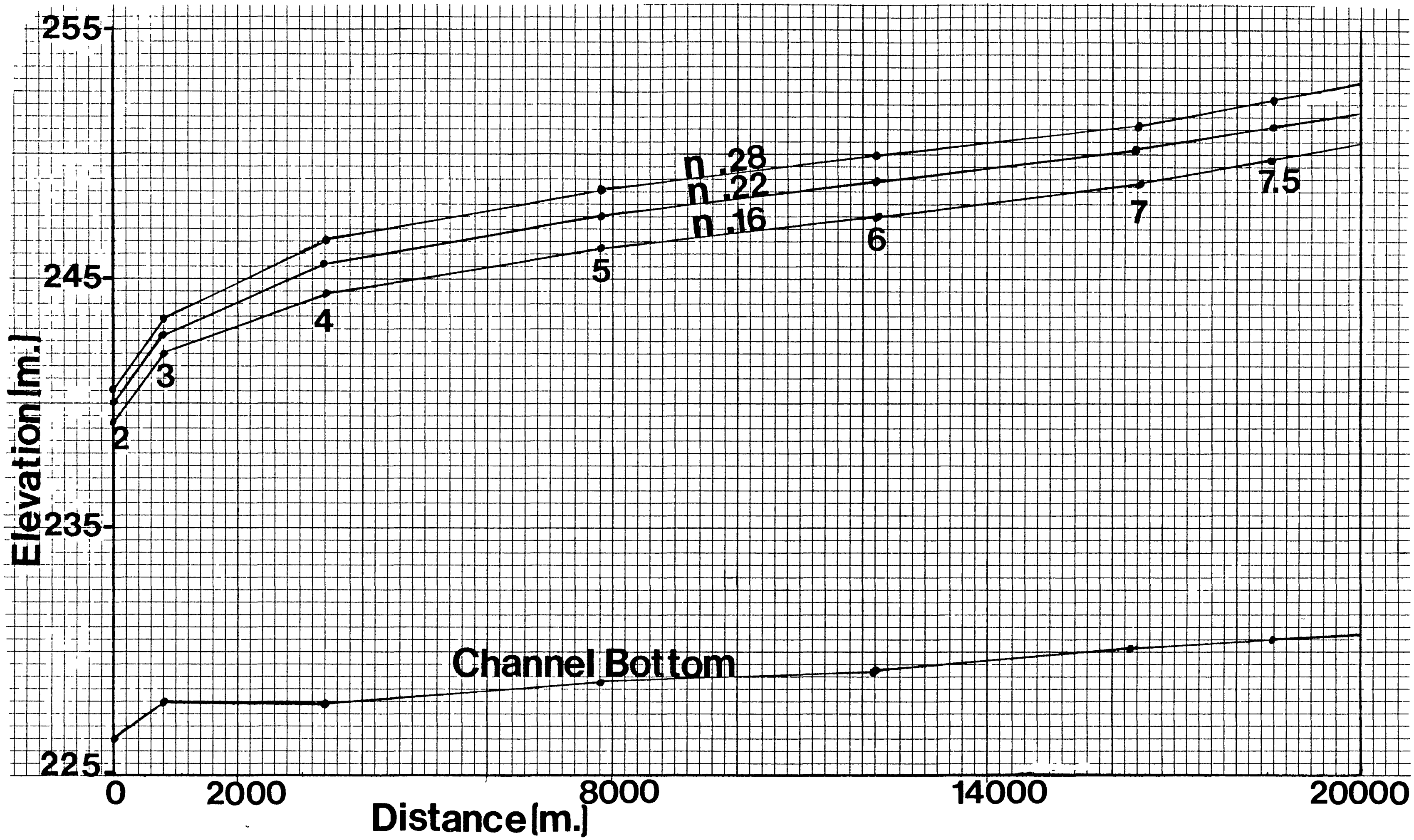

Figure 5.3. HEC-2 water surface profiles on present-day Crystal Creek landscape with varying Manning roughness coefficients at a discharge of 11,048 cms.

1990). The vegetation living on the floodplain and uplands under these paleoenvironmental conditions were primarily tall-grasses and shrubs (.16 n). A test used values of a channel roughness of .05 n, and floodplain areas at .16 n. Various water surface profiles were calculated for the reach until a discharge was obtained that produced an energy-balanced water surface profile that approximated the profile defined by the slackwater deposit at cross-section 29. This resulted in a starting water surface elevation of 265.2 meters at cross-section 24 after many iterations.

The first downstream constriction of the floodplain below the Turkey Creek confluence with Black Bear Creek, cross-section 29, allows backflooding of Turkey Creek by Black Bear Creek during large floods. The up-terrace procedure determined that the slackwater deposit pinched out at an elevation of 269.8 meters. A discharge of 5,807 cms was needed in this test to reach a water surface elevation of 269.8 meters at cross-section 29 (Table 5.4).

Various Manning n values for the paleolandscape were used to determine the effect of different types of vegetation on the floodplain (Table 5.3). Present-day vegetation patterns (.22 n) and wetter conditions (.28 n) were determined to have discharges of 4,391 cms and 3,399 cms, respectively to emplace the slackwater deposit at an elevation of 269.8 meters on the paleolandscape surface (Table 5.5).

TABLE 5.4

HEC-2 PROGRAM DISCHARGE CALCULATION NEEDED TO EMPLACE SLACKWATER UNIT AT CROSS-SECTION 29 ON PALEOLANDSCAPE AT TURKEY CREEK

Cross-section	Lowest Elevation In Channel (meters)	Discharge cms	Calculated Water Surface Elevation at Cross-section (meters)
24	249.1	5,807	265.2
25	249.4	5,807	266.2
26	250.3	5,807	267.1
27	252.4	5,807	268.1
28	253.7	5,807	268.6
29	253.4	5,807	269.8
30	254.6	5,807	270.6

TABLE 5.5

DISCHARGES CALCULATED BY HEC-2 COMPUTER MODEL TO REACH HEIGHT OF SLACKWATER PINCHOUT WITH VARIOUS MANNING ROUGHNESS COEFFICIENTS ON THE PALEOLANDSCAPE SURFACE

Turkey Creek		
Manning "n" Number	Cross-section 29 Elevation (m)	Discharge (cms)
.16	269.8	5,807
.22	269.8	4,391
.28	269.8	3,399

Impact Of Paleoflood Event On Present-day Turkey Creek Landscape

Cross-section elevations, determined in surveying the present surface, were used to generate the HEC-2 water surface profiles. The impact of a large flood with a discharge of 5,807 cms and with the present vegetation on the floodplain was determined. The roughness coefficient of .22 n was utilized for the floodplain, .05 n for the channel, starting water surface elevation of 265.2 meters at cross-section 24. The elevation reached by the flood waters at cross-section 29 would be 273.8 meters (Figure 5.4).

Manning n numbers were generated for the present-day surface to represent different vegetation on the floodplain which could develop as a result of climatic change. A Manning roughness coefficient of .28 n represented wetter conditions than today, and generated a water surface elevation of over 275 meters. Drier conditions than today were represented by .16 n, and the water surface elevation of 272 meters (Figure 5.4).

Results:

A discharge of 5,807 cms was needed to emplace the slackwater deposit at an elevation 269.8 meters on the paleolandscape surface in approximately 3,590 years B.P. The same discharge, 5,807 cms, would reach 272 meters on the present-day land surface. The paleoflood discharge estimated by the HEC-2 model will be used to statistically

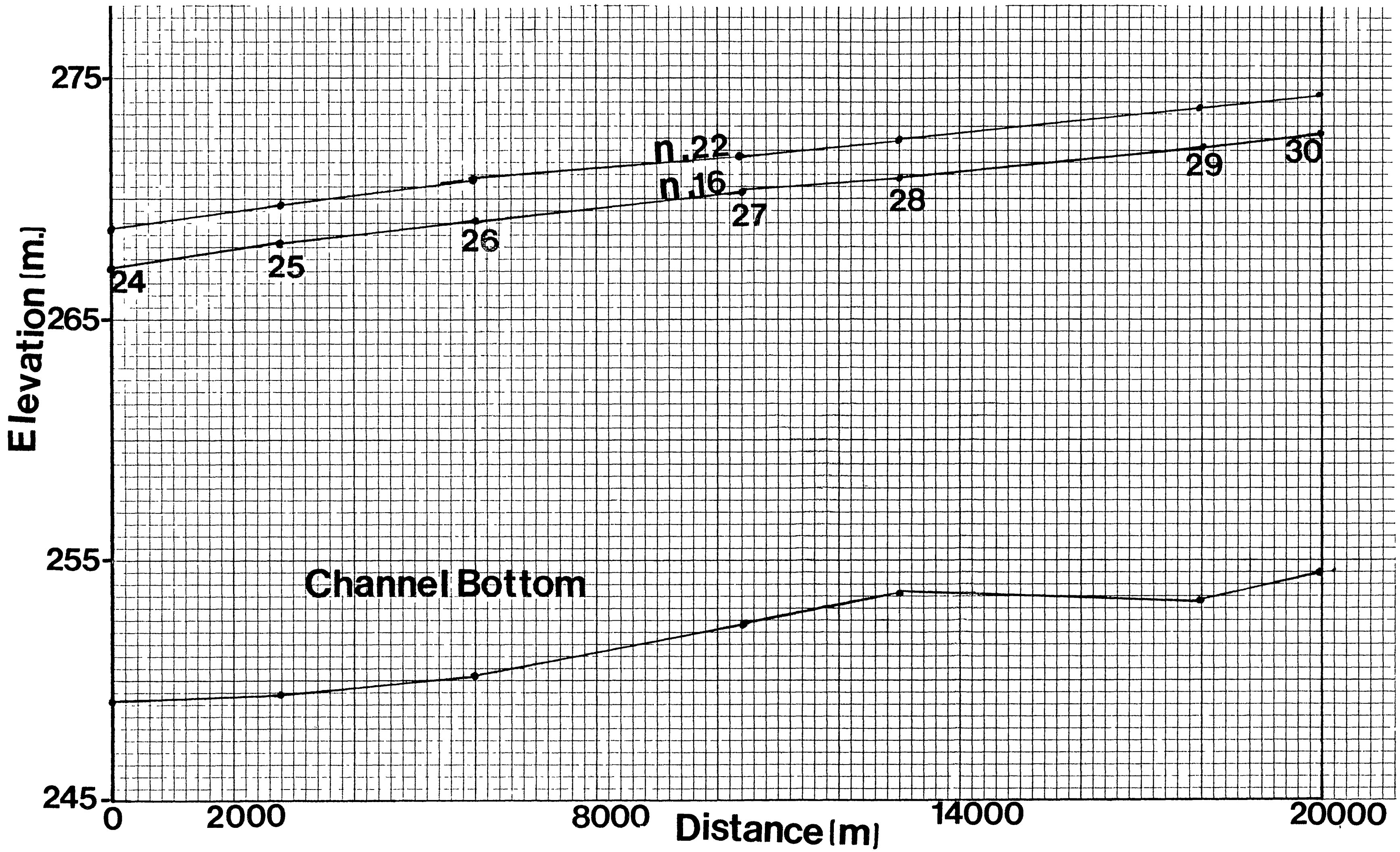

Figure 5.4. HEC-2 water surface profiles on present-day Turkey Creek landscape with varying Manning roughness coefficients at a discharge of 5,807 cms.

extend the flood record for lower Black Bear Creek in chapter 6.

Precipitation Requirements For Paleoflood Discharges

Paleostage indicators along Black Bear Creek were used to determine paleodischarges by the HEC-2 model, and the discharges obtained were 5,807 cms and 11,048 cms. Can flood events of these magnitudes be generated by storm events within a 24-hour period? The amount of rainfall (depth) that can be expected to occur in a given period of time (duration) on the average once every so many years (frequency) is known as depth-duration-frequency relationships (Hahn, 1977). These relationships have been developed for the United States (Hershfield, 1961) for durations of 30 minutes to 24 hours and return periods of 1 to 100 years, and are published in Technical Paper 40 by the U.S. Weather Bureau.

To determine if precipitation rates could be possible to produce these floods, a graph was constructed for probable maximum discharge versus probable precipitation within a 24-hour period (Figure 5.5).

The 45-year systematic flood record for Black Bear Creek was fit to a log Pearson Type III distribution, and return intervals were determined for the maximum annual flow events. The return intervals for the 24-hour precipitation events were taken from charts made by the U.S. Wea-

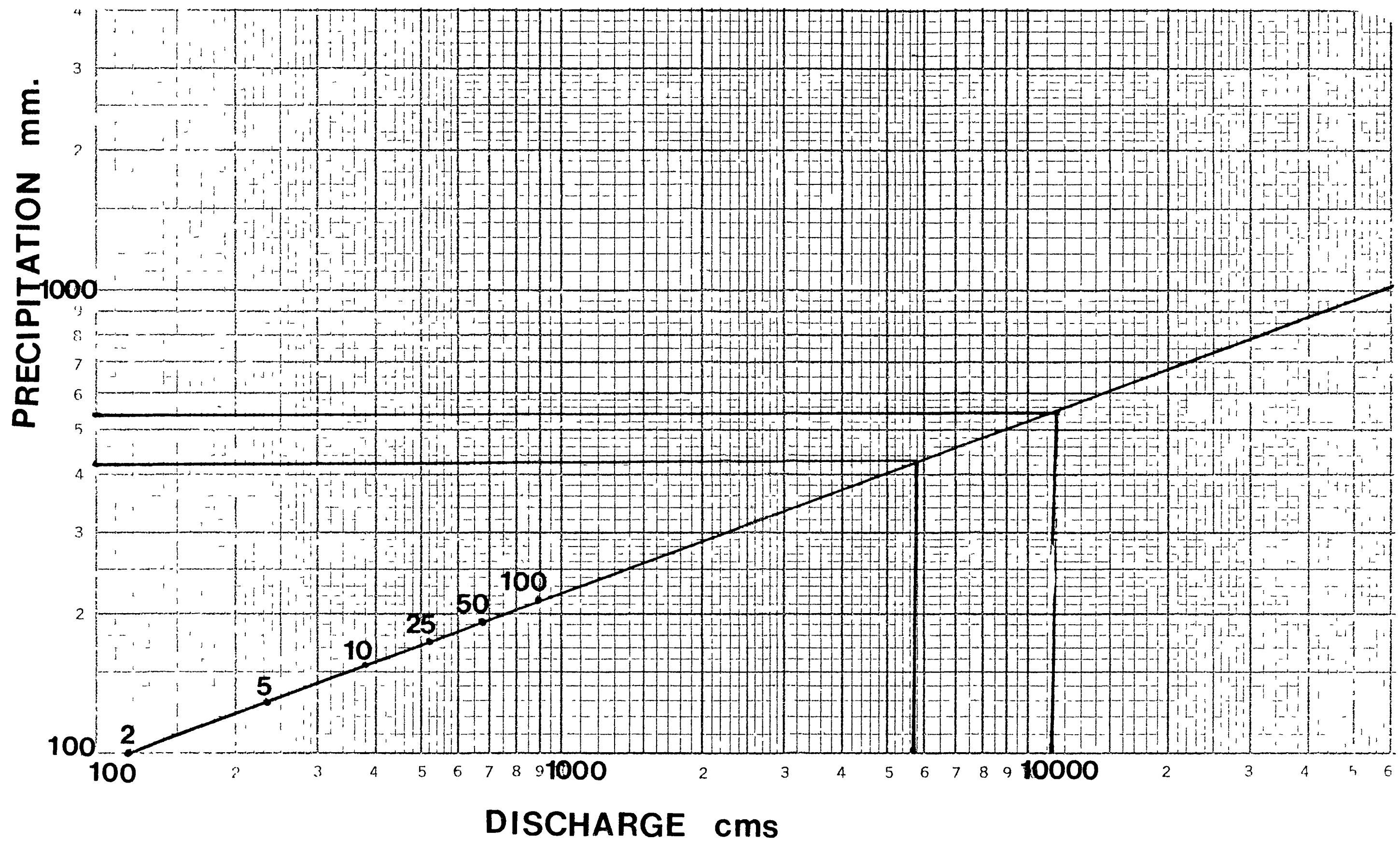

Figure 5.5. Graph of probable maximum discharge versus maximum 24-hour precipitation. Precipitation amounts needed to produce paleodischarges were extrapolated from graph.

ther Bureau (1961). It was graphically determined that a precipitation event of 420 mm in a 24-hour period could produce a flow of 5,807 cms, and 540 mm within a 24-hour period could generate a flow of 11,048 meters. These precipitation events are possible with present climatic conditions.

In summary, the various Manning n values for the roughness of the floodplain area have a direct response on the water surface elevation reached during a large flood event. The type of vegetation, ie. roughness, is directly related to the climatic conditions which will be discussed in chapter 7.

From the discharges estimated to emplace the slackwater units at Turkey and Crystal Creeks, it was ascertained that the precipitation needed to produce such discharge within a 24-hour period are possible today. The paleodischarges determined by the HEC-2 model will be used in the statistical extension of the flood frequency record of lower Black Bear Creek in chapter 6.

CHAPTER VI

THE STATISTICAL EXTENSION OF THE FLOOD FREQUENCY RECORD FOR LOWER BLACK BEAR CREEK

Introduction

In this section, systematic and paleohydrologic records are examined, and the value of these types of records in the estimation of rare flood frequencies is demonstrated. The statistical methodology used in the extension of the flood frequency analysis of lower Black Bear Creek was prepared by Ellen Stevens, Department of Agriculture Engineering, Oklahoma State University. Her computations are included in Appendix E.

Distributions Used For Gaged Discharge Records

The flood frequency for a gauged stream can be defined by fitting an array of annual peak discharges to a theoretical distribution. The U. S. Water Resources Council (1976) suggested a uniform technique for determining flood flow frequencies by fitting the logarithms of the annual peak discharges to a log Pearson Type III distribution by use of the (logrithmic) sample mean, standard deviation, and a skew coefficient. Procedures are given for calculating generalized skew coefficients, weighted averages of the logarithmic sample skew, in the Water Resources Council Bulletin 17B (1982).

The Lognormal and log Pearson Type III distributions have been used extensively for gaged discharge records in the determination of return periods for flood events. These techniques for estimating flood exceedence probabilities assume that the underlying probability distribution for a random variable, such as flood recurrence, remains constant through time. Accurate assignment of return periods beyond the period covered by the systematic record requires that the distribution truly represents the population. The flow record (sample) from which the distribution parameters were estimated must be a representative sample (Stevens, 1991). The systematic record refers to data which have been collected in a consistent or systematic manner such as gaged data. Data of this type would be continuous over periods of time and reflect both large and small annual floods. Paleohydrologic records, data which include only extreme events, are not continuous (Lane, 1986).

The Statistical Distribution Of The Systematic Record

The first method to analyze the systematic record with standard procedures was outlined in Bulletin 17B (1982). Forty-five years of flow records were fit to a Lognormal distribution and a log Pearson Type III distribution. Figures 6.1 and 6.2 show that the systematic record follows closely a normal distribution when fit to these distributions. This approach shows the frequency analysis obtained when assuming only the systematic record is available for the lower Black Bear Creek drainage basin. The systematic data fit the distributions well; however, when historic data are incorporated, the limitations of the methodology of Bulletin 17B (1982) become apparent.

Extrapolation Of The Systematic Record To Predict Extreme Flood Events

Problems are encountered when extreme events in the tail of the distribution are under consideration. A small difference between the derived cumulative distribution frequency and the true population cumulative distribution frequency can make a significance difference in the calculated return flow. Figure 6.3 is an example of when the return periods for an identical discharge may differ by an order of magnitude when both the cumulative distribution frequencies appear to fit the data (Stevens, 1991). A short systematic record to predict the return interval of rare flow events, located in the tails of the distribution, will not yield reliable results as is demonstrated in Figure 6.3. Extrapolation of the systematic record to predict the return intervals for the two paleoflood events proved

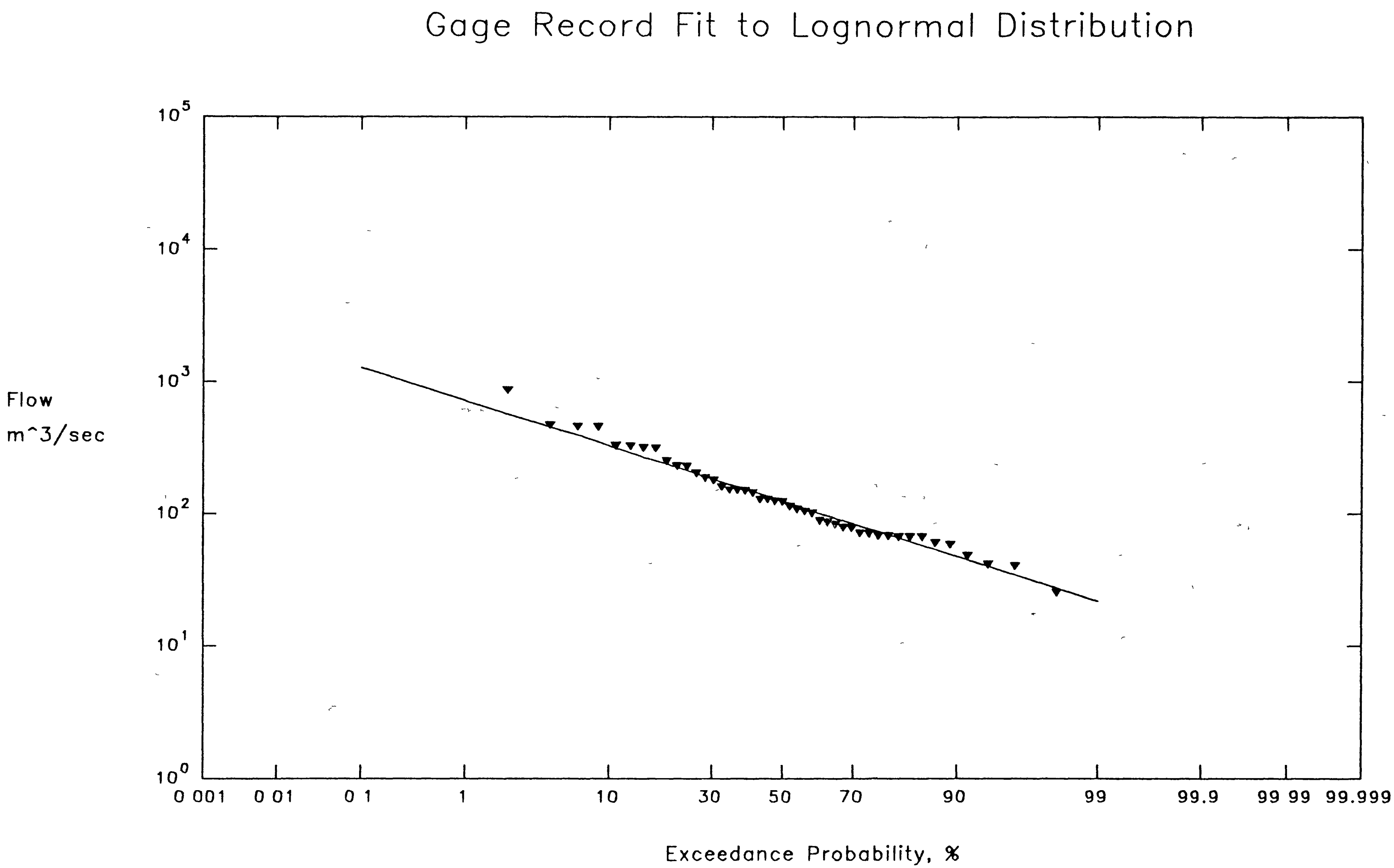

Figure 6.1. The systematic record of Black Bear Creek fit to a Lognormal distribution. From Stevens (1991).

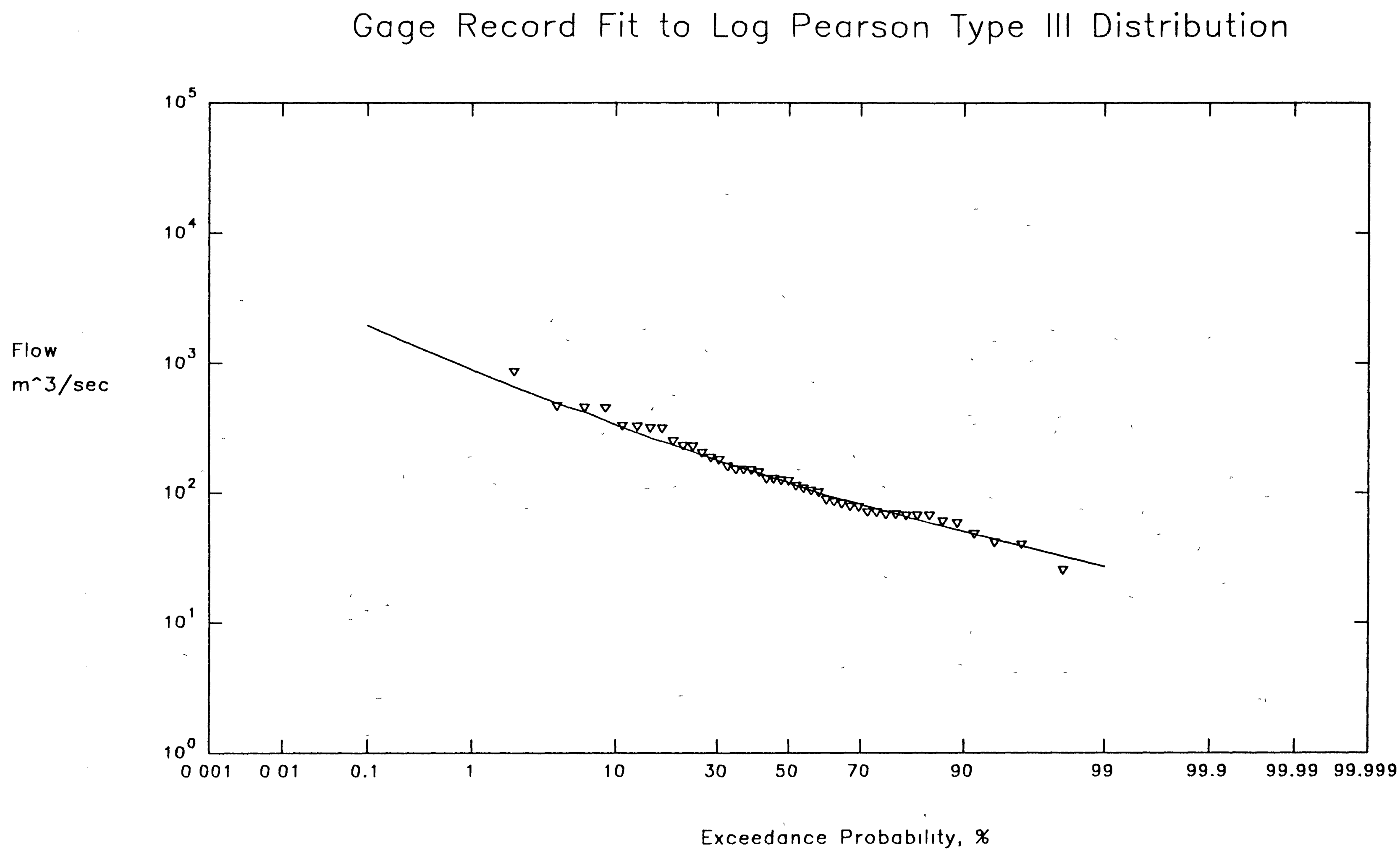

Figure 6.2. A log Pearson Type III distribution of the forty-five years of systematic record for Black Bear Creek. From Stevens (1991).

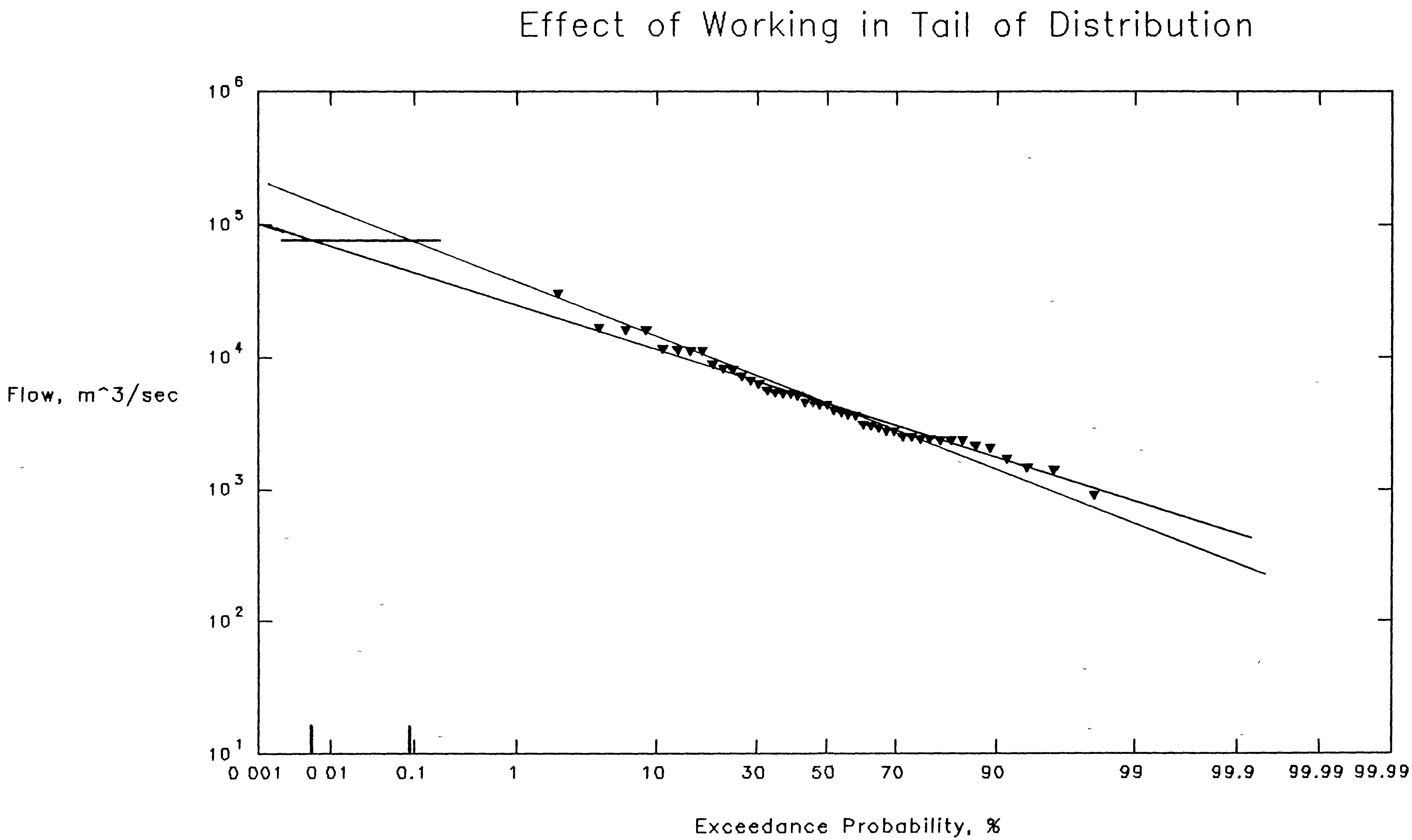

Figure 6.3. The short systematic record of Black Bear Creek makes the prediction of the return interval of rare flow events unreliable. From Stevens (1991).

unreliable. The return period of the 11,048 cms flow was determined to be a once in 18 million year-event, and the 5,805 cms flow was a 400 thousand year-event.

The Incorporation Of The Paleohydrologic Data According To Bulletin 17B

The treatment of the two paleoflood events determined from slackwater deposits from lower Black Bear Creek, and the systematic record were interpreted and modified according to the guidelines of Bulletin 17B (1982) before being used in parameter estimation for the log-Pearson Type III distribution. Lane (1986) found that the use of historic data outlined in Bulletin 17B will always increase the mean, standard deviation, and skew of the log flows. However, Bulletin 17B claims that incorporation of the historic data will improve frequency estimates. But the incorporation of the paleohydrologic flows of 11,048 cms and 5,807 cms with the systematic record did not improve the frequency record. Table 6.1 shows that the return period of the 11,048 cms flow is 500,000 years and the 5,807 cms event is 45,456 years. Figure 6.4 shows the distribution that would result from the Bulletin 17B method. This method provides too little weight to paleoflood data, produces biased results, and skews the distribution towards higher flows (Lane, 1986).

Possible sources of errors from the addition of paleohydrologic data with the Bulletin 17B technique follows.

The assumption is that the systematic records are representative of the entire historic period less the historic data years (Lane, 1986). The two paleoflood events represent the largest floods out of an historic period of 3,590 years. According, to the procedure of Bulletin 17B, the forty-five years of systematic records define a distribution in which 3,588 years out of the 3,590-year historic period are assumed to follow. Bulletin 17B treats the systematic records as representative of the 3,588 years, and in effect fits a distribution to the systematic records which is used to provide 3,588 data points. By weighting the systematic record, the result is that the flow estimates for the rare floods are artificially enlarged.

TABLE 6.1

THE RETURN INTERVALS PREDICTED FOR THE TWO PALEOFLOODS OF LOWER BLACK BEAR CREEK FROM VARIOUS METHODS

Method	Q = 11,044 m^3/sec	Q = 5,805 m^3/sec
Extrapolation	18,180,919	402,064
Censored Sample	37,549	3,991
Adjusted Moments		
Log Pearson	500,000	45,456
Plotting Positions	3,601	1,801
Plotting Positions		
MLE Eq, N=3600	5,405	2,703
MLE Eq, N=5400	8,130	4,048
Weibull Type, N=3600	3,597	1,801
Weibull Type, N=5400	5,405	2,703

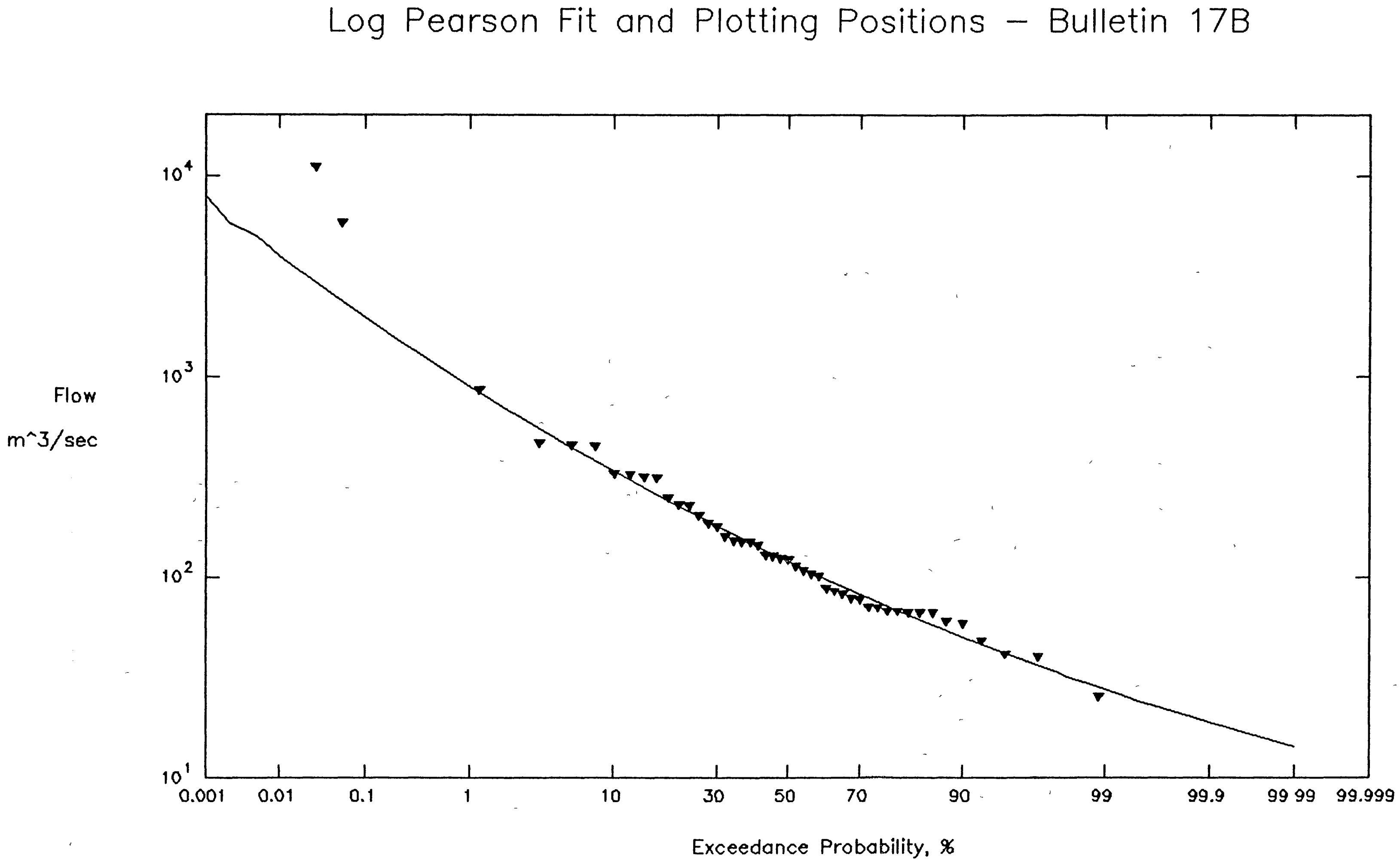

Figure 6.4. The Log-Pearson Type III distribution obtained by following the procedure outlined in Bulletin 17B to handle the incorporation of Paleofloods with the systematic record. From Stevens (1991).

Previous investigators have shown that flood frequency analysis can be improved with the use of historical floods in conjunction with the systematic record. The addition of the historical record allows the reduction of sampling variances of statistical parameters, shortens the range of extrapolation of a frequency curve, and obtains a more accurate frequency curve. If statistical flood frequency analysis is directly applied to a non-continuous sample consisting of both historical floods and the records of observed floods, however, the results of the estimation will be biased as was shown by the implementation of the procedure outlined in Bulletin 17B.

Application Of New Statistical Methods To Improve The Incorporation Of Historical Flood Data

New statistical treatments which make more realistic use of paleoflood data in flood frequency analysis have recently been incorporated with the systematic record. The use of maximum likelihood estimators, new plotting position formulas adapted to include historical information, and the use of the censored sample principle allow for more reliable results in flood frequency statistical extensions.

The use of censored samples in flood frequency analysis with the incorporation of paleoflood events can yield more reliable results as noted by Condie and Lee (1982). The utilization of any historic information effectively increases the sample size and will improve the frequency analysis. The number of fully specified floods for Black Bear Creek have increased by two. It can be assumed, therefore, that the intervening years when no record was available that the maximum annual floods were all less than the paleofloods whose values are known. The magnitude and years of occurrence of the two paleofloods were established by the HEC-2 model and by the radiocarbon dating of paleosols, respectively. The annual floods in the intervening years were always less than 5,807 cms, which is taken as the censoring threshold. A Type II censored sample is exemplified by the lower Black Bear Creek paleohydrologic data and systematic record. Figure 6.5 shows the fitted distribution of the censored sample to a three parameter Lognormal distribution.

Stevens (1991) in Appendix E, discussed the application of these methods in extending the flood frequency of lower Black Bear Creek. She found that the results obtained from fitting a three parameter Lognormal distribution to a Type II censored sample appear to give the most reasonable results with the inclusion of the two paleoflood events. Table 6.1 shows that the 11,048 cms event is determined to have a return period of 37,549 years, and the 5,807 cms event a recurrence of 3,991 years. Stevens determined that a 37,549 year flow has a 9 percent probability of occurring in a 3600 year time period, and a 3,991 year flow has a 59 percent chance of occurring. The 856 cms

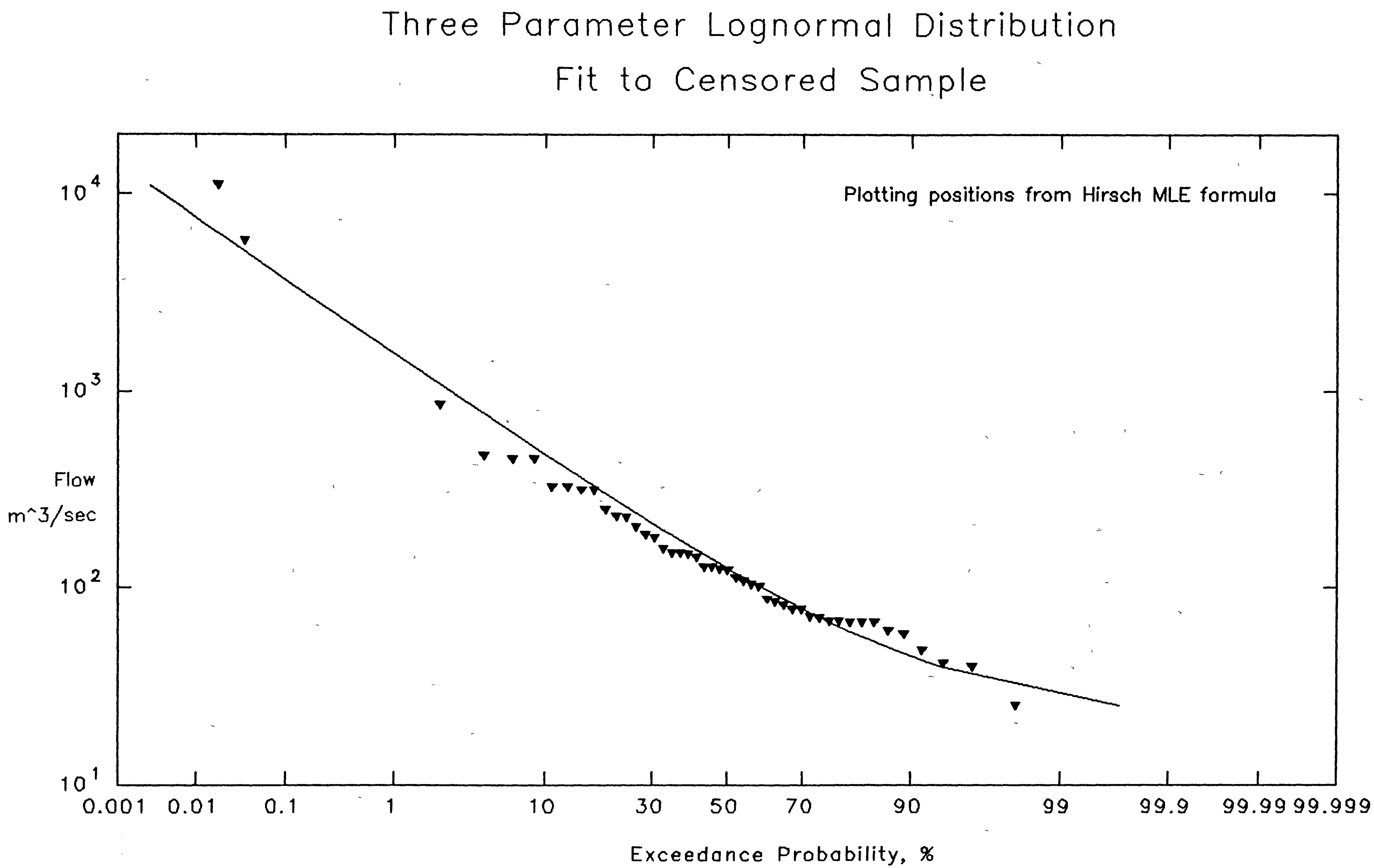

Figure 6.5. The most reliable results from the incorporation of the two paleofloods with the systematic record is the distribution obtained from a three parameter Lognormal distribution fit to a censored sample. From Stevens (1991).

event of 1959 with the incorporation of the historical data has an estimated return period of 28 years.

Plotting Positions With Historical Data

The application of new plotting positions as suggested by Hirsch (1987) were used with a modified Weibull formula and a formula based on the maximum likelihood estimator for the exceedance probability of the threshold flow (Stevens, 1991 in Appendix E). She found that the plotting position results agreed reasonably well with the censored sample results for the 5,807 cms flow, but not the 11,048 cms event. This was expected because the plotting positions only consider the rank of the flow whereas the distribution accounts for rank and magnitude.

In conclusion, the flood frequency record of lower Black Bear Creek can be extended with the incorporation of the two paleoflood events. The systematic record with the incorporation of the two paleoflood events requires application of new plotting positions, censored sample methods, and the use of maximum likelihood estimators to yield reliable results. The results obtained from fitting a three parameter Lognormal distribution to a Type II censored sample appears reasonable according to Stevens (1991).

The limitations of the treatment of historic data with the methodologies set forth in Bulletin 17B become apparent with the addition of the two paleoflood events of lower

Black Bear Creek. Bulletin 17B, which gives too little weight to paleoflood data, produces biased results and skews the distribution toward higher flow values.

Appendix E should be consulted for confidence limits, and the effects of change in threshold values and record lengths with the incorporation of the historic data with the systematic record.

CHAPTER VII

CLIMATIC IMPLICATIONS OF PALEOFLOOD EVENTS ALONG BLACK BEAR CREEK

Introduction

The deposition of slackwater sediments may be used to extend the record of large floods. Paleofloods represent only one indication of weather events in a region (large intensity storm events), and should be considered restrictive reflections of climatic conditions. Reconstruction of paleohydrologic conditions on the lower Black Bear Creek drainage basin can be used along with other climatic indicators to assess climatic shifts during the late Holocene.

Late Holocene Paleoclimate Conditions Of North-Central Oklahoma

The climatic history of north-central Oklahoma is based upon several studies conducted by Henry (1978), and Hall (1977; 1982; and 1990). These studies reconstructed the paleoclimate of the region for the Holocene based on archeologic, palynologic, and paleontologic climatic indicators. Hall (1982) proposed that the middle Holocene (7000 to 5000 years B.P.) was characterized by a drier, warmer environment than at present. He noted that the

Southern Plains were unprecedentedly wetter between 2,000 and 1,000 years B.P. His conclusion was based on higher percentages of hickory and grass pollen, and an abundance of land snails. The climate gradually changed to drier conditions about 1,000 years B.P. This change is documented by a decrease in abundance of hickory in the Cross Timbers Land Resource Area, a decrease in abundance of moist-habitat land snails, and the appearance and increased abundance of dry-habitat land snails in rock-shelter deposits (Hall, 1982). The drying trend ended about 600 to 400 years B.P. because precipitation increased to present average values (Figure 7.1).

A radiocarbon dated pollen record is sparse for the study region during the early late Holocene (5,000 to 3,000 years B.P.). Pollen studies, conducted at the Ferndale bog located in southeastern Oklahoma, indicate the existence of a mid-Holocene grassland or oak-savanna with an increase in oak and hickory, and a decrease in grasses from 3,700 to 1,900 years B.P. (Albert, 1981).

Direct And Indirect Climate Influences

Knox (1985) noted that climate influences magnitudes and frequencies of floods directly through temperature and precipitation, and indirectly through the effects on vegetation. During humid phases, the increased vegetative cover causes a reduction in sediment yield. Flood peaks are attenuated because of the lag effects related to increased

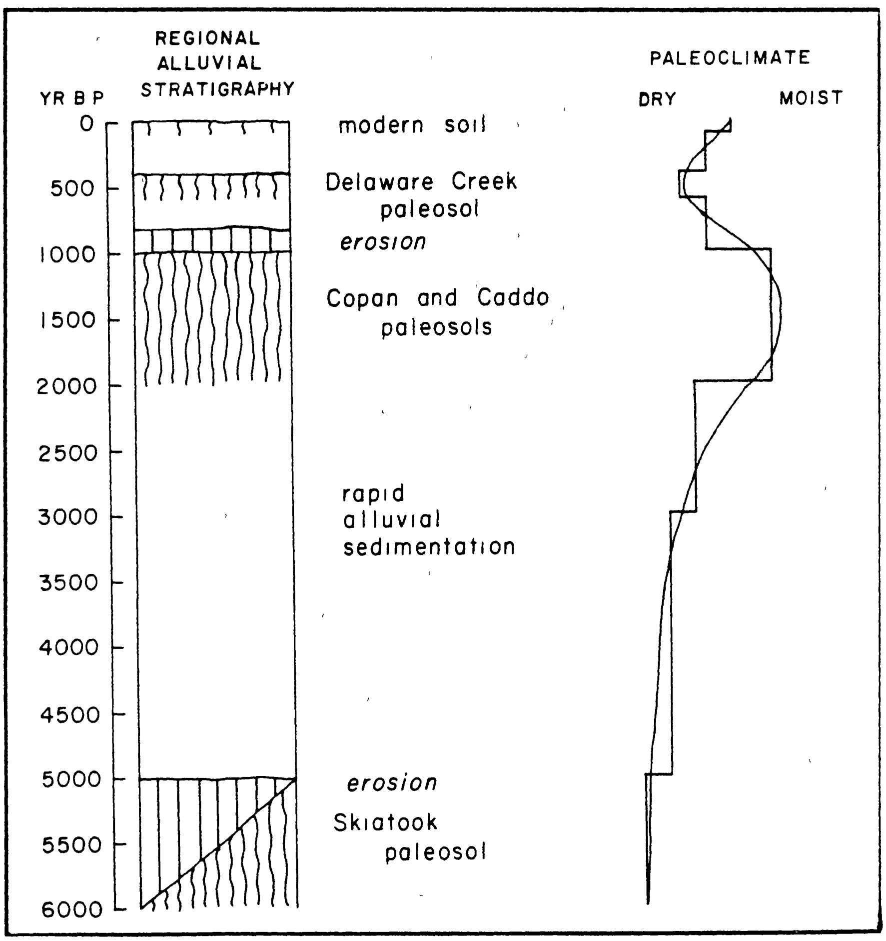

Figure 7.1. Reconstruction and correlation of alluvial stratigraphy in Oklahoma over the past 6,000 years. Paleoclimatic changes are shown as gradual and step-wise. It is not known which of these trends is more correct. From Hall (1988).

interception, surface retention, evapotranspiration, and surface roughness of vegetation on the floodplain (Patton and Dibble, 1982). During semi-arid periods, the reduction in vegetative cover, increases the hydrologic response of the basin. Sediment stored on the slopes and floodplains is readily transported during floods. The effect of slight moisture and temperature changes on stream runoff processes is amplified because of changes in the diversity and density of vegetation (Patton and Dibble, 1982).

Flood Sedimentation Sequences And General Climatic Trends Along Black Bear Creek

A general hypothesis can be proposed to explain the observed correlation between distinctive flood sedimentation sequences and general climatic trends in north-central Oklahoma. Hall (1982) suggested slight semi-arid to humid fluctuations occurred in the region as the climate gradually evolved to its present state. The buried soils of lower Black Bear Creek are indicative of floodplain stability, and relatively small flood events. This is indicated by the cumulic nature of the paleosols detected in the total organic tests in Appendix B. Cumulization is a term used to express the accumulation of mineral material onto the surface by either air or water. The rate of sediment deposition from flood events on the paleosols was much slower than the rate of pedogenesis as indicated by the cumulic nature of the paleosols.

Climatic Significance Of Turkey Creek Sediments

The paleosol present at the Turkey Creek type section, dated with Carbon-14 at 3,580 +/-80 years B.P., was recognized at all bank sites, SCS wells, and in core 7. Cores 5 and 6 did not encounter the buried soil because they were not drilled deep enough.

The percent organic matter for the paleosol was determined with the procedure described in chapter 3. Greater than 1.0 per cent organic matter in the upper 24 cm is required for a soil to be classified as a Mollisol. Because the buried soil contained greater than 1 per cent organic matter suggests that it did form beneath prairie vegetation. The buried soil is gleyed which indicates either formation under a high sustained water table or a horizon that limits water infiltration. The Turkey Creek buried soil contains a high percentage of clay which locally may have reduced infiltration of water and caused local saturation.

Recent pollen studies conducted by Hall (1988) indicate that a very dry, warm climate existed in the area during the formation of the Turkey Creek paleosol. The gleyed paleosol is locally expressed, and by the degree of gleization is contradictory to the model of a drier, warmer climate. One possible explanation is that the gleying could have resulted from a local perched water table, and not the result of a sustained high regional water table.

The regional expression of the soil is not documented, but more studies should be conducted to determine its areal extent and pollen history.

The interruption of floodplain stability is documented by the presence of the Turkey Creek paleosol being overlain by a distinct flood unit, approximately 2 meters in thickness. The discharge needed to emplace the deposit was estimated to be 5,800 cms with a return period of once in 1,800 years. It can not be determined whether the change in flood hydrology represents a change in the type and intensity of precipitation and/or the effectiveness of the vegetation to reduce flood runoff. The slackwater unit preserved at Turkey Creek could be indicative of a time of lower vegetative density, and therefore, a time of greater geomorphic effectiveness of the erosive ability of floods because of large, intense storm events.

Climatic Significance Of Crystal Creek Sediments

The paleosol preserved at Crystal Creek, dated with Carbon 14 at 1,150 +/-100 years B.P. can be correlated to a regionally expressed soil found in the region called the Copan. The Copan is characterized by the presence of a very thick, organic rich A-horizon, up to 1 meter thick, and generally buried by more than a meter of alluvium. The soil, named after the type section found in the vicinity of Copan, Oklahoma, formed about 1,800 to 1,000 years B.P.

(Hall, 1977).

The paleoenvironment of the Copan indicates formation under a high water table during a climate wetter than present. The wetter conditions allowed vegetation to attain high density on the uplands (hickory, oak, grasses) which decreased erosion. The accumulation and concentration of organics from the vegetation decaying on the floodplain promoted the formation of the very organic rich A-horizon. The samples from cores, banks, and terrace sites in the Crystal Creek floodplain showed that the organic matter was greater than 1.1 per cent in the Copan alluvial horizon.

The slackwater unit preserved above the paleosol at Crystal Creek is estimated to have been emplaced by a flood discharge of 11,048 cms with a return period of once in 3,600 years. Pollen studies indicative of the last 1,000 years show a change from the moisture climate of the Copan to drier conditions similar today. The change from wetter to drier conditions suggest a change in the density of vegetative cover. In drier conditions geomorphic effectiveness increases during rare precipitation events.

Another line of evidence, supporting a change from more moisture to drier conditions around 1,000 years B.P., is channel incision (Hall, 1990). The trenching of floodplains and erosion of the Copan soil at 1,000 years B.P. coincide with evidence for simultaneous regional climate change from wet to drier conditions. The drier conditions culminated around 600 to 400 years B.P., after which precipitation increased to present average values (Hall, 1990).

The variations in flood magnitude along Black Bear Creek are related to climatic change, because no significant evidence points to changes in tectonics, eustatic sea levels, and/or anthropogenic factors. Knox (1985) stated that the relationship between floodplain processes and flood magnitudes supports the notion that even modest changes of climate can be an important contribution to episodic mobility and storage of sediments in watersheds. Comparison of the flood history of Black Bear Creek with palynologic and paleontologic studies of this area supports climatic variations.

When alluvial stratigraphic data from other parts of Oklahoma, and adjoining states of Nebraska, Missouri, and Oklahoma are correlated with the periods of floodplain stability along lower Black Bear Creek, a strong regional synchroneity in alluvial events is indicated. Johnson and Martin (1987) from the examination of data from radiocarbon documented sites from the east-central and southern Great Plains region, have identified several periods of stream stability during the late Holocene at 4,300-4,000; 2,600-2,400; 2,100-1,600; and 1,200 years B.P. These periods represent times of floodplain stability during which soils developed, and are subsequently buried by flood events. More information from the east-central and southern Great Plains region is required before the response of stream systems to climate changes can be assessed as gradual or abrupt.

In summary, the geomorphic effectiveness of rare floods during the late Holocene may result from direct or indirect (vegetation) climate change. Much more work is needed in the study area to determine the rate of climatic shifts and the impact that these shifts have on flood events.

This chapter reviewed palynologic, archeologic, and geomorphic studies from the region, and correlated paleoenvironmental evidence with rare flood events preserved along the study reach. Chapter 8 presents the summary and conclusions of this study along lower Black Bear Creek.

CHAPTER VIII

CONCLUSIONS AND FUTURE RESEARCH

Conclusions

The purpose of this research was to investigate the utilization of slackwater deposits as paleostage indicators in the reconstruction of the paleoflood history of lower Black Bear Creek, and to identify rare flow events. Previous investigations of slackwater deposits have primarily focused on bedrock channels in semi-arid climatic settings. Assumption for these conditions were tested in the humid, alluvial setting of lower Black Bear Creek.

Slackwater Deposits Found Representative Of The Paleoflood History Of Lower Black Bear Creek

Initial field investigations of lower Black Bear Creek found slackwater deposits present at all the tributaries. Two tributaries, Turkey Creek and Crystal Creek, were selected to be most representative, because well-preserved slackwater deposits overlie recognizable paleosols. These tributaries also defined the upper and lower bounds of the study reach.

Flood deposits at these tributaries provide evidence for flood events during the last 3,600 years. Large floods occurred approximately 1,150 years B.P., and 3,590 years B.P. These events were used to reconstruct a paleoflood history for the study reach. The preserved paleoflood records at these localities are representative of the flood history for the late Holocene. The number of recorded paleofloods at any one site may be regarded as a minimum record, because the possibility exists that slackwater deposits were not preserved, or were eroded by subsequent flows.

Slackwater Deposits Used As Paleostage Indicators

Slackwater deposits, to be used as paleostage indicators, must have adequate preservation ie., no indication of abrupt particle size change can occur. Particle size distribution tests were conducted on slackwater deposits found in cores, banks, and up-slope sites. Because slackwater preservation was confirmed by tests of the particle size distribution, the maximum elevation of the pinchout of these deposits provides a reliable estimate of the minimum paleostage emplacing them.

Radiocarbon dating of the paleosols (soil organic) at the two selected tributary type sections provided minimum dates of occurrence of the paleoflood events depositing the slackwater units. The dates obtained, 1,150 +/- 100 years B.P at Crystal Creek, and 3,590 +/-80 years B.P. at Turkey

Creek, showed that the paleofloods preserved at the type sections were representative of different flood events occuring on two distinct landscape surfaces.

Paleostages of the floods were established by determining where the slackwater units pinched out up-slope. The up-tributary method used in steep, bedrock channels did not prove adequate in the humid, alluvial channel of the study reach. The maximum elevation of the slackwater units were used as a minimum indicator of the paleostages of the paleoflood events. A computer program, the HEC-2 Water Surface Profile, was implemented to determine the paleo-discharge that could emplace a slackwater unit at the surveyed elevations where the pinch-out occurred.

The HEC-2 program required detailed survey cross-sections along Black Bear Creek which characterized all constrictions, restrictions, and other changes in the channel geometry and floodplain; estimates of channel and floodplain roughness; and the elevation of the maximum height of the slackwater deposits. Manning roughness coefficients, which characterized the channel and floodplain under varying Holocene climatic conditions, were estimated.

Paleoclimatic conditions were reconstructed from palynologic, archeologic, and paleontologic studies completed by other investigators in the study area. The vegetation type that may have existed at the time of the flood events was determined, because Manning roughness values of the floodplain and channel are strongly influenced by vegetational type. The discharges that deposited the slackwater deposits along lower Black Bear Creek were ascertained by an iterative process.

A paleoflood discharge of 11,048 cms was calculated to have emplaced the slackwater deposit at an elevation of 250 meters in the lower portion of the study reach (Crystal Creek area) in approximately 1,150 years B.P. A precipitation event within a 24-hour period to produce a discharge of this size was estimated to be 98 mm. It was determined that a flood of 11,048 cms on the present-day landscape would impact a slightly larger area than the 1,150 years B.P. flood event. The estimated water surface elevation would reach 253 meters.

The same procedure was utilized to estimate the discharge of the paleoflood which occurred in the upper portion of the study area (Turkey Creek area). The flood event which deposited the slackwater deposit at an elevation of 261 meters on the Black Bear landscape in approximately 3,590 years B.P., was calculated to have a discharge of 5,807 cms. The precipitation event required to produce a flood of this magnitude was estimated to be 71 mm in a 24-hour period. A flood of this magnitude today would also impact a slightly larger area than the paleoflood event. The estimated water surface elevation would reach 274 meters on the present day landscape.

Extension Of The Flood Frequency Record

Forty-five years of discharge records for Black Bear Creek are available from the gage station located in Pawnee, Oklahoma. The systematic record was fit to a Lognormal distribution and a log Pearson Type III distribution according to the method outlined in Bulletin 17B. The systematic record fit these distributions well. The limitations of the Bulletin 17B method became apparent with the incorporation of the two paleoflood events.

A short sytematic record to predict the return interval of rare flow events, located in the tails of the distribution, will not yield reliable results. The Bulletin 17B method will always increase the mean, standard deviation, and skew of the log flows. The incorporation of the paleohydrologic flows of 11,048 cms and 5,807 cms with the systematic record were determined to have a return period of 500,000 years and 45,456 years, respectively. This method provides too little weight to paleoflood data which skews the distribution towards higher flows.

New statistical treatments which make more realistic use of paleoflood data in flood frequency analysis have recently been incorporated with the systematic record. The use of maximum likelihood estimators, new plotting position formulas, and censored samples allow for more reliable results. Stevens (1991), in Appendix E, described the application of these methods to extend the flood frequency of lower Black Bear Creek. She found that fitting a three parameter Lognormal distribution to a Type II censored sample appeared to give the most reasonable results with the inclusion of the two paleoflood events. The 11,048 cms has a return period of 37,549 years, and the 5,807 cms event a recurrence of 3,991 years. The 11,048 cms flow has a 9 percent probability of occurring in a 3,600 year time period, and the 5,807 cms event has a 59 percent chance of occurring. The largest flow of the systematic record, 856 cms, was determined to have an estimated return period of 100 years, and with the incorporation of the two paleoflood events a return period of 28 years.

Climatic Implications Of The Paleoflood Events

Climatic implications of the paleoflood events along lower Black Bear Creek were considered restrictive reflections of climatic conditions, representing one component of climate in the region: high intensity precipitation events. They were used in conjunction with other climatic indices ie., palynologic, archeologic, and paleontologic climatic documentations. A general hypothesis evolved which implied that variations in flood magnitudes were the result of gradual climatic change.

Climatic shifts throughout the Holocene in this region are gradual events as shown by paleosol development in the stable floodplain along lower Black Bear Creek. The landscape at Crystal Creek developed during wetter conditions than today and indicates landscape stability of over a thousand years. The landscape present at Turkey Creek may have formed during a time of extreme dryness, but the gleyed paleosol unit indicates wetter conditions than palynologic studies suggest. A local perched water table or gleization at a later time are two explanations for its characteristics.

Based on evidence provided in this study, the following conclusions can be made:

(1) Paleoflood records preserved along major tributaries are representative of the paleoflood history of lower Black Bear Creek.
(2) The slackwater deposits provide a minimum estimate of the paleo-stage of the flood events emplacing them.
(3) Holocene stratigraphic deposits in humid, alluvial channel settings can be used extend the historical record of flood frequencies.
(4) Paleoclimates of the area can be inferred from slackwater deposits and paleosol relationships.
(5) The impact of paleofloods on the present landscape was established.

Future Research

Future research conducted in alluvial, humid settings should not utilize the assumptions of semi-arid, steep bedrock channels, but should use the following guidelines:

(1) Maximum preservation of slackwater deposits does not always occur at the present mouths of tributaries in humid, alluvial settings. The greatest accumulation is a function of the location of the mainstream channel during a large flood event. During rare floods the mouths of the tributaries will be displaced farther upstream dependent

upon the magnitude of the flood event along the mainstream. The tributary mouths along the study reach were displaced three hundred meters upstream of the present mouths. A general hypothesis about the location of maximum slackwater preservation cannot be established for other streams because of variations in basin characteristics. Flume studies should be conducted to establish what relationships may exist.

(2) Up-slope drilling to determine the maximum height of the slackwater deposit in alluvial settings characterized by a landscape of moderate to gentle slopes is more appropriate than up-tributary methods. The farther the distance up-tributary the more likely the large flood events of the mainstream will be masked by tributary flood events. Drilling should be conducted up-slope from the type section to insure the slackwater deposit is representative of a flood event of the mainstream.

(3) Other methods to simulate preflood landscape surfaces from the cross-section station elevations should be evaluated. An accurate method would be to drill parallel to the cross-sections. The actual elevation of the paleosol could then be determined. This would increase the cost of the study, but would be the most reliable procedure. An alternative method of estimating the elevation of the paleosurface would be the use of vertical distances for determining the adjustment versus the use of horizontal distances as utilized in chapter 4. Additional research is

needed to determine which method would be more accurate.

(4) Extensive radiocarbon dating is required for the chronstratigraphic reconstruction of paleoflood events. The correlation of slackwater deposits and associated paleosols along the study reach from cores and up-slope localities to the type sections would be more definitive if radiocarbon dates obtained could establish similar ages of emplacement of slackwater deposits. Radiocarbon carbon dates are also needed in frequency analyses to provide time intervals for the computation of recurrence intervals.

(5) Calculations of paleoflood discharges are subject to numerous errors and uncertainities. Estimation of channel roughness and vegetation types for events 3,600 years in the past introduces a nonquantifiable error in the calculations. Palynologic and paleontologic studies could help to establish the vegetational type present which would improve the estimation of Manning roughness coefficients.

Summary

This study has shown that slackwater deposits, used as paleostage indicators in humid, alluvial settings, can be used in paleoflood reconstruction, and to identify large flood events. Assessing the flood frequency distribution of rare flood events in this portion of the southern Great Plains will contribute to knowledge of paleoclimate and landscape evolution. Such records may prove useful for landuse studies and planning.

This doctoral study represents an initial reconstruction of the paleoflood history of lower Black Bear Creek. Because sediments preserve information about rare flood events in the basin, a large systematic effort remains to assess paleoclimatic change and landscape evolution. Future research should be part of a larger team effort. A team comprised of hydrologists, geomorphologists, soil scientists, statisticians, and climatologists could further assess the paleoflood history of the lower Black Bear Creek drainage basin. This dissertation has created a framework from which to develop a complete history.

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APPENDIXES

APPENDIX A

SOIL DESCRIPTIONS OF CORES 1 THROUGH 7

SOIL DESCRIPTION

CORE 1

H.#	Horizon Name	Depth (cm)	Dominant Color	Tex-ture	Structure	Consis.	B.	Sp. Features
1	Ap	0 - 13	5YR 3/4	fS	SG	vfr	CS	Vf,f rts; no rx.
2	C1	13 - 18	5YR 5/6	LS	SG	fr	CS	F,f rts; no rx.
3	A1,b1	18 - 38	5YR 4/2	LS	1fG	fr	CS	C,m rts; no rx.
4	BA,b1	38 - 51	5YR 4/4	SiL	1fG	fr	CS	F,f rts; no rx.
5	BC,b1	51 - 74	5YR 5/6	LS	1fG	fr	Gs	F,f rts; no rx.
6	C1,b1	74 - 180	5YR 6/6	S	SG	vfr	CS	No rx
7	C2,b1	180 - 211	5YR 4/6	SL	SG	vfr	CS	No rx.
8	C3,b1	211 - 229	5YR 4/4	LS	SG	vfr	CS	No rx.
9	C4,b1	229 - 325	7.5YR 5/6	SL	SG	vfr	CS	No rx.
10	C5,b1	325 - 340	5YR 4/6	LS	SG	vfr	CS	No rx.
11	C6,b1	340 - 361	7.5YR 5/4	LS	1mSBK	fr	CS	No rx; x-bed. w/org. drapes (7.5YR 4/2); F, f Si partings (5YR 4/2)
12	A1,b2	361 - 419	5YR 4/4	SL	2mSBK	fr	CS	No rx.
13	C1,b2	419 - 449	7.5YR 5/4	vfSL	SG	vfr	CS	No rx.
14	A1,b3	449 - 546	10YR 3/3	SiL	2MSBK	fr	CS	No rx.; 1mm CSL partings in mid (7.5YR 5/6)
15	C1,b3	434 - 455	5YR 5/6	S	SG	vfr	CS	No rx.
16	A1,b4	455 - 546	5YR 3/1	SiL	1mSBK	fr	GS	No rx.; Si coat bet. ped surf. (10YR 6/4)
17	AB,b4	546 - 554	10YR 3/3	L	2mSBK	fr	CS	No rx.,f,vfS part.(10YR5/4)
18	AC,b4	554 - 594	5YR 4/6	L	SG	vfr	CS	No rx.
19	A1,b5	594 - 772	5YR 4/2	SiL	2mSBK	fr	GS	Mod. efferv.; Si coat. on ped surf (7.5YR 5/4)
20	AB,b4	772 - 935	5YR 4/2	SiCL	2mBK	fr	GS	No. rx; Si coat. on ped surf (7.5YR 5/4)

* See Key

SOIL DESCRIPTION

CORE 2

H.#	Horizon Name	Depth (cm)	Dominant Color	Tex-ture	Structure	Consis	B.	Sp. Features
1	Ap	0 - 10	7.5YR 4/2	vfSL	SG	fr	GS	M,c rt.,no rx.
2	Bt1	10 - 33	7.5YR 4/4	SiL	1mSBK	fr	GS	m,f rt.,no rx. S coat inside ped face (7.5 YR 5/4) F,f Mn stns (N 2/0)
3	Bt2	33 - 56	7.5YR 4/2	vfSL	2mSBK	fr	CS	No rx, M,f rts.
4	AB,b1	56 - 76	7.5YR 3/2	vfSL	2mSBK	fr	CS	No rx, M,f rts. Si coat on ped surf (7.5YR 5/4)
5	A,b1	76 - 114	7.5YR 4/2	L	2mBK	fr	GS	No rx, M,f rts, Si coat on ped surf (7.5YR 5/4)
6	A,b2	114 - 155	5YR 3/4	SiC	2mSBK	fr	CS	No rx, M,f rts, marble appear., blk lens (N 2/0)
7	A,b3	155 - 221	5YR 3/3	L	2mBK	fr	CS	No rx, M,f rts. Mn(N 2/0) Fe stn F,f
8	Bt1,b3	221 - 231	5YR 4/3	L	1mSBK	fr	CS	No rx, F,f rts, Mn(N 2/0) Fe stn M,f
9	Bt2,b3	231 - 249	5YR 4/6	SL	2mSBK	fr	CS	No rx, F,f rts, C,f Mn (N 2/0)
10	A,b4	249 - 450	7.5YR 4/4	L	2mSBK	vfr	CS	No rx, x-bedd w/org drapes
11	Bt1,b4	450 - 508	5YR 5/6	SiC	2mBK	fr	GS	No rx, F,f rts, M,f Mn (2/0) Fe stn.
12	Bt2,b4	508 - 528	5YR 5/4	SiCL	2mBK	fr	GS	No rs, M,f Mn (2/0) Fe stn, F Si part in bet ped surf
13	C1,b4	528 - 579	5YR 4/4	SL	1mBK	fr	CS	No rx, M Si part (5YR 7/6) in bet ped surf
14	A,b5	579 - 602	5YR 4/6	L	1mBK	fr	CS	No rx, F, f Mn (N 2/0) Fe stn, F Si part. on ped faces (5YR 7/6)
15	C1,b5	602 -627	7.5yr 5/6	cS	SG	vfr		No rx

* See Key

SOIL DESCRIPTION

CORE 3

H.#	Horizon Name	Depth (cm)	Dominant Color	Tex-ture	Structure	Consis	B.	Sp. Features
1	Ap	0 - 20	5YR 5/3	SL	2mBK	fr	GS	No rx, C,f rts, C,vf S coats (5YR 5/4)
2	A1	20 - 203	7.5YR 4/2	SiL	2mSBK	fr	GS	No rx, M,f rts, C, vf S coats (5YR 5/4)
3	A2	203 - 343	5YR 3/4	SL	2mSBK	fr	CS	No rx, F, f (.25 mm)Mn-Fe stn; Si coat on ped surf (5YR 5/6)
4	A3	343 - 381	5YR 4/6	VfSL	2mP	fr	CS	No rx, C, f (.50 mm) Fe-Mn stn; Si coat on ped surf (5YR 5/6)
5	A4	381 - 455	5YR 3/4	SiL	2mBK	fr	CS	No rx, C, m (.50 mm) Fe-Mn stn; M, Si coat in part(7.5 YR 6/4) Marble appearance
6	A5	455 - 490	5YR 4/1	SiL	1mSBK	fr	CS	No rx, C, S on & within ped surf (7.5YR 4/4)
7	C1	490 - 511	7.5YR 5/6	LS	1fSBK	fr	CS	No rx, C,S on & within ped surf (7.5YR 4/4) Limonite Stn (7.5YR 5/8) on ped surf btm 5mm.
8	A1,b1	511 - 518	7.5YR 4/2	VfSL	1fSBK	fr	CS	No rxt.
9	A2,b1	518 - 539	7.5YR 3/0	SiL	1fSBK	fr	CS	No rxt.
10	C1,b1	539 - 559	7.5YR 4/4	S	SG	vf	CS	No rxt.
11	C2,b1	559 - 569	5YR 3/4	cS	SG	vfr		No rxt.

* See Key

SOIL DESCRIPTION

CORE 4

H.#	Horizon Name	Depth (cm)	Dominant Color	Texture	Structure	Consis	B.	Sp. Features
1	Ap	0 - 5	7.5YR 4/2	vfSL	1fSBK	fr	CS	C,c rts, No rx.
2	A	5 - 23	5YR 4/6	SiL	2mSBK	fi	GS	No rx, Si coat on ped surf & in bet (5YR 3/4); F,f Mn-Fe stn; M,f rts
3	Bt1	23 - 74	5YR 3/4	SiCL	2mSBK	fr	GS	No rx, Si coat on ped surf (5YR 4/6) F,f rts; F,f Mn-Fe stn; C, x-bed lens (7.5YR 5/6) w/org. drapes
4	Bt2	74 - 267	5YR 3/3	SiCL	2mSBK	fr	GS	No rx, C,m S part up to 1mm thick (7.5YR 6/4)
5	BA	267 - 279	7.5YR 4/4	SiL	2mBK	fr	GS	No rx; M,m S part up to 2mm thick w/org. drapes (7.5YR 6/4)
6	AB	279 - 295	7.5YR 3/2	vfSL	2mSBk	fr	CS	No rx; C,m S part (.25 to .50 mm) w/org. drapes (7.5YR 6/4)
7	A1,b1	295 - 669	7.5YR 3/2	L	2mSBK	fr	GS	No rx; S coat in bet & on ped surf (7.5YR 4/4) (7.5YR 4/4)
8	C,b1	699 - 719	7.5YR 5/4	cS	SG	vfr	CS	No rxt.
9	R	719 - 724	7.5YR 3/2	Sh/Gr				No rxt.

* See Key

SOIL DESCRIPTION

CORE 5

H.#	Horizon Name	Depth (cm)	Dominant Color	Texture	Structure	Consis	B.	Sp. Features
1	Ap	0 - 20	5YR 4/3	L	1fSBK	fr	CS	C,f rts; No rx.
2	BA	20 - 38	5YR 4/3	vfSL	2mG	fr	CS	F,f rts; No rx.
3	A,b1	38 - 91	5YR 2.5/1	L	1mP	fr	CS	F,f rts; No rx.
4	AB,b1	91 - 109	5YR 3/2	L	1mSBK	fr	AS	F,f rts; No rx.
5	Bt1,b1	109 - 145	5YR 3/3	SCL	2mP	fi	CS	F,f rts; No rx.; F,m (.5mm) Fe-Mn stn; C, vf S coat (5YR 4/6) along ped surf.
6	Bt2,b1	145 - 173	5YR 3/3	SL	2mSBK	fr	CS	F, f rts; No rx; C,vf S coat (5YR 4/6) along ped surf.
7	Bt3,b1	173 - 274	5YR 4/2	SCL	2cP	fi	AS	C,m (.5mm) Fe-Mn stn;No rx; F,f,f (10YR 5/3) mtls
8	Bt4,b1	274 - 295	5YR 3/3	SCL	1mSBK	fi	CS	C,m (.5mm) Fe-Mn stn; No rx; C,m f (5YR 4/2) & F, f, d (10YR 5/3) mtls.
9	Bt5,b1	295 - 318	5YR 3/3	L	1mSBK	fi	CS	No rx; C, f,d (10YR 5/3) & C, m,f (5YR 4/2) mtls; C,m (.5mm) Fe-Mn stn.
10	Bt6,b1	318 - 366	5YR 4/2	SCL	1mSBK	fi	AS	No rx; F, f(.5mm Fe-Mn stn; C,f,d (10YR 5/3) mtls.
11	BC1,b1	366 - 432	5YR 3/4	L	1mSBK	fi	AS	No rx; C,m (.5mm Fe-Mn stn; C,m,d (5YR 4/2) & F,f, d (10YR 5/3) mtl
12	BC2,b1	432 - 465	5YR 3/3	SCL	1mSBK	fi	AS	No rx; C,vf S coat (5YR 4/6) along ped surf
13	C1,b1	465 - 531	5YR 3/4	SiL	SG	vfr	GS	No rx.
14	C2,b1	531 - 688	5YR 4/3	SiCL	SG	vfr	AS	No rx.
15	C3,b1	688 - 876	5YR 4/3	SiCL	SG	vfr	GS	No rx.
16	C4,b1	876 - 925	2.5YR 4/2	SiC	SG	vfr		No rx.

* See Key

SOIL DESCRIPTION

CORE 6

H.#	Horizon Name	Depth (cm)	Dominant Color	Texture	Structure	Consis	B.	Sp. Features
1	Ap	0 - 20	5YR 3/4	SL	2fBK	fr	CS	M,f rts; No rx.
2	Bt	20 - 46	5YR 4/6	L	2mSBK	fr	CS	C,f rts; No rx.
3	A,b1	46 - 74	5YR 3/3	L	2mSBK	fr	GS	C,f rts; No rx.
4	BA1,b1	74 - 163	5YR 4/3	L	2mP	fr	CS	F,f rts; No rx.
5	BA2,b1	163 - 201	5YR 3/4	L	1mSBK	fr	CS	F,f rts; No rx.
6	Bt1,b1	201 - 221	5YR 3/3	SiL	2mP	fi	CS	F,f rts; No rx. F,f(.5mm) Fe-Mn (N 2/0) stn
7	Bt2,b1	221 - 292	5YR 4/4	SiCL	2mP	fr	CS	C,m Fe-Mn (N 2/0) stn.
8	Btk1,b1	292 - 328	5YR 3/4	SCL	2mP	vfi	CS	M, m irregular branches of CaCO3 (5YR 8/1) F,f rts; Strng Ste
9	Btk2,b1	328 - 343	5YR 4/6	SCL	1mSBK	vfi	GS	C,m irregular branches of CaCO3 (5YR 8/1) F,f rts; Sle F,f (.5mm) Fe-Mn stn
10	Btk3,b1	343 - 445	5YR 4/6	SCL	1mSBK	vfi	GS	F,f irregular branches of CaCO3 (5YR 8/1) F,f rts; vsle; M,f (.5mm) Fe-Mn stn
11	BCk1,b1	445 - 488	5YR 4/6	L	1mP	fr	GS	C,m irregular brnchs of CaCO3 (5YR 8/1) sle F,f (.5mm) Fe-Mn stn
12	BC1,b1	488 - 511	5YR 5/6	SCL	1mP	fr	GS	F,f irreg brnch of CaCO3 (5YR 8/1); vsle M,f (.5mm) Fe-Mn stn
13	CB1,b1	511 - 620	5YR 4/4	SL	1mP	fr	CS	F,f (.5mm) Fe-Mn stn; vsle

* See Key

SOIL DESCRIPTION

CORE 6 (continued)

H.#	Horizon Name	Depth (cm)	Dominant Color	Tex-ture	Structure	Consis	B.	Sp. Features
14	C1,b1	620 - 653	5YR 3/4	SCL	1fSBK	fr	CS	Vsle, Upper (.5mm) Limonite nodul (10YR 3/4; Manganese nod upper & lower (N 2/0); Pebb bottom 4 mm
15	C2,b1	653 - 688	5YR 3/4	L	1fSBK	fr	CS	No rx; F, f Manganese nod (N 2/0)
16	C3,b1	688 - 721	7.5YR 4/4	SCL	1fSBK	fr	CS	No rx
17	C4,b1	721 - 881	5YR 4/6	SL	1fSBK	fr	CS	No rx; F,f Manganese nod (N 2/0)
18	C5,b1	881 - 922	5YR 3/4	SCL	1fSBK	fr		No rx, F,vf Fe-Mn stn

* See Key

SOIL DESCRIPTION

CORE 7

H.#	Horizon Name	Depth (cm)	Dominant Color	Texture	Structure	Consis	B.	Sp. Features
1	Ap	0 - 23	5YR 4/4	vfSL	2fSBK	fr	GS	C,f rt; No rx.
2	BA	23 - 56	5YR 4/3	vfSL	2fBK	fi	GS	M,f rt; No rx. C,vf S coats (5YR 4/4) along ped surf
3	A1,b1	56 - 102	5YR 4/2	SiC	2mSBK	fr	CS	F,f rts; C,vf S coats (5YR 4/4) along ped surf; No rx
4	A2,b1	102 - 130	5YR 3/2	SiL	2mSBK	fi	GS	Vf, f rts; C,vf S coats (5YR 4/4) along ped surf; No rx.
5	AB,b1	130 - 147	5YR 3/3	SiL	2mSBK	fi	GS	No rx
6	BA,b1	147 - 168	5YR 3/4	SiCL	2mSBk	fi	CS	No rx; F,f Fe-Mn stn
7	Btk,b1	168 - 193	5YR 4/6	SiL	2mSBK	fr	CS	Strng efferv.; M ,m rnd CaCO3 concret (5YR 8/1 F,f Fe-Mn Stn
8	Bt1,b1	193 - 239	5YR 5/6	VfSL	1mP	fr	CS	M,m rt; M,f threadlike Fe-Mn stn; No rx.
9	Bt2,b1	239 - 312	5YR 5/8	SiL	2fBK	fr	GS	F,f Fe-Mn stn; No rx.
10	Bt3,b1	312 - 353	5YR 5/6	SL	2mSBK	fr	GS	No rx; F,f Fe-Mn stn
11	Bt4,b1	353 - 389	5YR 5/6	L	2mSBK	fr	CS	Mod efferv; F,f rnd CaCO3 concr (5YR 8/1) Vf,f Fe-Mn stn
12	C1,b1	389 - 406	5YR 6/6	SL	1fSBK	vfr	CS	No rx;F,f Fe-Mn stn
13	C2,b1	406 - 556	5YR 5/6	SL	1fSBK	vfr	CS	No rx; F,f Fe-Mn stn
14	C3,b1	556 - 620	5YR 4/6	SL	SG	vfr	CS	No rx;Org.Drap
15	C4,b1	620 - 640	5YR 4/6	SL	SG	vfr	CS	No rx
16	C5,b1	640 - 671	5YR 3/2	cS	SG	vfr	CS	No rx
17	A,b2	671 - 762	5YR 3/3	SCL	2mSBK	fr		vsle; F,f thread-like CaCO3 (5YR 8/1)

* See Key

APPENDIX B

ORGANIC CARBON PROCEDURE

AND RESULTS

Organic Carbon Determination Procedures

The total organic carbon procedure followed the guidelines set forth by Gee and Bauder (1986), Methods of Soil Analysis, American Society of Agronomy, Inc.

The dry combustion method is based on the oxidation of organic carbon and thermal decomposition of carbonate minerals in a medium-temperature resistance furnace. The carbon dioxide is trapped in a suitable reagent (Ascarite) and weighed after each burn. Two standards are tested before each sample set run. The organic carbon determination method follows:

Percent Organic Carbon (Wet Weight) =
(Last Ascarite Bottle Weight - Previous Ascarite Bottle Weight) *.2729 *100/ Soil Weight
Percent Organic Carbon (Dry Weight) =
Wet Weight - Tin Weight = x
Dry Weight - Tin Weight = y
x - y = z   z/y *100 = percent water
100 - percent water = a/100
a * 1.024 = Oven dry weight
Percent Organic Carbon =
(Last Ascarite Bottle Weight - Previous Ascarite Bottle Weight) * .2729 * 100/Oven Dry Weight
Organic Matter = 1.72 * Percent Organic Carbon (Dry Weight) *

* Total Organic Carbon procedure is outlined in chapter 3, Laboratory Methods.

PERCENT ORGANIC CARBON DETERMINED FROM SOIL SAMPLES TAKEN FROM CORES ALONG TURKEY CREEK AND CRYSTAL CREEK

Depth (cm)	Horizon	% OC (dry)	%OM	Depth (cm)	Horizon	% OC (dry)	%OM
Core Site #1				Core Site #2			
10	C1	0.7358	1.2655	10	Ap	1.857	3.19
20	A,b1	0.5568	0.9577	20	Bt1	1.0275	1.7673
30	A,b1	0.9166	1.5766	30	Bt1	0.8719	1.4996
40	BA,b1	0.3539	0.6087	40	Bt2	1.0164	1.7483
50	BA,b1	0.3161	0.5437	50	Bt2	1.0297	1.7711
60	BC,b1	0.2692	0.4631	70	AB,b1	1.3601	2.3393
70	BC,b1	0.2514	0.4324	90	A,b1	1.0893	1.8736
180	C1,b1	0.2168	0.3728	120	A,b2	1.7619	3.0305
200	C2,b1	0.1561	0.2685	150	A,b2	1.7222	2.9621
210	C3,b1	0.0484	0.0833	180	A,b3	0.6306	1.0847
220	C3,b1	0.0556	0.0956	210	A,b3	0.7741	1.3314
290	C4,b1	0.0839	0.1442	240	Bt2,b3	0.4122	0.7090
300	C4,b1	0.2683	0.4615	270	A,b4	0.5563	0.9569
310	C4,b1	0.1505	0.2589	310	A,b4	0.4131	0.7106
330	C5,b1	0.2325	0.3999	370	A,b4	0.3323	0.5715
360	C6,b1	0.1347	0.2317	450	A,b4	0.2254	0.3877
390	A1,b2	0.5260	0.9047	520	Bt2,b4	0.2066	0.3553
420	C1,b2	0.2152	0.3701				
450	A1,b3	0.7710	1.3262				
470	A1,b3	0.3682	0.6333				
480	A1,b3	0.2860	0.4920				
510	A1,b3	0.3080	0.5297				
560	AC,b4	0.6359	1.0938				
620	A1,b5	0.7390	1.2711				
680	A1,b5	0.9785	1.6831				
730	A1,b5	0.6632	1.1408				
780	AB,b5	0.6296	1.0830				
860	AB,b5	0.7469	1.2846				
890	AB,b5	0.7723	1.3284				

PERCENT ORGANIC CARBON (Continued)

Depth (cm)	Horizon	% OC (dry)	%OM	Depth (cm)	Horizon	% OC (dry)	%OM
	Core Site #3				Core Site #4		
10	Ap	0.7509	1.2916	10	A	1.2139	2.0879
20	Ap	0.6933	1.1924	30	Bt1	0.7352	1.2646
30	A1	0.6247	1.0745	60	Bt1	0.4631	0.7965
40	A1	0.6667	1.1468	90	Bt2	0.4168	0.7169
50	A1	0.6770	1.1644	120	Bt2	0.4103	0.7057
60	A1	0.6181	1.0632	150	Bt2	0.4965	0.8540
90	A1	0.6751	1.1612	180	Bt2	0.3749	0.6449
120	A1	0.5961	1.0253	210	Bt2	0.3467	0.5964
180	A1	0.6269	1.0783	240	Bt2	0.4046	0.6959
210	A2	0.4997	0.8596	290	AB	0.4912	0.8449
240	A2	0.3556	0.6116	320	A1,b1	0.6933	1.1925
270	A2	0.3036	0.5222	350	A1,b1	0.6504	1.1186
300	A2	0.3118	0.5363	380	A1,b1	0.3420	0.5883
330	A2	0.2562	0.4406	410	A1,b1	0.3936	0.6771
360	A3	0.2236	0.3846	440	A1,b1	0.3905	0.6716
390	A4	0.2152	0.3701	470	A1,b1	0.3145	0.5410
420	A4	0.2837	0.4880	500	A1,b1	0.5546	0.9539
450	A4	0.1969	0.3386	530	A1,b1	0.9225	1.5868
480	A5	0.4406	0.7577	560	A1,b1	0.7558	1.3000
510	C1	0.1126	0.1937	590	A1,b1	0.7439	1.2796
				650	A1,b1	0.6440	1.1077
				680	A1,b1	0.6718	1.1555
				710	C,b1	0.5940	1.0217
	Crystal Creek Type Section				Up-Slope Site 1		
140	A,b1	1.6030	2.8053	90	A,b1	2.0563	3.5985
180	A,b1	1.8432	3.2256	110	A,b1	1.8552	3.1909
220	A,b1	1.9006	3.3261				
240	A,b1	1.3253	2.2795				
260	A,b1	1.1429	1.9659				
	Up-Slope Site 3				Up-Slope Site 5		
60	A,b1	1.7591	3.0257	40	A,b1	1.4669	2.5670
70	A,b1	1.5946	2.7427	50	A,b1	1.7146	3.0006
	Up-Slope Site 7						
40	A,b1	1.5073	2.6377				
50	A,b1	0.9664	1.6622				

PERCENT ORGANIC CARBON (continued)

Depth (cm)	Horizon	% OC (dry)	%OM	Depth (cm)	Horizon	% OC (dry)	%OM
	Core Site #5				Core Site #6		
10	Ap	0.5634	0.9691	10	Ap	0.5024	0.8641
20	Ap	0.5187	0.8922	20	Ap	0.2939	0.5056
30	BA	0.5841	1.0046	30	Bt	0.4011	0.6900
40	BA	0.7128	1.2260	40	Bt	0.5855	1.0070
50	A,b1	0.9185	1.5798	50	A,b1	0.5835	1.0036
60	A,b1	0.9436	1.6230	60	A,b1	0.6035	1.0379
70	A,b1	0.9218	1.5856	70	A,b1	0.6824	1.1738
80	A,b1	0.9171	1.5774	80	BA1,b1	0.7188	1.2364
90	A,b1	1.3260	2.2807	90	BA1,b1	0.5734	0.9862
100	AB,b1	0.5620	0.9666	100	BA1,b1	0.8747	1.5045
110	AB,b1	0.4596	0.7906	110	BA1,b1	0.5462	0.9394
120	Bt1,b1	0.4468	0.7685	120	BA1,b1	0.1750	0.3010
130	Bt1,b1	0.4244	0.7300	130	BA1,b1	0.5918	1.0179
140	Bt1,b1	0.4063	0.6988	140	BA1,b1	0.7342	1.2628
150	Bt2,b1	0.4058	0.6980	150	BA1,b1	0.7313	1.2578
160	Bt2,b1	0.4302	0.7399	160	BA1,b1	0.6258	1.0764
170	Bt3,b1	0.4175	0.7180	170	BA2,b1	0.5426	0.9333
180	Bt3,b1	0.3854	0.6628	180	BA2,b1	0.5763	0.9912
190	Bt3,b1	0.4199	0.7222	190	BA2,b1	0.3873	0.6662
200	Bt3,b1	0.3832	0.6592	200	BA2,b1	0.2809	0.4832
210	Bt3,b1	0.3214	0.5528	230	Bt2,b1	0.2663	0.4581
220	Bt3,b1	0.2608	0.4486	280	Bt2,b1	0.1418	0.2439
230	Bt3,b1	0.3805	0.6544	330	BtK1,b1	0.2135	0.3672
240	Bt3,b1	0.0779	0.1340	350	BtK3,b1	0.1993	0.3427
280	Bt4,b1	0.0263	0.0453	400	BtK3,b1	0.1346	0.2315
320	Bt6,b1	0.2036	0.3502	450	BC1,b1	0.1150	0.1978
360	Bt6,b1	0.1802	0.3099	550	CB1,b1	0.1156	0.1989
400	BC1,b1	0.1578	0.2714	650	C1,b1	0.4429	0.7618
440	BC2,b1	0.0931	0.1602				
480	C1,b1	0.1824	0.3137				
560	C1,b1	0.1393	0.2396				
660	C2,b1	0.1850	0.3183				
760	C2,b1	0.1631	0.2805				
860	C3,b1	0.1793	0.3084				
940	C3,b1	0.2296	0.3949				

PERCENT ORGANIC CARBON (continued)

Depth (cm)	Horizon	% OC (dry)	%OM	Depth (cm)	Horizon	% OC (dry)	%OM
			Core Site #7				
10	Ap	0.7371	1.2679	160	BA,b1	0.2270	0.3905
20	Ap	0.6690	1.1507	170	BA,b1	0.5381	0.9255
30	BA	0.5207	0.8956	210	Bt1,b1	0.1717	0.2953
40	BA	0.3841	0.6607	290	Bt2,b1	0.1574	0.2708
50	BA	0.4118	0.7083	350	Bt3,b1	0.0876	0.1507
60	A1,b1	0.5750	0.9891	470	C2,b1	0.0381	0.0655
70	A1,b1	0.7778	1.3378	530	C2,b1	0.5591	0.9616
80	A1,b1	0.7258	1.2483	540	C2,b1	0.4983	0.8571
90	A1,b1	0.8263	1.4213	560	C2,b1	0.1936	0.3329
100	A1,b1	0.9115	1.5677	580	C3,b1	0.0904	0.1554
110	A2,b1	0.8458	1.4548	600	C3,b1	0.0593	0.1019
120	A2,b1	0.5988	1.0300	630	C4,b1	0.1491	0.2565
130	A2,b1	0.4483	0.7710	660	C5,b1	0.3041	0.5231
140	AB,b1	0.3304	0.5682	700	A,b2	0.4319	0.7429
150	BA,b1	0.3710	0.6382				
		Turkey Creek Type Section				Core 6 - Bank Site	
390	A,b1	0.9102	1.5656	490	A,b1	0.5816	1.0003
410	A,b1	0.7239	1.2669	500	A,b1	0.3701	0.6478
420	A,b1	0.6061	1.0606	510	A,b1	0.4575	0.7869
		SCS 302 - Bank Site					
300	A,b1	0.8553	1.4967				
310	A,b1	0.4428	0.7749				
320	A,b1	1.5073	2.6377				

APPENDIX C

PARTICLE SIZE PROCEDURE

AND RESULTS

Laboratory Procedure for Particle Size Distribution

The procedure for determining particle size distribution followed the guidelines set forth by Nelson and Sommers (1982), Methods of Soil Analysis, American Society of Agronomy, Inc. Two standards were used with each sample batch for quality control. The following is an outline of the method employed:

1. Weigh approximately 10 grams of soil in a centrifuge bottle.

2. Add H_2O_2 (5 ml) and H_2O (50 ml), cover with watchglass and allow to stand for couple of hours.

3. Place bottles in water bath and heat at 90 C for 30 minutes, then H_2O_2 (5 ml) is added at 30 minute intervals until frothing has ended (usually 4-5 intervals). After last addition of H_2O_2, allow samples to sit in bath for 30 minutes to boil off excess H_2O_2.

4. Allow bottles to cool, weigh bottles on Mettler balance to sample weight, and centrigure at 5000 rpm's for 10 minutes.

5. Pour off excess water and transfer soil to 100 ml beaker, and place in oven overnight at 105 C.

6. Place soil in a tared centrifuge bottle, and record weight of total soil.

7. Add dispersing agent (10 ml) and (200 ml) distilled water to soil, place in shaker at low speed overnight.

8. Using the 53 micron or No. 27 sieve, pour sample through sieve into a 1000 ml cylinder. Allow cylinder to come to room temperature.

9. Rinse sands thoroughly and place sands in a recorded beaker. Place sands in 105 C oven to dry overnight.

10. Weigh dry sands, record total weight.

11. Weigh dried beakers, and record empty weight for pipetting of 2, 5, and 20 microns.

12. Take temperature of water in cylinders to determine the settling time according to Stokes Law in the pipetting process.

Particle Size Procedure (Continued)

13. Using stirring rod, stir the first cylinder. Follow time chart for stirring samples, and pipetting samples. Use distilled water to flush pipet after each pipetting. Twenty micron pipetting is first, 5 micron is second, and 2 micron is last.

14. Place beakers with pipet solution in 105 C oven overnight.

15. Weigh and record dry beaker weights.

16. Place dry sands into a series of sieves, using 1 mm, 500, 250, 106, 53 micron, and catch pan, shake 5 minutes on sieve shaker. Weigh each sieve pan to obtain weight of each fraction.

17. Test values are input into a computer program. Each individual size fraction is determine, and the total percent of sand, silt, and clay is obtained.

PARTICLE SIZE DISTRIBUTION FOR SELECTED SOILS FROM CORES, BANK AND UP-SLOPE SITES ALONG TURKEY AND CRYSTAL CREEKS

		Sand (microns)					Silt (microns)			Percent		
Depth (cm)	Horizon	2000-1000	1000-500	500-250	250-100	100-50	50-20	20-5	5-2	Sand	Silt	Clay
					Core 1 - Crystal Creek							
13 - 18	C1	0.0	0.1	8.5	68.0	9.6	6.3	0.5	2.0	86.2	8.8	4.3
18 - 38	A,b1	0.0	0.0	9.1	60.3	9.4	8.3	4.7	0.6	78.8	13.6	6.7
38 - 51	BA,b1	0.0	0.1	10.3	68.3	8.8	6.0	1.8	0.3	87.4	8.0	4.1
51 - 74	BC,b1	0.3	0.1	0.1	65.6	10.2	10.1	1.4	0.0	83.1	11.3	5.0
74 - 180	C1,b1	0.0	0.0	0.0	64.9	21.5	6.2	1.3	0.0	86.4	7.5	5.0
211 - 229	C3,b1	0.0	0.1	0.1	67.4	14.3	5.1	5.1	0.6	87.2	7.6	4.7
325 - 340	C5,b1	0.1	0.1	0.1	31.6	24.7	19.4	9.1	0.9	56.9	29.4	13.3
361 - 419	A1,b2	0.0	0.1	0.1	10.2	17.0	37.7	13.4	1.5	27.6	52.7	18.4
449 - 546	A1,b3	0.1	0.2	0.2	9.0	15.1	42.6	8.2	2.0	24.7	52.9	21.2
546 - 554	AB,b4	0.5	0.3	0.3	11.3	19.7	32.7	11.9	3.5	32.2	48.2	18.5
554 - 594	AC,b4	0.0	0.1	0.1	31.3	11.7	28.8	9.0	9.0	46.6	38.6	14.3
594 - 772	A1,b5	0.0	0.1	0.1	5.9	13.8	33.1	15.6	4.0	20.4	52.7	26.2
772 - 935	AB,b4	0.7	0.5	0.5	1.5	3.4	28.2	25.9	5.6	6.4	59.8	33.2
					Core 2 - Crystal Creek							
10 - 33	Bt1	0.0	0.1	0.1	14.3	13.2	35.2	13.0	1.7	29.7	50.1	19.5
114 - 155	A,b2	0.0	0.2	0.2	3.6	17.6	46.6	9.4	2.2	21.8	58.1	18.7
155 - 221	A,b3	0.8	0.4	0.4	21.2	19.5	26.8	9.8	3.1	42.3	39.7	16.6
221 - 231	Bt1,b3	0.0	0.1	0.5	6.7	13.6	35.3	16.2	3.9	20.8	55.4	23.3
249 - 450	A,b4	0.0	0.4	0.5	7.5	18.3	37.6	37.6	2.8	26.8	53.6	19.1
508 - 528	Bt2,b4	0.3	0.5	0.5	10.7	7.2	31.1	11.8	3.8	19.3	46.7	33.3
602 - 627	C1,b5	0.2	0.4	1.7	13.6	30.3	15.6	11.3	2.8	46.2	29.7	23.4
					Core 3 - Crystal Creek							
20 - 203	A1	0.0	0.3	1.4	7.3	14.3	39.2	14.5	0.0	23.3	53.0	22.9
381 - 455	A4	0.4	0.5	1.4	6.9	11.8	38.4	13.3	2.4	21.0	54.1	24.5
455 - 490	A5	0.0	0.4	2.2	10.4	12.8	40.7	9.1	3.0	25.9	52.7	20.8
490 - 511	C1	26.9	18.3	13.6	14.1	6.9	7.7	2.7	5.3	79.8	15.6	2.7
518 - 539	A2,b1	0.8	1.3	3.3	7.2	10.4	37.7	11.9	15.3	22.9	64.9	11.8

PARTICLE SIZE DISTRIBUTION (continued)

		Sand (microns)					Silt (microns)			Percent		
Depth (cm)	Horizon	2000-1000	1000-500	500-250	250-100	100-50	50-20	20-5	5-2	Sand	Silt	Clay
					Core 4 - Crystal Creek							
5 - 23	A	0.0	0.1	0.2	0.8	5.0	36.4	22.4	5.7	6.1	64.5	28.6
23 - 74	Bt1	0.0	0.0	0.0	0.4	3.7	35.3	23.3	5.7	4.1	64.3	31.0
74 - 267	Bt2	0.0	0.0	0.0	2.2	15.1	57.2	4.1	1.0	12.2	62.2	24.9
267 - 279	BA	0.1	0.2	0.2	9.0	24.7	42.6	8.2	2.0	24.7	52.9	21.2
279 - 295	AB	0.1	0.1	0.1	31.6	17.1	19.4	9.1	0.9	56.9	29.4	13.3
295 - 699	A1,b1	3.4	0.3	0.2	3.0	14.7	39.2	11.4	2.1	24.0	52.7	22.0
699 - 719	C,b1	18.6	43.0	12.2	2.4	2.3	0.7	4.3	1.0	78.6	6.1	14.4
					Crystal Creek - Type Section							
48 - 121	Bt1	0.0	0.0	0.3	7.7	8.2	30.8	17.9	6.2	16.3	54.8	28.6
121 - 138	Bt2	0.0	0.4	2.2	10.4	12.8	40.7	9.1	3.0	25.9	52.7	20.8
138 - 335	A,b1	1.0	0.2	0.1	9.5	23.4	36.2	8.0	3.3	34.2	47.5	18.2
335 - 457	Bt,b1	0.1	0.2	0.1	2.2	17.3	31.7	15.2	5.5	19.8	52.3	27.4
					Up-Slope Site 1							
30 - 65	Bt1	0.0	0.0	0.0	1.4	20.8	44.3	3.8	1.4	22.2	49.5	27.9
65 - 91	Bt2	0.0	0.0	0.0	3.6	22.1	42.7	5.3	3.4	25.7	51.4	22.3
91 - 119	A,b1	0.0	0.0	0.9	11.7	24.1	38.9	6.1	3.2	36.7	48.2	14.2
					Up-Slope Site 3							
20 - 39	Bt1	0.0	0.0	0.3	2.6	15.3	40.2	5.9	3.7	18.2	49.8	31.6
39 - 60	Bt2	0.0	0.0	0.4	1.8	14.9	38.3	5.1	4.0	16.7	47.4	35.5
					Up-Slope Site 5							
9 - 31	Bt1	0.0	0.0	0.0	3.7	17.3	46.2	2.8	1.2	21.0	50.2	28.3
31 - 33	Bt2	0.0	0.0	0.0	4.6	20.1	44.7	5.9	2.5	24.7	53.1	21.0
					Up-Slope Site 7							
9 - 20	Bt1	0.0	0.0	0.0	3.2	15.9	47.1	2.1	1.6	19.1	50.8	29.4
20 - 39	Bt2	0.0	0.0	0.0	2.5	14.8	43.4	4.1	6.0	17.3	53.5	28.8

PARTICLE SIZE DISTRIBUTION (continued)

		Sand (microns)					Silt (microns)			Percent		
Depth (cm)	Horizon	2000-1000	1000-500	500-250	250-100	100-50	50-20	20-5	5-2	Sand	Silt	Clay
				Core 5 - Turkey Creek								
0 - 20	Ap	0.0	0.0	0.2	13.0	24.1	35.7	11.1	1.9	37.3	48.7	13.6
38 - 91	A,b1	0.1	0.1	0.3	10.1	17.7	35.4	11.4	3.3	28.2	50.0	21.4
91 - 109	AB,b1	0.0	0.2	0.5	13.9	16.9	28.6	12.9	3.6	31.4	45.2	22.8
145 - 173	Bt2,b1	0.1	0.2	0.3	7.4	13.6	33.8	15.6	3.5	21.6	52.9	25.3
295 - 318	Bt5,b1	0.4	0.4	0.6	14.0	18.2	28.6	12.8	3.3	33.6	44.7	21.4
366 - 432	BC1,b1	0.0	0.2	0.6	16.2	17.0	26.1	13.1	3.8	33.9	42.9	22.5
465 - 531	C1,b1	0.0	0.2	0.3	10.2	12.6	28.7	18.8	3.4	23.4	50.9	25.3
688 - 876	C3,b1	0.0	0.0	0.3	7.7	8.2	30.8	17.9	6.2	16.3	54.8	28.6
				Core 6 - Turkey Creek								
20 - 46	Bt	0.0	0.0	0.2	23.4	25.5	26.7	8.4	1.2	49.1	36.3	13.9
46 - 74	A,b1	0.0	0.0	0.1	14.6	22.5	35.0	11.2	1.6	37.2	47.7	14.3
74 - 163	BA1,b1	0.0	0.0	0.2	15.5	21.2	33.4	11.2	1.6	37.0	46.2	16.2
163 - 201	BA2,b1	2.4	1.0	1.4	15.1	14.3	24.3	12.5	3.4	34.2	40.1	25.1
221 - 292	Bt2,b1	0.1	0.2	0.2	4.8	13.6	32.8	18.1	4.6	16.3	55.4	27.8
343 - 445	Btk3,b1	0.5	0.3	0.4	4.7	12.3	39.3	14.6	3.7	18.3	57.6	23.8
445 - 488	Bck1,b1	0.4	0.2	0.3	12.1	17.0	31.8	11.5	2.8	29.9	46.1	23.6
653 - 688	C2,b1	3.2	1.9	2.0	18.4	12.8	19.7	11.9	6.5	38.4	38.2	23.1
721 - 881	C4,b1	0.1	0.9	2.3	35.9	22.1	14.7	4.8	3.2	61.3	22.7	15.1
				Core 7 - Turkey Creek								
56 - 102	A1,b1	0.0	0.2	0.2	0.6	0.3	5.1	13.3	13.9	1.3	32.3	66.2
102 - 130	A2,b1	0.8	0.1	0.2	2.6	7.7	22.6	15.8	6.1	10.8	44.4	44.2
130 - 147	AB,b1	0.0	0.1	0.1	2.0	7.2	22.3	18.3	30.2	9.5	70.9	19.4
147 - 168	BA,b1	0.1	0.2	0.1	2.2	9.3	31.7	15.2	5.5	11.8	52.3	35.4
239 - 312	Bt2,b1	0.1	0.1	0.2	1.1	7.0	47.8	19.3	0.0	8.5	66.4	24.6
353 - 389	Bt4,b1	1.0	0.2	0.1	9.5	23.4	36.2	8.0	3.3	34.2	47.5	18.2
406 - 556	C2,b1	0.2	0.2	0.2	20.4	38.0	17.6	6.4	9.8	59.1	33.8	6.7
620 - 640	C4,b1	0.1	0.4	0.8	26.4	29.0	22.2	5.6	2.2	56.6	30.0	13.4

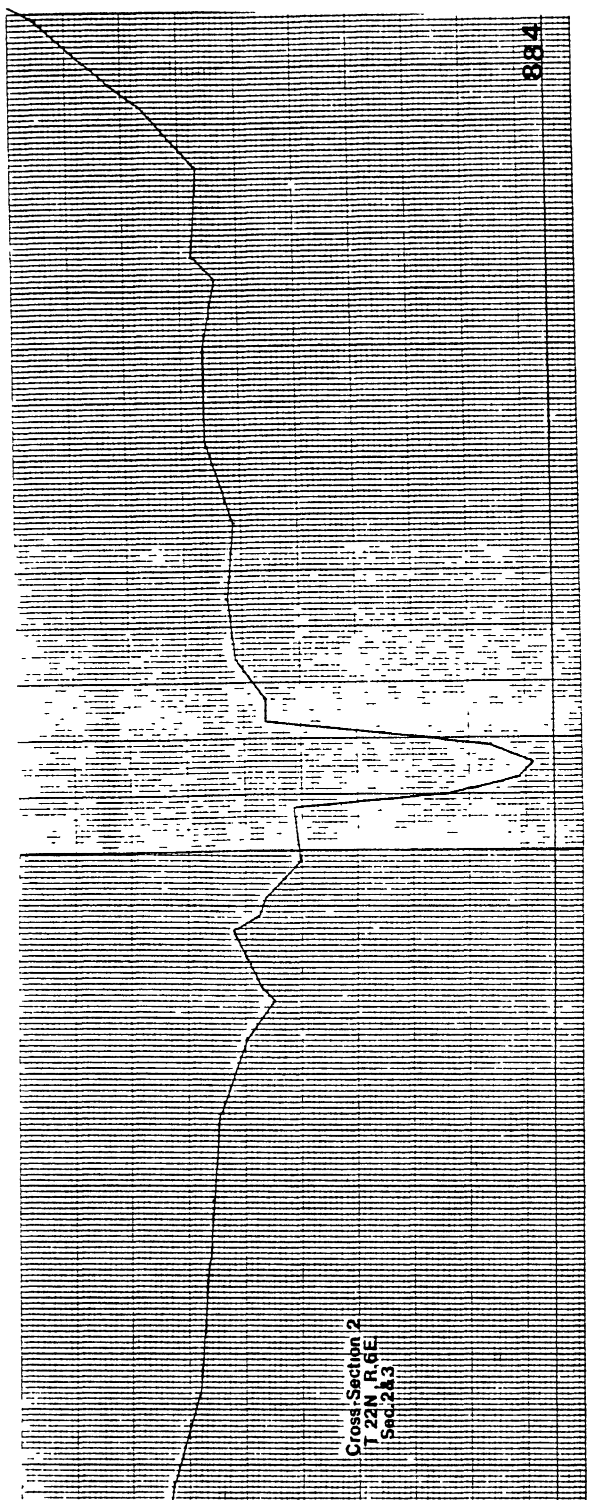
PARTICLE SIZE DISTRIBUTION (continued)

		Sand (microns)					Silt (microns)			Percent		
Depth (cm)	Horizon	2000-1000	1000-500	500-250	250-100	100-50	50-20	20-5	5-2	Sand	Silt	Clay
Turkey Creek - Type Section												
3 - 58	A1	0.0	0.0	0.0	0.1	9.4	31.7	15.2	5.5	9.5	52.2	37.4
84 - 142	Bt1	0.0	0.0	0.3	0.4	17.9	30.8	17.6	5.8	18.6	54.2	26.3
173 - 201	Bt3	0.0	0.2	0.3	9.9	11.7	27.5	19.1	4.1	22.1	50.7	26.7
201 - 221	BC	0.2	0.2	0.1	14.5	37.6	23.7	14.2	4.3	52.6	42.2	4.8
221 - 249	CB	0.2	0.1	3.3	23.6	21.2	27.8	11.5	2.8	48.4	42.1	9.2
249 - 353	C1	0.8	0.4	6.2	21.3	19.4	23.1	9.7	3.1	48.1	35.9	15.4
353 - 373	C2	5.5	8.4	12.1	15.5	11.2	19.0	12.4	3.7	52.7	35.1	11.8
373 - 391	C3	10.8	15.3	16.4	17.1	9.9	9.0	8.4	3.5	58.7	20.9	19.6
391 - ?	A,b1	0.0	0.0	0.3	1.8	10.9	3.7	15.1	14.3	13.0	33.1	53.4
SCS - 302 Bank Site												
97 -114	Bt3	0.0	0.1	0.3	8.7	13.6	31.7	19.2	3.1	22.7	54.0	23.1
114 - 201	C1	0.0	0.0	4.4	30.3	20.4	19.7	11.9	6.5	55.1	38.1	5.9
201 - 267	C2	0.1	0.3	7.7	11.1	30.2	19.3	11.4	5.8	49.4	36.5	13.5
267 - 290	C3	0.8	4.3	28.4	15.6	14.9	21.0	7.1	3.3	64.0	31.4	4.2
290 - 302	C4	8.9	16.8	18.8	15.6	9.2	11.1	9.1	2.7	69.3	22.9	7.3
302 - 335	A,b1	0.0	0.0	0.2	10.1	14.1	5.8	14.7	15.6	24.6	36.1	38.9
Core 6 - Bank Site												
94 - 150	Bt2	0.0	0.0	0.0	17.4	23.6	33.8	15.6	3.5	41.0	42.9	15.5
241 - 295	Bt5	0.0	0.0	0.0	9.6	21.1	35.0	11.2	1.6	30.7	47.8	21.0
295 - 345	C1	0.0	0.0	0.0	8.2	17.1	39.2	11.4	2.1	25.3	52.7	21.4
345 - 379	C2	0.0	0.0	0.2	24.9	27.6	20.3	11.2	1.6	52.7	33.1	14.1
379 - 414	C3	0.2	0.2	0.4	36.8	21.3	17.3	6.7	9.1	58.9	33.1	7.3
414 - 437	C4	0.1	0.9	2.3	35.9	22.1	14.7	11.9	6.5	61.3	33.1	5.4
437 - 455	C5	0.8	0.4	0.4	1.2	19.2	23.8	12.3	3.1	52.0	39.1	8.4
455 - 478	C6	3.1	9.4	14.9	22.6	10.6	15.1	11.4	2.4	60.6	28.9	10.4
478 - 490	C7	9.2	15.6	16.3	14.2	8.7	9.9	7.7	3.9	64.0	21.5	14.0
490 - ?	A,b1	0.0	0.0	0.1	1.8	9.5	6.5	15.1	12.6	11.4	34.2	54.1

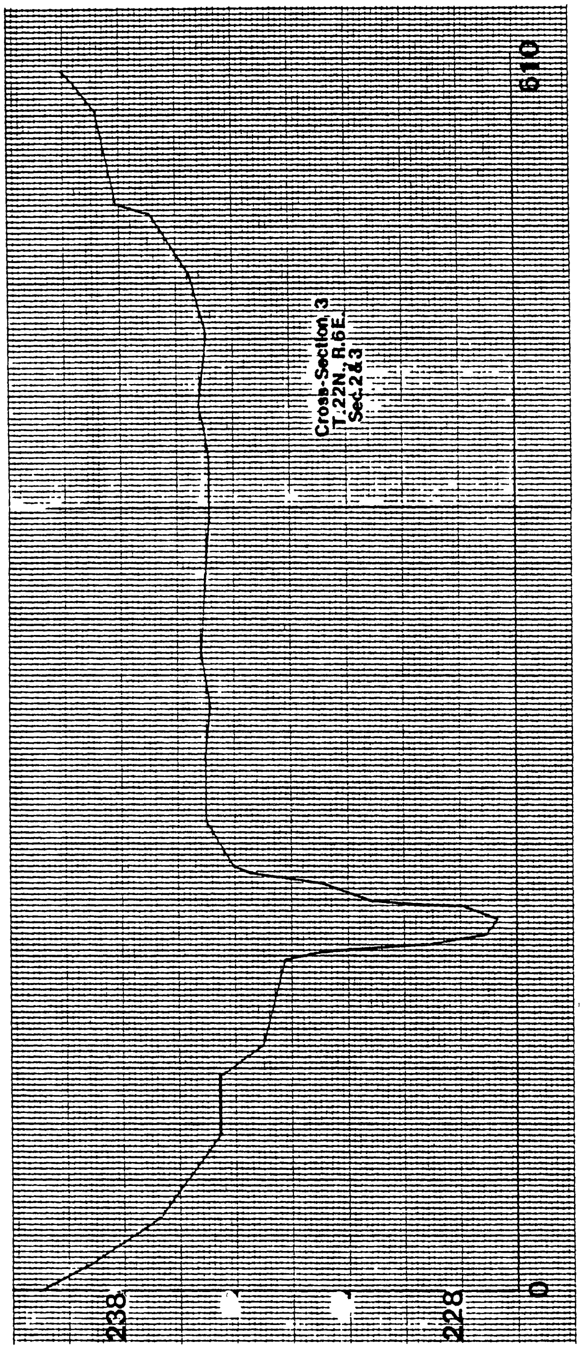
APPENDIX D

CROSS-SECTIONS UTILIZED

IN HEC-2 PROGRAM



Cross-Section 2
T 22N , R.6E
Sec.2&3
884
248
228
0


Cross-Section 3
T.22N, R.6E.
Sec. 2 & 3
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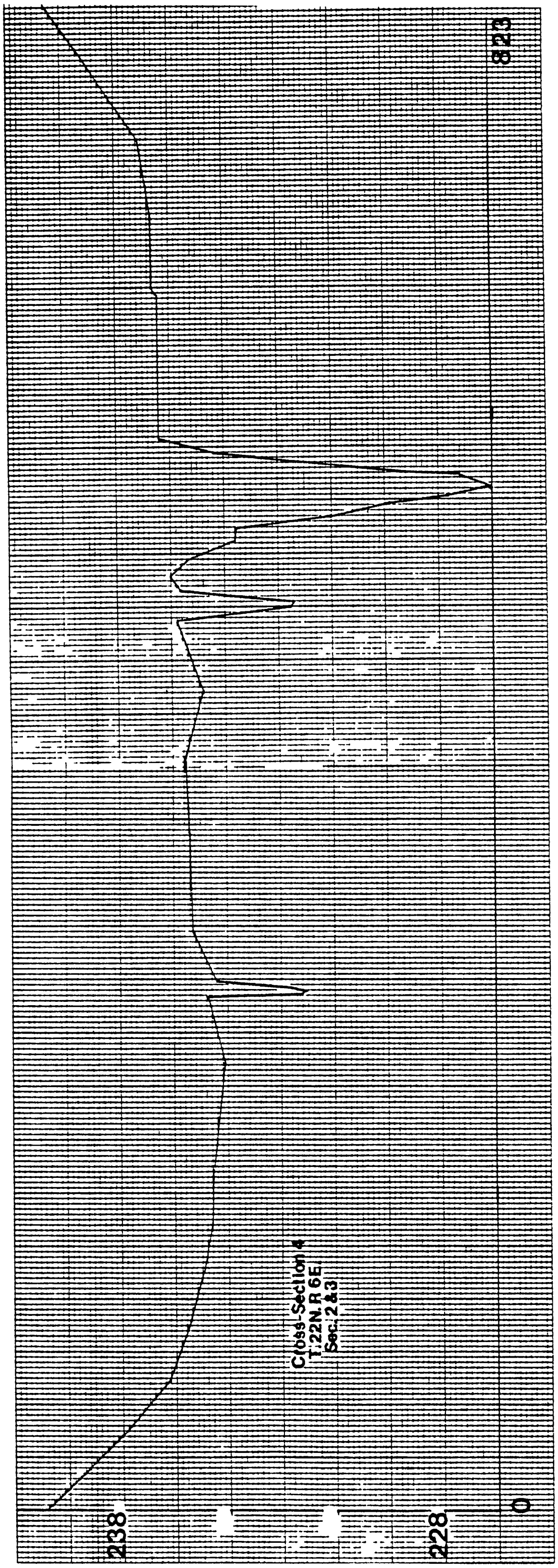
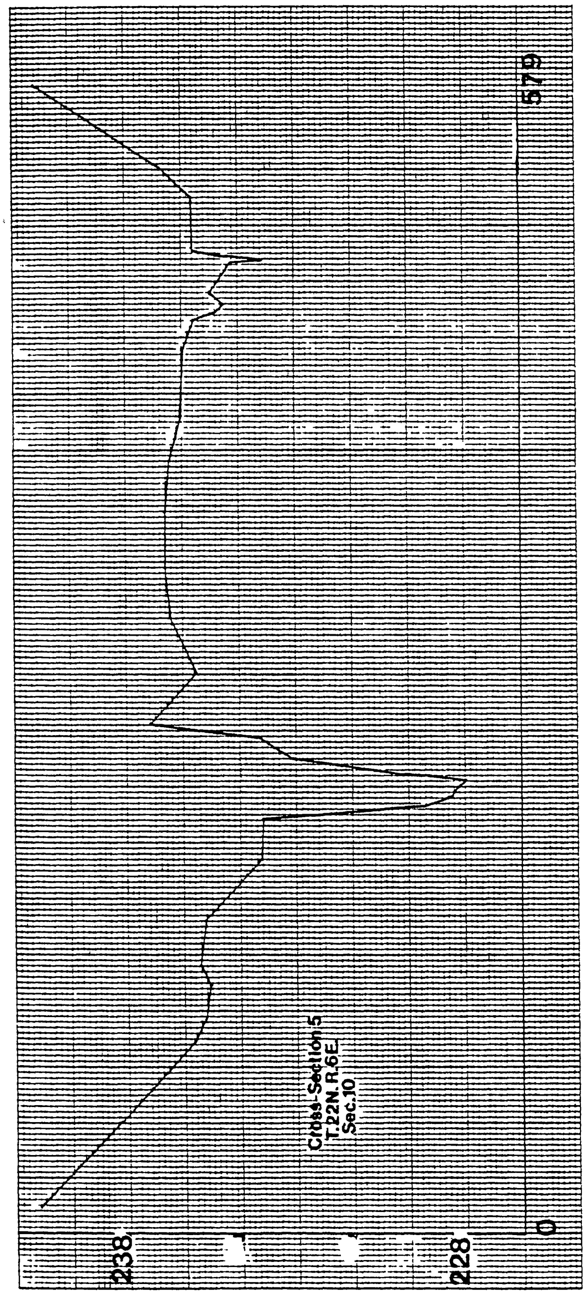
228
0
610


823
Cross-Section 4
T.22N. R.6E.
Sec. 2&3
238
228
0



Cross-Section 5
T.22N. R.6E.
Sec.10
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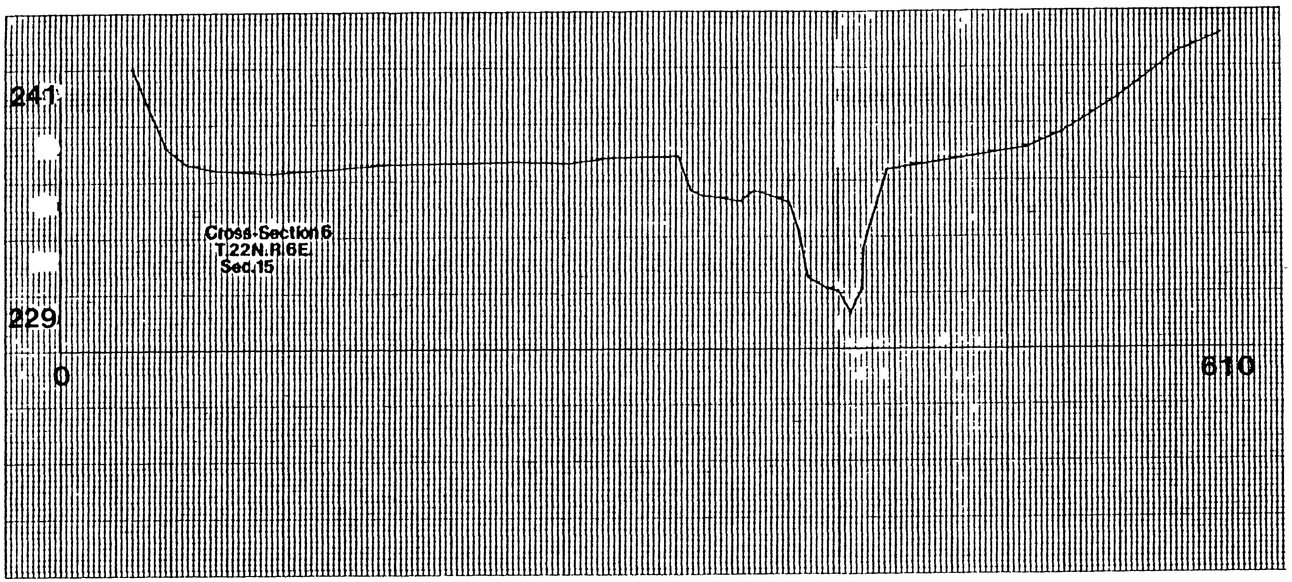
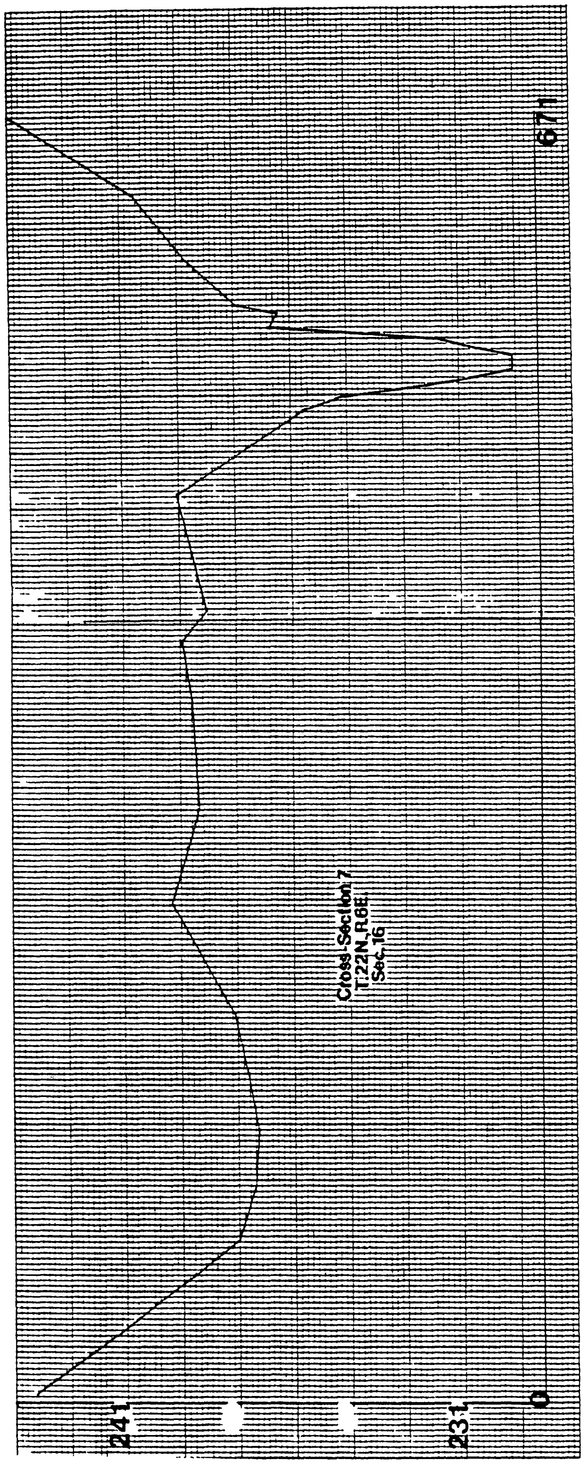
238
228


241
229
0
610
Cross-Section 6
T.22N.R.6E.
Sec.15


Cross Section 7
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Sec. 16
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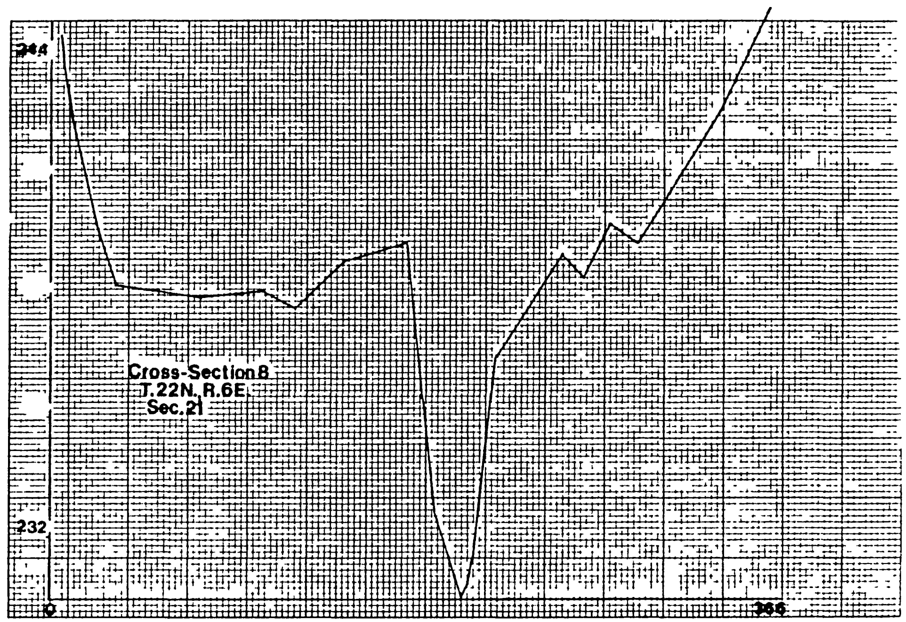
231
0
671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232
0
366
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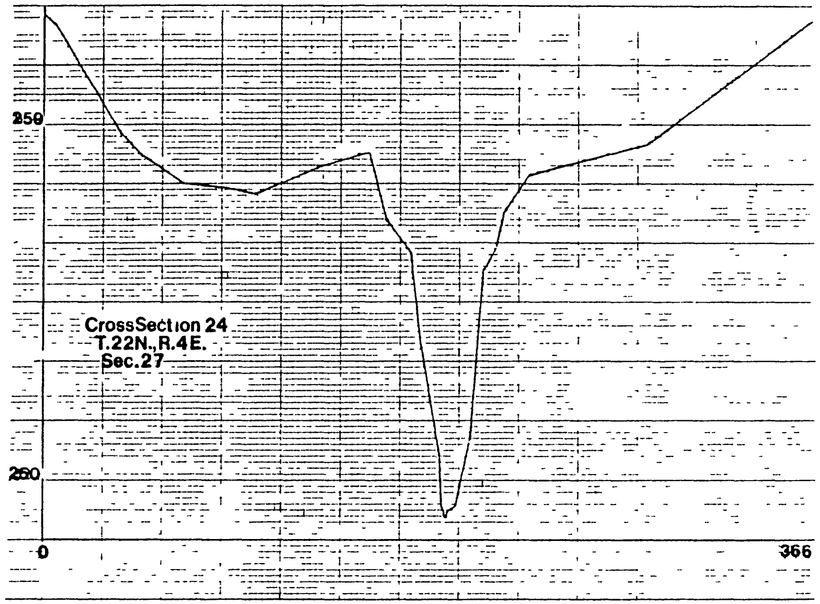
Sec.21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Sec.27
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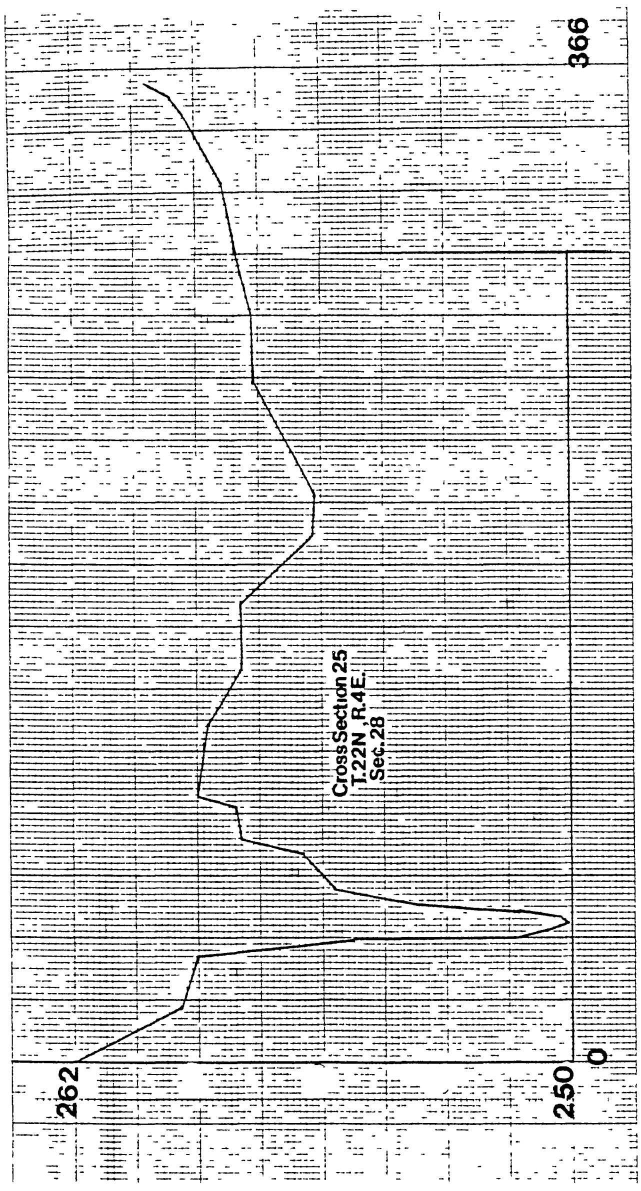
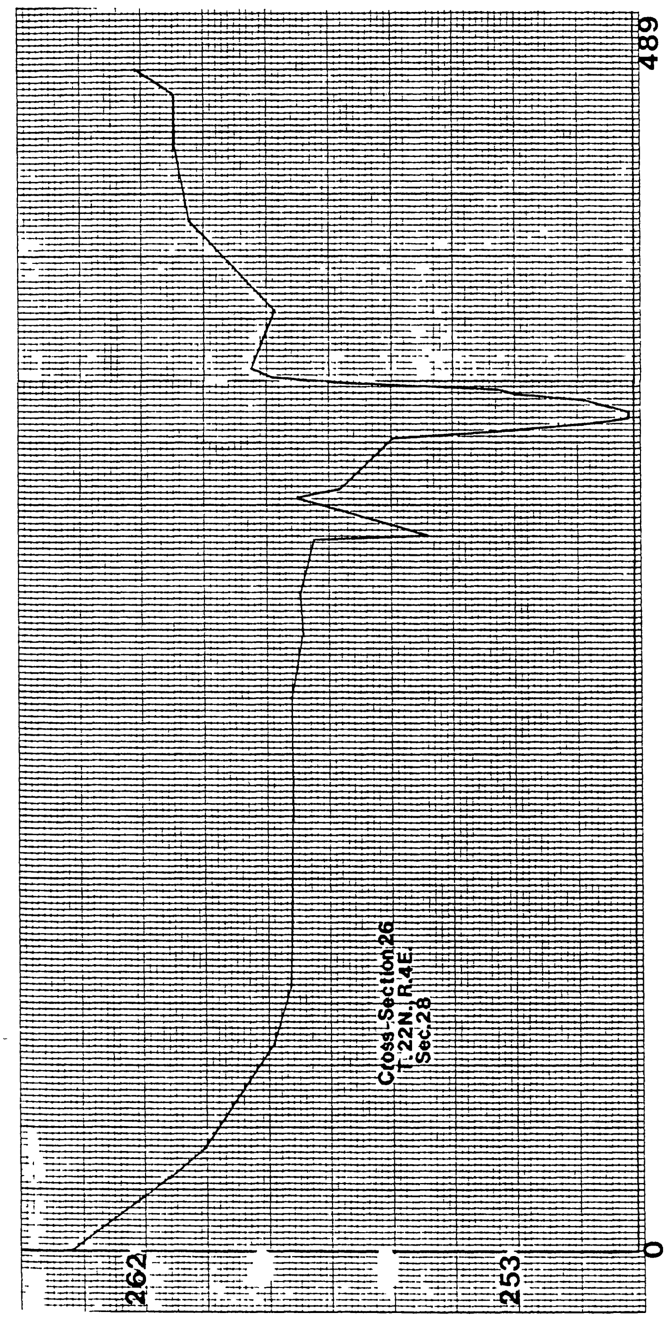

Cross Section 25
T.22N, R.4E.
Sec.28
262
250
0
366


Cross-Section 26
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Sec.28
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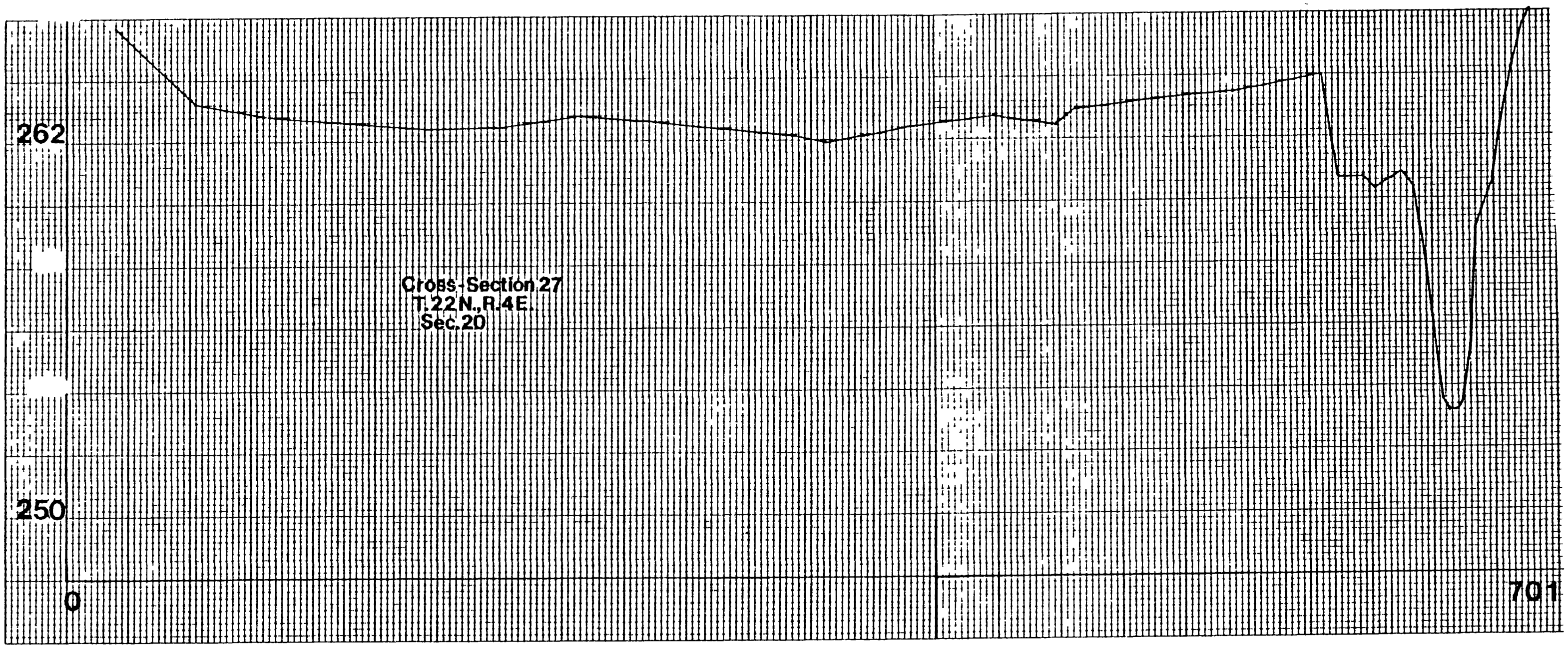
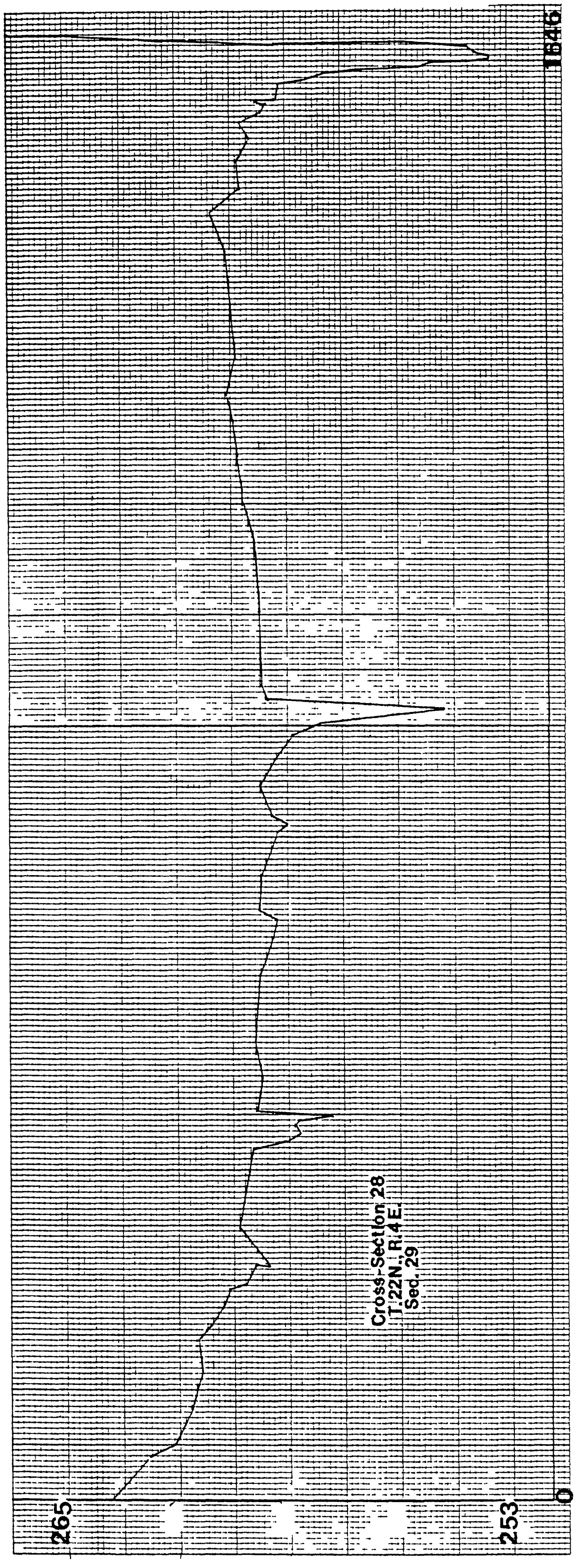
0
262
253


262
250
0
701
Cross-Section 27
T.22N., R.4E.
Sec.20


1646
0
265
253
Cross-Section 28
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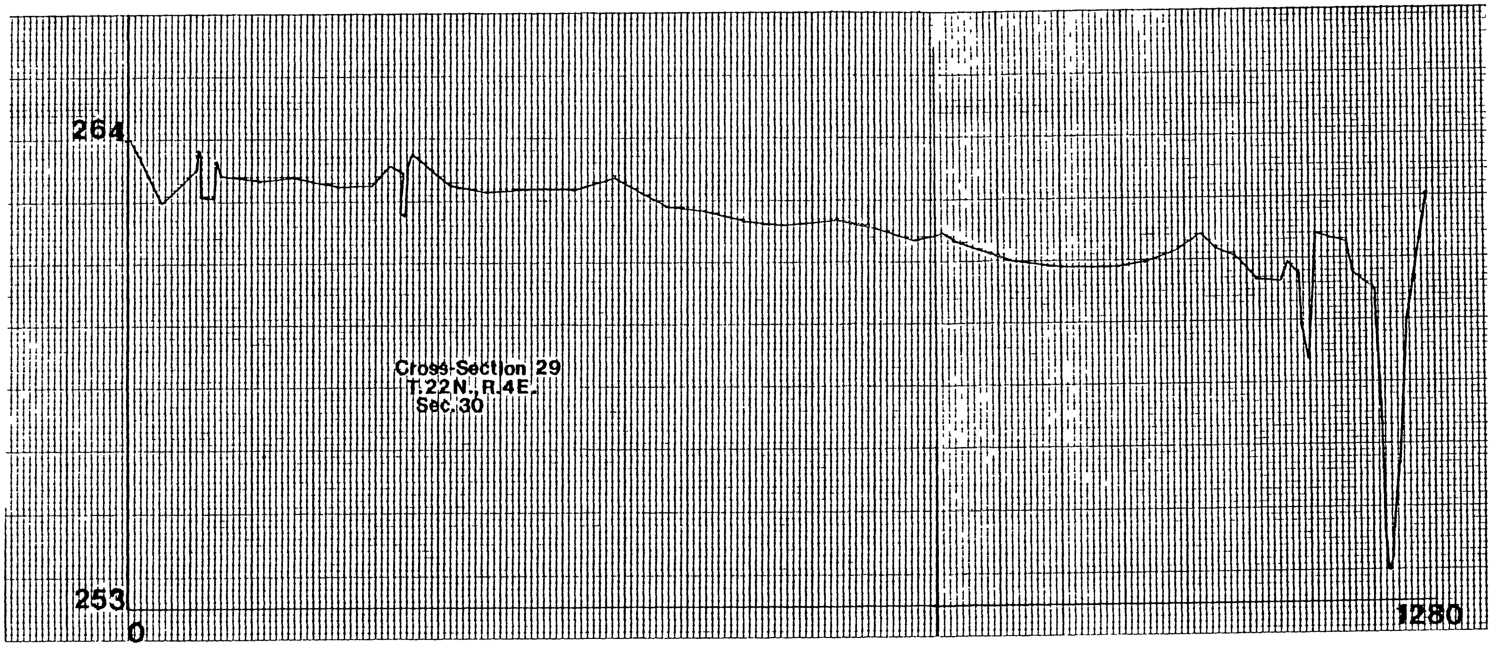
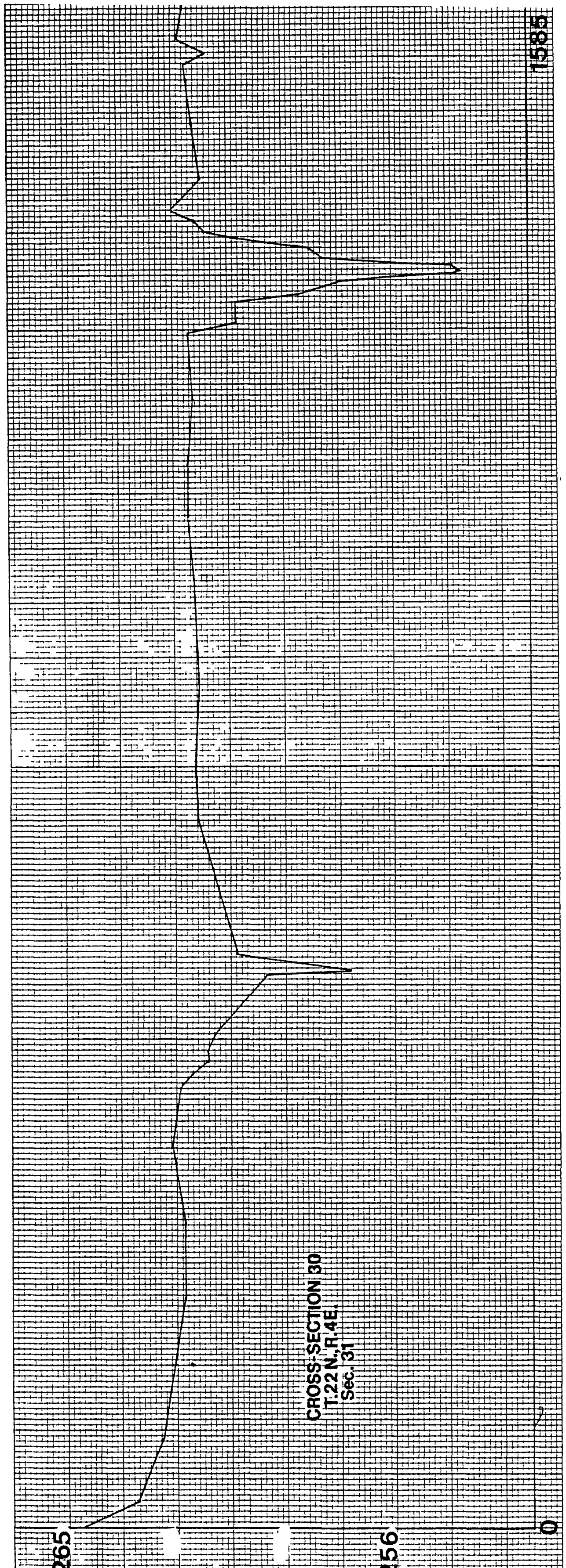
Sec. 29


264
253
0
1280
Cross-Section 29
T.22N., R.4E.
Sec.30


1585
CROSS-SECTION 30
T.22 N.,R.4E.
Sec. 31
265
256
0

APPENDIX E

STATISTICAL EXTENSION OF THE FLOOD FREQUENCY RECORD OF LOWER BLACK BEAR CREEK

RETURN PERIOD CALCULATION FOR CATASTROPHIC FLOODS IN THE RECENT GEOLOGIC PAST

Ellen W. Stevens

ABSTRACT

Return periods for two extraordinary flows in the recent geologic past are estimated by extrapolation beyond a distribution fit to a modern gage record, by fitting the censored sample to a three parameter lognormal distribution, by weighted moments, and by plotting positions. Approximate 90 percent confidence intervals for the return periods calculated using the three parameter lognormal distribution are derived. The effect on the return period of the unknown censoring threshold and record length are investigated. Suggestions for assessing the reasonableness of the results are made.

INTRODUCTION

The objective of this study is to examine ways to use a short, modern systematic record to determine the return period of extraordinary events in the recent geological past. The magnitude and time of these events were determined through geological investigation. Several methods of using historical or paleoflood data along with systematic gage records to improve frequency estimates have been proposed. The primary objective of these methods is to use the historical data to improve the estimate of a return period flow (for instance Q_{100}), which might be used for design purposes.

This paper presents ways of adapting these methods to estimating return periods for the extraordinary events and some criteria for evaluating the results.

BACKGROUND

Description of Problem

The study area is the lower portion of the Black Bear Creek watershed. Figure 1 shows the study area. There is a streamflow gage at Pawnee, and a 45 year record of annual peak flows is available. Investigation of slack water deposits on two tributaries to Black Bear Creek revealed that floods estimated to be 11044 m^3/sec (390,000 cfs) and 5805 m^3/sec (205,000 cfs) took place in 800 CE and 1640 BCE respectively.

It is recognized that the estimates of these flows and dates may lack precision. For purposes of the return period determination, a flow of 11044 m^3/sec (390,000 cfs) in the year 800 CE and a flow of and 5805 m^3/sec (205,000 cfs) in the year 1640 BCE will be considered to be accurately determined.

Literature Search

The incorporation of historic flow data into modern systematic records has been investigated by several researchers. Leese (1971) derived maximum likelihood estimators of the parameters of a Gumbel distribution based the theory of censored samples.

Condie and Lee (1982) presented a procedure for computing the maximum likelihood estimators of the parameters of a three parameter lognormal distribution. Condie (1986) described a means of finding the standard error of the estimate of a T-year flood which was estimated based on current and historical records. Cohn and Stedinger (1986, 1987) evaluated the inclusion of historical data on the basis of gains in terms of effective record length and resulting improvement in estimating the T-year flood Hirsch (1987) and Zhang (1982) presented plotting position formulas adapted to include historical information.

U. S. Water Resources Council Bulletin 17B describes a method for adjusting the moments of log Pearson Type III distribution to include historical information. Bulletin 17B also includes a revised plotting position formula.

METHODS OF ASSIGNING RETURN PERIODS TO EXTRAORDINARY EVENTS

EXCEEDANCE PROBABILITIES BASED ON SYSTEMATIC RECORD

The systematic record can be fit with a probability distribution function (PDF), from which a cumulative distribution function (CDF) can be derived. Several distributions have been found to describe flow frequencies fairly well. These include the normal, lognormal, log Pearson Type III, extreme value type III distributions. The log Pearson and lognormal distributions are particularly suitable for flows because they will never estimate negative values for the high frequency flows.

Accurate assignment of return periods beyond the period covered by the systematic record requires that the distribution selected truly represents the population and that the sample (flow record) from which the distribution parameters were estimated is a representative sample. Goodness of fit tests, such as the Chi-Square and Kolmogorov-Smirnov tests, can be used to determine if the selected distribution fits the data, but these are weak tests. It is difficult to determine how adequately a selected distribution and estimated parameters describe the population.

The problem is increased when extreme events in the tail of the distribution are under consideration. A small difference between the derived CDF and the true population CDF can make a significant difference in a calculated return flow. Figure 2 is an example of this. Both the CDFs appear to be a good fit to the data, but return periods for the same flow can differ by an order of magnitude.

Using a relatively short systematic record to predict return periods for extraordinary flows would not be expected to have particularly reliable results. This method was used as part of this study for comparison purposes.

DISTRIBUTIONS BASED ON CENSORED SAMPLES

Type I and Type II Censored Samples

A systematic flow record with one or more historical flows which are not fully defined can be considered a censored sample Here, fully defined means that the year and magnitude of the flood are known.

In a Type I censored sample, the threshold above or below which the sample was censored is known (or previously determined before starting some sort of test) and the number of fully defined sample members is a random variable. An example of this type of sample is a record of high water marks and dates of out of bank flows. It is assumed that out of bank flows were noteworthy, and therefore recorded. The censoring threshold is bank full discharge, and is a known quantity.

In a Type II censored sample, the number of fully defined sample members is known and the sample threshold is a random variable. A flow record with one or more extreme events which are fully defined and a short systematic record would be considered a Type II censored sample if the extreme events were so extreme that it can be assumed there were no larger flows between their time and the start of the systematic record. Here, the number of years between the extreme flows, and between the most recent extreme flow and the start of the systematic record are known The magnitude of the lesser of the extreme flows represents an upper bound of the censoring threshold, and the largest flow in the systematic record represents a lower bound of this threshold.

Maximum Likelihood Estimators

Given a random sample $(X_1,...X_n)$ from a population with PDF $f(x;\Theta)$, the likelihood function of the parameters of the distribution is

$$L(\Theta)=\prod_{i=1}^{n} f(x_i) \tag{1}$$

where Θ represents the vector of distribution parameters. This likelihood function represents the probability that a sample of size n from the population will contain these specific members. If this sample is assumed to be representative of the population, the best estimate of Θ will be one which maximizes the probability of obtaining this sample. This estimate of Θ can be obtained by maximizing this likelihood function.

Given a censored sample with n fully defined members and k additional members below the threshold x_c, the likelihood function becomes

$$\left[\frac{(n+k)!}{k!}\right] [F(x_c)]^k \prod_{i=1}^{n} f(x_i, \Theta) \tag{2}$$

This is based on the distribution of the first n order statistics of a population of size n+k. This function can be maximized by taking partial derivatives with respect to the parameters and setting them equal to zero.

Condie and Lee (1982) recommend the three parameter lognormal distribution to represent the population and derived maximum likelihood estimators for the three parameters. Stedinger and Cohn (1986) derived maximum likelihood estimators for the two parameter lognormal distribution. Estimators for the three parameter distribution will be described here. The PDF of the three parameter lognormal distribution is

$$f(x;\alpha,\mu,\sigma)=[2\pi\sigma^2(x-\alpha)^2]^{-\frac{1}{2}}\exp\left[-\frac{1}{2\sigma^2}[\ln(x-\alpha)-\mu]^2\right] \tag{3}$$

In general, the computation of derivatives and maxima is simplified by first taking the logarithm of the likelihood function. Since the logarithm is a one to one and increasing function, maximizing $\ln L(\Theta)$ will also maximize $L(\Theta)$. Taking the partial derivatives $\partial/\partial\alpha$, $\partial/\partial\mu$, and $\partial/\partial\sigma$ and rearranging gives the following equations which must be solved simultaneously for α, μ, and σ.

$$\left[\sum z_i-\frac{kf(z_c)}{F(z_c)}\right]/\sigma=0 \tag{4}$$

$$\left[-n+\sum z_i^2-\frac{kf(z_c)}{F(z_c)}\right]/\sigma=0 \tag{5}$$

$$\sigma\sum 1/(x_i-\alpha)+\sum z_i/(x_i-\alpha)-kf(z_c)/[(x_c-\alpha)F(z_c)]=0 \tag{6}$$

The calculated α, μ, and σ can be substituted into equation 3 and this distribution can be used to make inferences about the population.

METHOD OF WEIGHTED MOMENTS

U.S. Water Resources Council Bulletin 17B proposes a method of using historical data and a systematic flow record to estimate the parameters of a log Pearson Type III distribution.

The extraordinary events are given a weight of 1.0 and the data in the systematic record is weighted based on the assumption that it is representative of the years for which the flows are not fully defined. This is a much stronger assumption than the assumption made in the censored sample procedure. All that was assumed then was that the remaining flows were less than a threshold flow.

The moment estimators given for including the historical flows are analogous the estimators given for use with a record without historical data. The weighing factor W is calculated as:

$$W=\frac{H-Z}{N+L} \tag{7}$$

where H = number of years in historic period
Z = number of extraordinary events
N = number of years in systematic record
L = number of low values to be excluded

The adjusted log mean is given by the formula

$$M=\frac{W\Sigma X+\Sigma X_z}{H-WL} \tag{8}$$

where ΣX = sum of the common logs of the flows in the systematic record
ΣX_z = sum of the logs of the extraordinary flows

This is analogous to the log mean used with a systematic record only. The formula for that is $M=\Sigma X/N$ As H approaches N and if L is small, the adjusted mean will approach the unadjusted mean.

The adjusted sample standard deviation is calculated as

$$S^2=\frac{W\Sigma\,(X-M)^2-\Sigma\,(X_z-M)^2}{(H-WL-1)} \tag{9}$$

where M is the previously computed adjusted log mean. The unadjusted sample standard deviation is given by

$$S=[\frac{\Sigma\,(X-\overline{X})^2}{(N-1)}]^{0.5} \tag{10}$$

The adjusted standard deviation will approach this value as N approaches H and if L is small

The adjusted skew coefficient is estimated with the equation

$$G=\frac{H-WL}{(H-WL-1)\,(H-WL-2)}\,[\frac{W\Sigma\,(X-M)^3+\Sigma\,(X_z-M)^3}{S^3}] \tag{11}$$

This, too, is analogous to the skew coefficient in the unadjusted form.

The adjusted moments are substituted for the unadjusted moments and the flow frequencies are calculated in exactly the same manner. K values, corresponding to probabilities, are selected from the Tables in

Appendix 3. The flows corresponding to the probabilities are computed as

$$\log Q = M + KS \qquad (12)$$

The Bulletin also suggests an adjusted plotting position formula.

PLOTTING POSITION METHODS

Hirsch (1987) and Zhang (1982) suggested plotting position formulas for including historical information with systematic records.

Hirsch presents two formulas. Both are based on the assumption that a threshold exists, and that the historical floods are over the threshold, while all other flows in the period between the systematic record and the historical flows are lower than the threshold flows.

He points out that the threshold quantity is an estimate, and that the time spanned by the historical and systematic record flows is only a lower bound estimate of the actual record length.

One formula is based on the traditional formula

$$p_i = \frac{i-a}{n+1-2a} \qquad (13)$$

where i = rank of the flow, with flows arranged in descending order
n = number of flows
a = a constant

With a=0, this is the Weibull formula, a=0.44 gives the Gringorten formula, and a=0.5 gives the Hazen formula This will be the case for the a's in the remainder of the formulas presented.

The traditional formula was modified to include two formulas which were derived based on the assumption that the k largest floods are ranked in the total (n year) record, and the systematic record flows are ranked in a shorter (s year) period. The modified formulas are

$$p = \frac{i-a}{n+1-2a}, \qquad i=1,\ldots,k \qquad (14a)$$

$$p = \frac{k-a}{n+1-2a} + \frac{n-a+1-k}{n+1-2a} \times \frac{i-k-a}{s-e+1-2a} \qquad i=k+1,\ldots,g \qquad (14b)$$

where k = number of extraordinary events
s = length of the systematic record
e = number of extraordinary events included within the systematic record

Hirsch proposed another formula based on the maximum likelihood estimator of p_e, which is the probability that the threshold flow will be equalled or exceeded in any given year. The maximum likelihood estimator for p_e is k/n. The unbiased estimates of p_i are then

$$p_i = \frac{i}{k+1} p_e, \qquad i=1,\ldots,k \qquad (15a)$$

$$p_i = p_e + (1-p_e)\frac{i-k}{(s-e+1)}, \qquad i=k+1,\ldots,g \tag{15b}$$

These equations can be modified to create Weibull, Gringorten, and Hazen type formulas by inclusion of the a terms as follows:

$$p_i = \frac{i-a}{k+1-2a}\frac{k}{n}, \qquad i=1,\ldots,k \tag{16a}$$

$$p_i = \frac{k}{n} + \frac{n-k}{n}\frac{(i-k-a)}{(s-e+1-2a)}, \qquad i=k+1,\ldots,g \tag{16b}$$

APPLICATION OF METHODS

EXCEEDANCE PROBABILITIES BASED ON SYSTEMATIC RECORD

Figures 3 and 4 show lognormal and log Pearson Type III distributions fit to the 45 years of systematic record. Both of these distributions appear to fit the data well. The three parameter lognormal was chosen for use in this study because maximum likelihood estimators for the parameters are more mathematically tractable, and because the results can be compared to the three parameter lognormal distribution based on the censored sample.

The PDF for the three parameter lognormal distribution is

$$f(x;\alpha,\mu,\sigma) = [2\pi(x-\alpha)^2\sigma^2]^{-\frac{1}{2}}\exp[-\frac{1}{2\sigma^2}[\ln(x-\alpha)-\mu]^2] \tag{17}$$

The likelihood function $L(x;\alpha,\mu,\sigma)$ is

$$L(\alpha,\mu,\sigma) = [\prod_{i=1}^{n}(x_i-\alpha)]^{-1}[2\pi\sigma^2]^{-\frac{n}{2}}\exp[-\frac{1}{2\sigma^2}[\sum_{i=1}^{n}[\ln(x_i-\alpha)]^2-2\mu\sum_{i=1}^{n}\ln(x_i-\alpha)+n\mu^2] \tag{18}$$

Taking the logarithms of both sides gives

$$lnL(\alpha,\mu,\sigma) = -\Sigma\ln(x_i-\alpha)-\frac{n}{2}[\ln 2\pi+\ln\sigma^2]-\frac{1}{2\sigma^2}[\Sigma[\ln(x_i-\alpha)]^2-2\mu\Sigma\ln(x_i-\alpha)+n\mu^2] \tag{19}$$

Summations are over n, the number of fully defined flows. This is maximized by taking the partial derivatives $\partial/\partial\alpha$, $\partial/\partial\mu$, and $\partial/\partial\sigma$.

$$\frac{\partial lnL(\alpha,\mu,\sigma)}{\partial\alpha} = -[\frac{\mu}{\sigma^2}-1]\sum[\frac{1}{(x_i-\alpha)}]+\frac{1}{\sigma^2}\sum[\frac{\ln(x_i-\alpha)}{x_i-\alpha}]=0 \tag{20}$$

$$\frac{\partial lnL(\alpha,\mu,\sigma)}{\partial\mu}=-\frac{1}{\sigma^2}[-\Sigma\ln(x_i-\alpha)+n\mu)=0 \quad (21)$$

$$\frac{\partial lnL(\alpha,\mu,\sigma)}{\partial\sigma^2}=-\frac{n}{2}[\frac{1}{\sigma^2}]+\frac{\Sigma[\ln(x_i-\alpha)]^2}{2(\sigma^2)^2}-\frac{\mu\Sigma\ln(x_i-\alpha)}{(\sigma^2)^2}+\frac{n\mu^2}{2(\sigma^2)^2}=0 \quad (22)$$

An expression for μ can be obtained from $\partial/\partial\mu$,

$$\mu=\frac{1}{n}\Sigma\ln(x_i-\alpha) \quad (23)$$

and then from $\partial/\partial\sigma^2$, an expression for σ can be derived.

$$\sigma^2=\frac{\Sigma[\ln(x_i-\alpha)]^2}{n}-\frac{2\mu}{n}\Sigma\ln(x_i-\alpha)+\mu^2 \quad (24)$$

These equations are solved by first estimating α (about 10 percent less than the lowest flow in the record is a good starting estimate), using that estimate to determine μ, and then those two estimates to solve for σ. The estimates are checked by substituting their values into $\partial/\partial\alpha$ and adjusting α until that equation is within an acceptable tolerance of being equal to zero.

A numerical search procedure was used to solve the equations and resulted in the following estimated parameters·

α = 500
μ = 8.2696
σ^2 = 0.7515

The three parameter lognormal distribution can not be solved explicitly for cumulative probabilities The following equation can be used to find the probability associated with a given flow.

$$x_p=\alpha+\exp(\mu-z_p\sigma) \quad (25)$$

x_p is the flow, in cfs, which corresponds to an area under the PDF equal to p (between zero and one), as shown in Figure 5. z_p is the standard normal deviate associated with that probability. The equation can be solved for z_p, and standard normal distribution tables can be consulted to determine the probability corresponding to z_p.

The probability that flow x will be equalled or exceeded in any given year is 1-p = p_e. The return period is then computed as $1/p_e$.

Table 1 gives the probabilities, exceedance probabilities, and return periods of the flows in the systematic record and of the extraordinary flows calculated in this manner. Figure 6 is a plot of the data and the distribution.

FITTING THREE PARAMETER LOGNORMAL DISTRIBUTION TO CENSORED SAMPLE

Equations (4), (5), and (6) can be solved for α, μ, and σ by an iterative procedure. An estimate for α is selected, usually approximately 10 percent lower than the lowest data point. With this estimate, μ can be calculated as

$$\mu = \frac{num}{den} \qquad (26)$$

where

$$num = \frac{n\Sigma\ln(x_i-\alpha)}{(x_c-\alpha)\Sigma 1/(x_c-\alpha)} - \frac{n\Sigma(x_i-\alpha)/(x_i-\alpha)}{\Sigma 1/(x_i=\alpha)} - \Sigma[\ln(x_i-\alpha)]^2 + \ln(x_c-\alpha)\Sigma\ln(x_i-\alpha) \qquad (27)$$

and

$$den = -n - \Sigma\ln(x_i-\alpha) + n\ln(x_c-\alpha) + n^2/[(x_c-\alpha)\Sigma 1/(x_i-\alpha)] \qquad (28)$$

Summations are done over the n fully defined flows. x_c is the threshold value, which is estimated as the lowest of the extraordinary flows. z_i and z_c are the normalized x_i and x_c values, which are computed as

$$z_i = [\ln(x_i-\alpha) - \mu]/\sigma \qquad (29)$$

The estimates of α and μ are used to estimate σ^2 as follows:

$$\sigma^2 = \frac{1}{n}[\Sigma[\ln(x_i-\alpha)]^2 - \mu\Sigma\ln(x_i-\alpha) + \mu n\ln(x_c-\alpha) - \ln(x_c-\alpha)\Sigma\ln(x_i-\alpha)] \qquad (30)$$

The estimates are checked by substituting their values into

$$[z_i - kf(z_c)/F(z_c)]/\sigma = 0 \qquad (31)$$

Different values of α are tried until this equation is equal to zero within an acceptable tolerance.

Using the 45 flows in the record, the two extraordinary flows, n=47, and k=3600, the parameters were computed as

α = 729
μ = 8.225
σ = 1.15

These parameters were calculated based on flows in units of cfs.

The return period calculations are done as described in the procedure for fitting a distribution to the systematic record and extrapolating. Table 2 summarizes the probabilities and return periods of the flows in the systematic record and of the two extraordinary flows. Figure 7 is a plot of the data and the distribution

METHOD OF WEIGHTED MOMENTS

The method of weighted moments presented in U.S. Water Resources Council Bulletin 17B was applied to the data to determine the parameters of a log Pearson Type III distribution.

From Eq. 7, the weighing factor was determined to be 79.96. The calculated log mean and sample standard deviation were found to be 3.65 and 0.326 respectively. The skew coefficient, G, was 0.42. These parameters are based on flows expressed as cfs.

Discharges in units of cfs corresponding to probabilities between .001 and .9999 were calculated using the formula

$$\log Q = M + KS \tag{32}$$

The K values were obtained from the table in Appendix 3 of the Bulletin. The discharges obtained did not cover the necessary range, so additional K's corresponding to lower probabilities were estimated using Eq. 3-1

$$K=\frac{2}{G}\left[\left[\left(K_n-\frac{G}{6}\right)\frac{G}{6}+1\right]^3-1\right] \tag{33}$$

where G = skew coefficient
K_n = Standard normal deviate corresponding to the desired probability

The K_n values corresponding to p=.00005, .00001, and .000005 were substituted into the equation, and the distribution was extended to cover the extraordinary events.

The equation for log Q can be solved for K, so K values for the extraordinary flows can also be determined. Eq. 33 can then be solved for the value of K_n and the corresponding probability determined. This was done for the two extraordinary flows with the following results:

FLOW m^3/sec	K	K_n	Exc.Prob	Ret.Pd years
5805	5.097	4.089	.000022	45,455
11044	5.954	4.615	.000002	500,000

The Bulletin stresses that the formula yields approximations for K, and that use of the tables instead is recommended. The formula has the further restriction that $-1 \le G \le 1$, which is met in this case.

Bulletin 17B also proposes a plotting position formula, which is a modification of the Weibull-Gringorten-Hazen type formulas. The plotting position is computed as

$$PP=\frac{m-a}{H+1-2a}\times 100 \tag{34}$$

where m is the event number, E (ranked in descending order) if $1 \le E \le Z$. Z is the number of extraordinary events. If E is between Z+1 and (Z+N+L), where N is the number of flows in the systematic record and L is the number of low values to be excluded, then

$$m = WE - (W - 1)(Z + 0.5) \tag{35}$$

Table 3 summarizes the probabilities and return periods obtained by fitting the log Pearson Type III distribution. Table 4 gives the plotting positions for the flows in the systematic record and the extraordinary flows Figure 8 shows the fitted distribution and the plotting positions.

PLOTTING POSITIONS BY HIRSCH METHOD

Plotting positions were calculated using the modified Weibull formula and the formula based on the maximum likelihood estimator for p_e, the exceedance probability of the threshold flow.

Equations 14 and 16 were used and Table 5 summarizes the results. Since Hirsch felt that the total records length could be a critical factor, and pointed out that the time spanned by the current record and the extraordinary events was only a lower bound of that record length, an arbitrary extension of 1800 years (the approximate time between the extraordinary events was added to the number of years in the record, and the calculations repeated. Table 5 also gives these results. Figures 9 and 10 show the Weibull type and maximum likelihood results. Figure 11 shows a comparison between n=3600 and n=5400.

DISCUSSION OF RESULTS

As expected, the application of several different methods will yield several different results. The following table summarizes the return periods calculated based on the different methods.

METHOD	Q=11,044 m^3/sec	Q=5805 m^3/sec
Extrapolation	18,180,919	402,064
Censored Sample	37,549	3,991
Adjusted Moments		
Log Pearson	500,000	45,456
Plotting Positions	3,601	1,801
Plotting Positions		
MLE Eq, N=3600	5,405	2,703
MLE Eq, N=5400	8,130	4,048
Weibull Type, N=3600	3,597	1,801
Weibull Type, N=5400	5,405	2,703

The results obtained by extrapolation do not appear at all reasonable, and were not expected to be. The probability of a T-year flood occurring in an N year period is $1-(1-1/T)^N$. The probabilities of an 18 million year flow and of a 402,064 year flow occurring in the past 3600 years are 0.0002 and 0.009 respectively. Similarly, the results obtained with the method of adjusted moments do not appear reasonable either. Condie and Lee (1982) concluded that estimates of the T-year flow derived with the adjusted moment procedure had more bias and variability than did estimates derived from censored sample estimators.

The plotting position results agree reasonably well with the censored sample results for the 5805 m^3/sec flow. There is not good agreement for the 11044 m^3/sec flow. Agreement is not necessarily expected, since the plotting positions only consider the rank of the flow and the distribution accounts for rank and magnitude.

The procedure presented by Condie (1986) was used to derive 90 percent confidence intervals for the return periods. The effect of changing the threshold level, which could be anywhere between the smaller of the extraordinary flows and the largest flow in the systematic record, was also investigated. Since Hirsch stressed the importance of accurately determining the record length, the effect of longer record lengths was also evaluated.

There are other possible means of assessing results which were not done as part of this study. For instance, the largest flow in the gage record is approximately 30,000 cfs. Considering just the gage record, this is estimated to be approximately a 100 year flow. If the population is assumed to follow the three parameter lognormal distribution estimated based on the censored sample procedure, this flow is a 28 year flow. The elevation of the water surface is either known or can be estimated. It may be possible to get information from long time residents, local newspapers, or other sources of local information to establish whether or not a flow of this magnitude occurred in the sixty years prior to the start of the record.

Another possibility is to estimate the amount of rainfall required to produce that amount of runoff and determine if the recurrence interval of the rainfall is close to T years. While a T-year rain does not always cause a T-year flood, there should not be extreme discrepancies between the two.

CONFIDENCE LIMITS BASED ON STANDARD ERROR OF THE ESTIMATE

Given the log likelihood function $lnL(\mu,\sigma,\alpha)$, the elements of the inverse of the variance-covariance matrix are of the form

$$r_{i,j}=-E[\partial^2 lnL/\partial\beta_i\partial\beta_j] \tag{36}$$

where the β_i are the parameters of the distribution. The $r_{i,j}$ values were calculated using formulas presented in Condie (1986) and the inverse of the variance-covariance was found to be

44.83	32.64	.0187
32.64	188.3	-.0424
.0187	-.0424	4.54E-05

The variance-covariance matrix is

	μ	σ	α
μ	0.0194	-0.0013	9.2016
σ	-0.0013	0.0045	-4.7017
α	9.2016	-4.7017	-13837

The variance of the T-year flow, x, is then calculated as

$$\begin{aligned}Var(x) = {} & (\partial x/\partial\mu)^2 var(\mu)+(\partial x/\partial\sigma)^2 var(\sigma)+(\partial x/\partial\alpha)^2 var(\alpha)\\ & +2(\partial x/\partial\mu)(\partial x/\partial\sigma)cov(\mu,\sigma)+2(\partial x/\partial\mu)(\partial x/\partial\alpha)cov(\mu,\alpha)\\ & +2(\partial x/\partial\sigma)(\partial x/\partial\alpha)cov(\sigma,\alpha).\end{aligned} \tag{37}$$

The following results were obtained, using the μ, σ, and α derived with the maximum likelihood estimators and the censored sample.

	T=37549 Q=11044	T=3991 Q=5805
$\partial x/\partial\mu$	389317	204230
$\partial x/\partial\sigma$	1573231	710719
$\partial x/\partial\alpha$	1	1
Var(x)	1.25E+10	2.70E+09
Std. Dev.	111705	51980 (cfs)

The variance of the flow was then used to establish approximate upper and lower 90 percent confidence intervals for the flows. The Q values represent mean values of the T-year flows. These mean values can be assumed to be approximately normally distributed with mean Q and variance Var(x). Since n is not precisely known and is large, a $z_{1-\alpha/2}$ can be used instead of a $t_{1-\alpha/2}$ value. The upper and lower limits on Q are therefore calculated as

$$UL \text{ or } LL = Q \pm z_{1-\alpha/2} \times std(Q) \tag{38}$$

where $z_{1-\alpha/2}$ is $z_{95} = 1.645$ and std(Q) is the standard deviation of Q. The return periods of these upper and lower limits of flow can be calculated from the three parameter lognormal distribution, as demonstrated previously, giving upper and lower limits of the return periods of the two extraordinary flows. The 90 percent confidence limits are as follows:

Q		Q	z_p	Prob	Exc.Prob	Ret.Pd
5805	UL	8226	3.784	0.999923	0.000077	12987
	LL	3383	3.009	0.998689	0.001311	763
11044	UL	16247	4 377	0.999994	0.000006	166667
	LL	5840	3.485	0.999754	0.000246	4065

These are wide ranges, which demonstrates the high level of uncertainty encountered when making inferences far out in the tail of a distribution.

EFFECT OF CHANGE IN THRESHOLD VALUE

With a Type II censored sample, the threshold level, x_c is a random variable which can have values between the magnitude of the largest flow in the systematic record and the magnitude of the smallest of the extraordinary events. This threshold value is used in the maximum likelihood estimate procedure, which is derived based on the assumption that all the remaining non-extraordinary flows in the n year total record are below this threshold.

Due to the type of investigation done, it is known that all the flows between the present and the year 800 were smaller than 5805 m³/sec (205,000 cfs). Otherwise, the sediment investigation would have uncovered a deposition layer overlaying the one that was analyzed and dated Similarly, there would have been slack water deposit material overlaying the deposit identified and dated to 1640 BCE had there been a larger flow between then and the present.

It is possible, however, that the remaining flows in the record are all below a threshold value that is lower than 5805 m³/sec (205,000 cfs). To investigate the effect of lower threshold on the return period, maximum likelihood estimators were computed for threshold values between 35,000 and 205,000 cfs, and the resulting return periods for Q=11044 m³/sec (390,000 cfs) and Q=5805 m³/sec (205,000 cfs) were calculated The results are shown in Table 6 and Figure 12. The figure shows that lowering the threshold by up to 50,000 cfs does not have a profound effect on the return period.

EFFECT OF CHANGE IN RECORD LENGTH

Hirsch (1987) pointed out that the number of years between the earliest historical flood and the present only represents a lower bound of the actual number of flows with magnitude under the threshold value He felt that using this lower bound would result in biased probabilities and biased T-year flows

The effect of using the lower bound estimate on the calculated return periods was investigated by estimating the distribution parameters based on record lengths between 3600 years and 10600 years The results are shown in Table 7 and Figure 13. Lengthening the record up to 3000 years longer did not cause extreme changes in the return period.

SUMMARY AND CONCLUSIONS

The two extraordinary events were assigned return periods using a variety of methods, with significantly different results. The results based on extrapolation and adjusted moments are obviously unreasonable

The results obtained from fitting a three parameter lognormal distribution to a Type II censored sample appear to be reasonable. Return periods of 37549 years and 3991 years were assigned to the 11044 m³/sec (390,000 cfs) and 5805 m³/sec (205,000 cfs) flows respectively A 37549-year flow has a 9 percent probability of occurring in a 3600 year time period, and a 3991-year flow has a 59 percent chance of occurring

The plotting position results also appeared to be reasonable It should be noted, however, that return periods based on a plotting position are not a function of the magnitude of the flow. For example, if the largest flow was 50,000 m^3/sec instead of 11044 m^3/sec, it would still be assigned the same return period. This is obviously unreasonable, and points out the problem of using plotting positions to determine return periods.

The standard deviations of the 37549- and 3991-year flows were computed and used to establish approximate 90 percent confidence intervals for the return periods. These intervals were quite wide, as would be expected when working far out in the tail of the distribution.

The effect of using different thresholds and different record lengths was investigated. It was found that changes less than 50,000 cfs and 3000 years did not have a profound effect on the results.

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Table 1. Probabilities and Return Periods - Distribution Fit to Systematic Record

Year	Flow m^3/sec	z_p	Prob.	Exc.Prob	Ret.Pd.
800	11043	5.310	1.000000	5.50E-08	18180919
1640BC	5805	4.567	0.999998	0.000002	402064
1960	855	2.341	0.990381	0.009619	104
1987	467	1.627	0.948168	0.051832	19.3
1975	453	1.591	0.944164	0.055836	17.9
1945	450	1.583	0.943318	0.056682	17.6
1946	326	1.195	0.883980	0.116020	8.62
1974	323	1.185	0.881909	0.118091	8.47
1957	314	1.152	0.875420	0.124580	8.03
1961	311	1.141	0.873160	0.126840	7.88
1947	248	0.865	0.806389	0.193611	5.17
1955	229	0.766	0.778032	0.221968	4.51
1962	227	0.753	0.774373	0.225627	4.43
1986	202	0.613	0.730007	0.269993	3.70
1959	185	0.504	0.692724	0.307276	3.25
1985	178	0.451	0.673945	0.326055	3.07
1980	158	0.306	0.620268	0.379732	2.63
1973	150	0.239	0.594260	0.405740	2.46
1988	149	0.231	0.591453	0.408547	2.45
1956	148	0.222	0.587676	0.412324	2.43
1982	143	0.177	0.570174	0.429826	2.33
1977	127	0.028	0.511250	0.488750	2.05
1983	127	0.022	0.508944	0.491056	2.04
1949	123	-0.013	0.494858	0.505142	1.98
1984	122	-0.028	0.488859	0.511141	1.96
1952	112	-0.139	0.444693	0.555307	1.80
1969	107	-0.201	0.420463	0.579537	1.73
1950	103	-0.247	0.402315	0.597685	1.67
1951	100	-0.288	0.386536	0.613464	1.63
1963	87	-0.478	0.316460	0.683540	1.46
1989	85	-0.519	0.302027	0.697973	1.43
1966	82	-0.571	0.284102	0.715898	1.40
1948	78	-0.641	0.260882	0.739118	1.35
1968	77	-0.646	0.259208	0.740792	1.35
1979	71	-0.777	0.218538	0.781462	1.28
1970	70	-0.789	0.215114	0.784886	1.27
1965	67	-0.843	0.199687	0.800313	1.25
1971	67	-0.843	0.199687	0.800313	1.25
1953	66	-0.868	0.192820	0.807180	1.24
1954	66	-0.868	0.192820	0.807180	1.24
1958	66	-0.868	0.192820	0.807180	1.24
1972	60	-1.022	0.153490	0.846510	1.18
1964	58	-1.065	0.143350	0.856650	1.17
1967	48	-1.370	0.085301	0.914699	1.09
1978	41	-1.630	0.051540	0.948460	1.05
1981	40	-1.692	0.045278	0.954722	1.05
1976	25	-2.666	0.003838	0.996162	1.00

Table 2. Three Parameter Lognormal Distribution Fit to Censored Sample

Year	Flow m^3/sec	z_p	Prob.	Exc.Pr.	Ret. Pd.
800	11043	4.041	0.999973	0.000027	37549
1640BC	5805	3.480	0.999749	0.000251	3991
1960	855	1.797	0.963805	0.036195	27.6
1987	467	1.253	0.894894	0.105106	9.51
1975	453	1.225	0.889706	0.110294	9.07
1945	450	1.219	0.888626	0.111374	8.98
1946	326	0.921	0.821580	0.178420	5.60
1974	323	0.913	0.819455	0.180545	5.54
1957	314	0.888	0.812862	0.187138	5.34
1961	311	0.880	0.810589	0.189411	5.28
1947	248	0.666	0.747340	0.252660	3.96
1955	229	0.589	0.722140	0.277860	3.60
1962	227	0.580	0.718940	0.281060	3.56
1986	202	0.470	0.680906	0.319094	3.13
1959	185	0.385	0.649803	0.350197	2.86
1985	178	0.343	0.634358	0.365642	2.73
1980	158	0.230	0.590785	0.409215	2.44
1973	150	0.176	0.569882	0.430118	2.32
1988	149	0.170	0.567633	0.432367	2.31
1956	148	0.163	0.564605	0.435395	2.30
1982	143	0.127	0.550596	0.449404	2.23
1977	127	0.009	0.503502	0.496498	2.01
1983	127	0.004	0.501657	0.498343	2.01
1949	123	-0.024	0.490382	0.509618	1.96
1984	122	-0.036	0.485573	0.514427	1.94
1952	112	-0.126	0.450020	0.549980	1.82
1969	107	-0.175	0.430363	0.569637	1.76
1950	103	-0.213	0.415539	0.584461	1.71
1951	100	-0.247	0.402574	0.597426	1.67
1963	87	-0.402	0.343809	0.656191	1.52
1989	85	-0.436	0.331407	0.668593	1.50
1966	82	-0.479	0.315827	0.684173	1.46
1948	78	-0.538	0.295316	0.704684	1.42
1968	77	-0.542	0.293823	0.706177	1.42
1979	71	-0.653	0.256765	0.743235	1.35
1970	70	-0.663	0.253572	0.746428	1.34
1965	67	-0.709	0.239026	0.760974	1.31
1971	67	-0.709	0.239026	0.760974	1.31
1953	66	-0.731	0.232460	0.767540	1.30
1954	66	-0.731	0.232460	0.767540	1.30
1958	66	-0.731	0.232460	0.767540	1.30
1972	60	-0.865	0.193596	0.806404	1.24
1964	58	-0.903	0.183170	0.816830	1.22
1967	48	-1.180	0.118996	0.881004	1.14
1978	41	-1.430	0.076377	0.923623	1.08
1981	40	-1.492	0.067801	0.932199	1.07
1976	25	-2.750	0.002981	0.997019	1.00

Table 3. Exceedance Probabilities and Return Periods Calculated from Bulletin 17B Plotting Position Formulas

Year	Rank	Flow m^3/sec	Exc.Prob.	Ret.Pd.
800	1	11045	0.000278	3601
1640BC	2	5806	0.000555	1801
1960	3	855	0.011797	84.8
1987	4	467	0.034002	29.4
1975	5	453	0.056207	17.8
1945	6	450	0.078412	12.8
1946	7	326	0.100616	9.94
1974	8	323	0.122821	8.14
1957	9	314	0.145026	6.90
1961	10	312	0.167231	5.98
1947	11	248	0.189436	5.28
1955	12	229	0.211641	4.72
1962	13	227	0.233846	4.28
1986	14	202	0.256051	3.91
1959	15	185	0.278256	3.59
1985	16	178	0.300461	3.33
1980	17	158	0.322666	3.10
1973	18	150	0.344871	2.90
1988	19	149	0.367076	2.72
1956	20	148	0.389281	2.57
1982	21	143	0.411486	2.43
1977	22	127	0.433691	2.31
1983	23	127	0.455896	2.19
1949	24	123	0.478101	2.09
1984	25	122	0.500305	2.00
1952	26	112	0.522510	1.91
1969	27	107	0.544715	1.84
1950	28	103	0.566920	1.76
1951	29	100	0.589125	1.70
1963	30	87	0.611330	1.64
1989	31	85	0.633535	1.58
1966	32	82	0.655740	1.52
1948	33	78	0.677945	1.48
1968	34	77	0.700150	1.43
1979	35	71	0.722355	1.38
1970	36	70	0.744560	1.34
1965	37	67	0.766765	1.30
1971	38	67	0.788970	1.27
1953	39	66	0.811175	1.23
1954	40	66	0.833380	1.20
1958	41	66	0.855585	1.17
1972	42	60	0.877790	1.14
1964	43	58	0.899994	1.11
1967	44	48	0.922199	1.08
1978	45	41	0.944404	1.06
1981	46	40	0.966609	1.03
1976	47	25	0.988814	1.01

Table 4. Exceedance Probabilities From Log Pearson Type III Distribution Fit by Bulletin 17B Method

Exc.Prob.	K	log Q	Q m^3/sec	Ret.Pd.
0.999900	-2.8991	2.705	14	1.00
0.999500	-2.6539	2.785	17	1.00
0.999000	-2.5326	2.824	19	1.00
0.998000	-2.3994	2.868	21	1.00
0.995000	-2.2009	2.933	24	1.01
0.990000	-2.0293	2.988	28	1.01
0.980000	-1.8336	3.052	32	1.02
0.975000	-1.7463	3.081	34	1.03
0.960000	-1.6057	3.127	38	1.04
0.950000	-1.5236	3.153	40	1.05
0.900000	-1.2311	3.249	50	1.11
0.800000	-0.8551	3.371	67	1.25
0.700000	-0.5687	3.465	83	1.43
0.600000	-0.3136	3.548	100	1.67
0.570400	-0.2404	3.572	106	1.75
0.500000	-0.0665	3.628	120	2.00
0.429600	0.1115	3.686	138	2.33
0.400000	0.1892	3.712	146	2.50
0.300000	0.4723	3.804	180	3.33
0.200000	0.8164	3.916	233	5.00
0.100000	1.3167	4.079	340	10.0
0.050000	1.7505	4.221	471	20.0
0.040000	1.8804	4.263	519	25.0
0.025000	2.1420	4.348	632	40.0
0.020000	2.2613	4.387	691	50.0
0.010000	2.6154	4.503	901	100
0.005000	2.9490	4.611	1157	200
0.002000	3.3657	4.747	1582	500
0.001000	3.6661	4.845	1983	1000
0.000500	3.9561	4.940	2465	2000
0.000100	4.5969	5.149	3987	10000
0.000050	4.9074	5.250	5034	20000
0.000022	5.0970	5.311	5806	45455
0.000010	5.5150	5.448	7943	100000
0.000002	5.9540	5.591	11045	500000

Table 5. Exceedance Probabilities from Formulas in Hirsch Paper

Rank	Year	Flow m^3/sec	Exceedance Probabilities MLE Formula N=3600	MLE Formula N=5400	Modified Weibull N=3600	Modified Weibull N=5400
1	800	11045	0.000185	0.000123	0.000278	0.000185
2	1640BC	5806	0.000370	0.000247	0.000555	0.000370
3	1960	855	0.022283	0.022101	0.022282	0.022101
4	1987	467	0.044010	0.043833	0.044010	0.043832
5	1975	453	0.065737	0.065564	0.065737	0.065564
6	1945	450	0.087464	0.087295	0.087464	0.087295
7	1946	326	0.109191	0.109026	0.109191	0.109026
8	1974	323	0.130918	0.130757	0.130918	0.130757
9	1957	314	0.152645	0.152488	0.152645	0.152488
10	1961	312	0.174372	0.174219	0.174372	0.174219
11	1947	248	0.196099	0.195950	0.196099	0.195950
12	1955	229	0.217826	0.217681	0.217826	0.217681
13	1962	227	0.239553	0.239412	0.239553	0.239412
14	1986	202	0.261280	0.261143	0.261280	0.261143
15	1959	185	0.283007	0.282874	0.283007	0.282874
16	1985	178	0.304734	0.304605	0.304734	0.304605
17	1980	158	0.326461	0.326337	0.326461	0.326337
18	1973	150	0.348188	0.348068	0.348188	0.348068
19	1988	149	0.369915	0.369799	0.369915	0.369799
20	1956	148	0.391643	0.391530	0.391642	0.391530
21	1982	143	0.413370	0.413261	0.413369	0.413261
22	1977	127	0.435097	0.434992	0.435097	0.434992
23	1983	127	0.456824	0.456723	0.456824	0.456723
24	1949	123	0.478551	0.478454	0.478551	0.478454
25	1984	122	0.500278	0.500185	0.500278	0.500185
26	1952	112	0.522005	0.521916	0.522005	0.521916
27	1969	107	0.543732	0.543647	0.543732	0.543647
28	1950	103	0.565459	0.565378	0.565459	0.565378
29	1951	100	0.587186	0.587110	0.587186	0.587109
30	1963	87	0.608913	0.608841	0.608913	0.608841
31	1989	85	0.630640	0.630572	0.630640	0.630572
32	1966	82	0.652367	0.652303	0.652367	0.652303
33	1948	78	0.674094	0.674034	0.674094	0.674034
34	1968	77	0.695821	0.695765	0.695821	0.695765
35	1979	71	0.717548	0.717496	0.717548	0.717496
36	1970	70	0.739275	0.739227	0.739275	0.739227
37	1965	67	0.761002	0.760958	0.761002	0.760958
38	1971	67	0.782729	0.782689	0.782729	0.782689
39	1953	66	0.804457	0.804420	0.804456	0.804420
40	1954	66	0.826184	0.826151	0.826184	0.826151
41	1958	66	0.847911	0.847882	0.847911	0.847882
42	1972	60	0.869638	0.869614	0.869638	0.869614
43	1964	58	0.891365	0.891345	0.891365	0.891345
44	1967	48	0.913092	0.913076	0.913092	0.913076
45	1978	41	0.934819	0.934807	0.934819	0.934807
46	1981	40	0.956546	0.956538	0.956546	0.956538

Table 6. Effect of Changing Threshold

$Q=11044\ m^3/sec$

Threshold m^3/sec	α	μ	σ	z_p	Prob.	Exc.Prob.	Ret.Pd.
5522	726	8.222	1.151	4.041	0.999973	0.000027	37588
5239	723	8.218	1.143	4.073	0.999977	0.000023	43072
4956	720	8.214	1.135	4.105	0.999980	0.000020	49462
4673	716	8.209	1.124	4.147	0.999983	0.000017	59294
4390	712	8.204	1.114	4.189	0.999986	0.000014	71409
4106	707	8.198	1.102	4.242	0.999989	0.000011	90053
3823	702	8.192	1.090	4.296	0.999991	0.000009	114563
3540	697	8.185	1.077	4.351	0.999993	0.000007	147016
3257	691	8.177	1.063	4.417	0.999995	0.000005	199549
2974	684	8.167	1.047	4.496	0.999997	0.000003	287689
2690	676	8.156	1.028	4.587	0.999998	0.000002	444342
2407	668	8.142	1.009	4.687	0.999999	0.000001	719857
2124	659	8.125	0.988	4.807	0.999999	0.000001	1301119
1841	648	8.103	0.961	4.965	1.000000	0.000000	2897046
1558	638	8.073	0.932	5.148	1.000000	0.000000	7580412
1274	629	8.029	0.899	5.390	1.000000	0.000000	28394248
991	627	7.958	0.861	5.706	1.000000	0.000000	1.73E+08

$Q=5805\ m^3/sec$

Threshold m^3/sec	α	μ	σ	z_p	Prob.	Exc.Prob.	Ret.Pd.
5522	726	8.222	1.151	3.481	0.999750	0.000250	4001
5239	723	8.218	1.143	3.509	0.999775	0.000225	4442
4956	720	8.214	1.135	3.537	0.999798	0.000202	4940
4673	716	8.209	1.124	3.574	0.999824	0.000176	5678
4390	712	8.204	1.114	3.611	0.999847	0.000153	6550
4106	707	8.198	1.102	3.657	0.999872	0.000128	7827
3823	702	8.192	1.090	3.704	0.999894	0.000106	9418
3540	697	8.185	1.077	3.752	0.999912	0.000088	11410
3257	691	8.177	1.063	3.811	0.999931	0.000069	14433
2974	684	8.167	1.047	3.880	0.999948	0.000052	19124
2690	676	8.156	1.028	3.960	0.999963	0.000037	26727
2407	668	8.142	1.009	4.048	0.999974	0.000026	38762
2124	659	8.125	0.988	4.154	0.999984	0.000016	61183
1841	648	8.103	0.961	4.294	0.999991	0.000009	113536
1558	638	8.073	0.932	4.457	0.999996	0.000004	239562
1274	629	8.029	0.899	4.673	0.999999	0.000001	671707
991	627	7.958	0.861	4.958	1.000000	0.000000	2795761

Table 7. Effect of Record Length

Q=11044 m^3/sec

Rec.Len. Years	α	μ	σ	z_p	Prob.	Exc.Prob.	Ret.Pd.
4600	723	8.221	1.144	4.065	0.999976	0.000024	41535
5400	719	8.219	1.135	4.100	0.999979	0.000021	48400
6600	714	8.217	1.124	4.144	0.999983	0.000017	58435
7600	710	8.215	1.115	4.178	0.999985	0.000015	67787
8600	707	8.214	1.108	4.203	0.999987	0.000013	75770
9600	704	8.212	1.102	4.228	0.999988	0.000012	84678
10600	701	8.211	1.096	4.252	0.999989	0.000011	94284
15600	689	8.208	1.073	4.347	0.999993	0.000007	144682
20600	680	8.206	1.057	4.415	0.999995	0.000005	197459
25600	673	8.204	1.045	4.466	0.999996	0.000004	250349
30600	667	8.203	1.036	4.509	0.999997	0.000003	306020
35600	662	8.203	1.028	4.544	0.999997	0.000003	360774

Q=5805 m^3/sec

Rec.Len. Years	α	μ	σ	z_p	Prob.	Exc.Prob.	Ret.Pd.
4600	723	8.221	1.144	3.501	0.999768	0.000232	4315
5400	719	8.219	1.135	3.532	0.999794	0.000206	4848
6600	714	8.217	1.124	3.570	0.999821	0.000179	5596
7600	710	8.215	1.115	3.599	0.999840	0.000160	6266
8600	707	8.214	1.108	3.621	0.999853	0.000147	6820
9600	704	8.212	1.102	3.643	0.999865	0.000135	7421
10600	701	8.211	1.096	3.664	0.999876	0.000124	8053
15600	689	8.208	1.073	3.746	0.999910	0.000090	11145
20600	680	8.206	1.057	3.805	0.999929	0.000071	14107
25600	673	8.204	1.045	3.849	0.999941	0.000059	16883
30600	667	8.203	1.036	3.886	0.999949	0.000051	19653
35600	662	8.203	1.028	3.916	0.999955	0.000045	22256

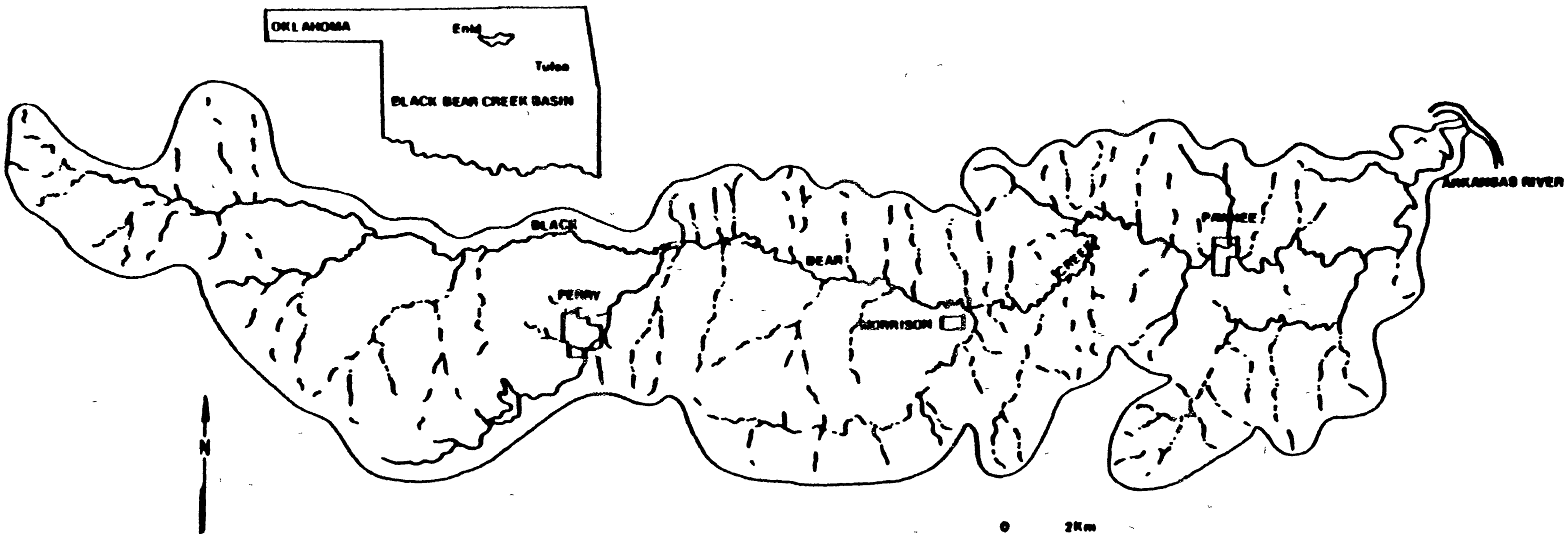

Figure 1. Location map of Black Bear Creek drainage basin and study reach. Numbers indicate tributaries used in study: 1. Turkey Creek; 2. Pepper Creek; 3. Skedee Creek; 4. Camp Creek; 5. Crystal Creek.

Effect of Working in Tail of Distribution

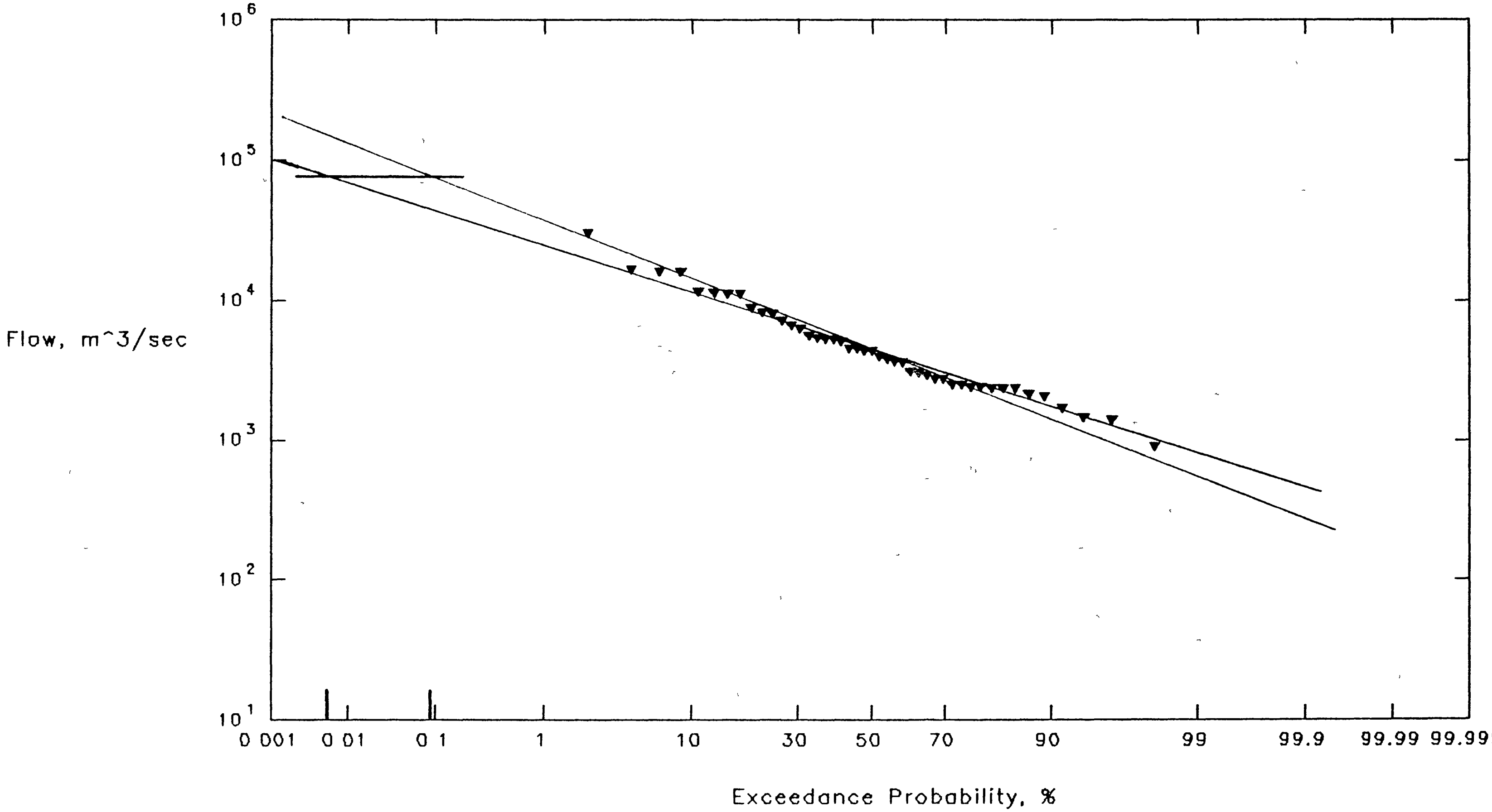

Figure 2

Gage Record Fit to Lognormal Distribution

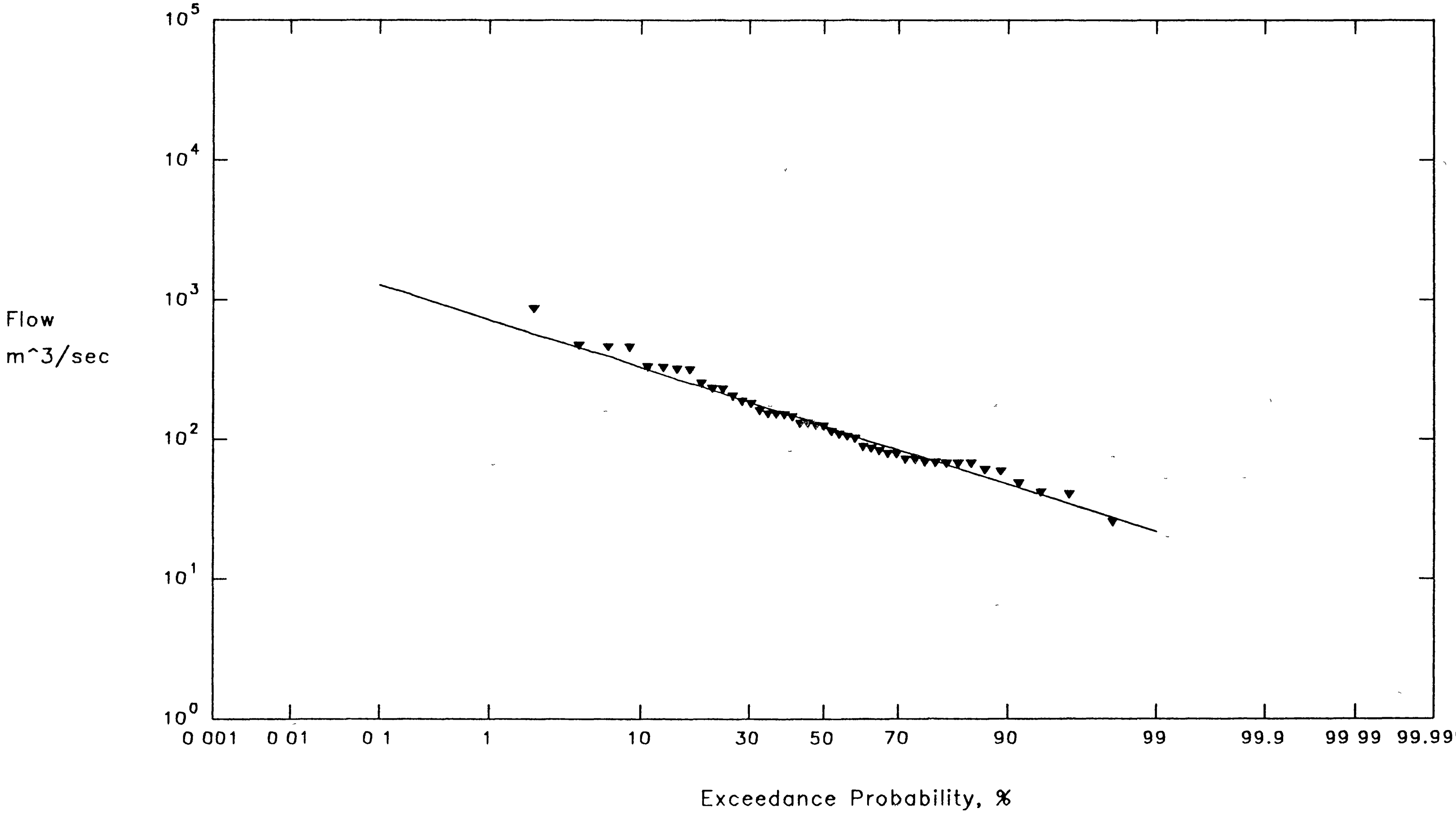

Figure 3

Gage Record Fit to Log Pearson Type III Distribution

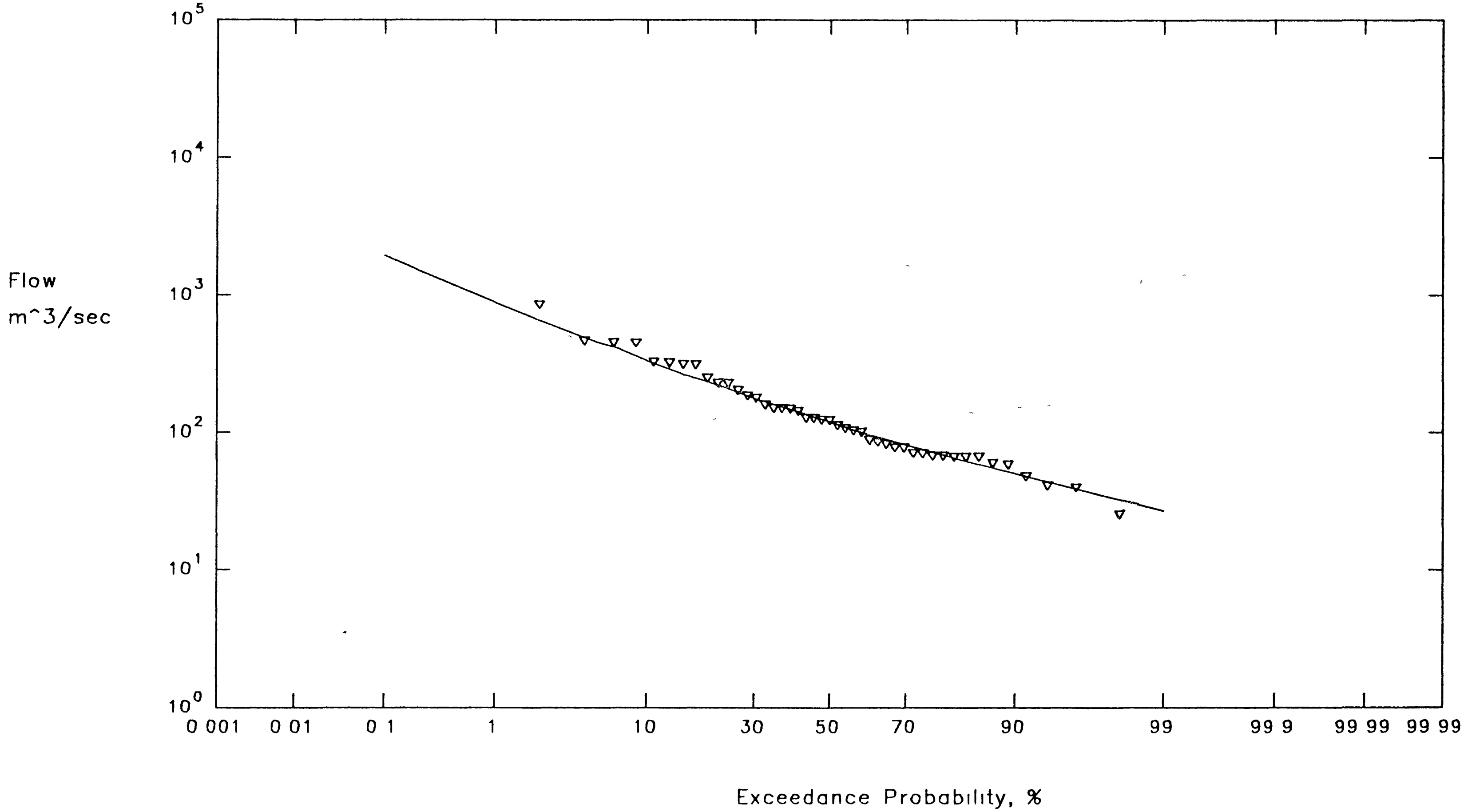

Figure 4

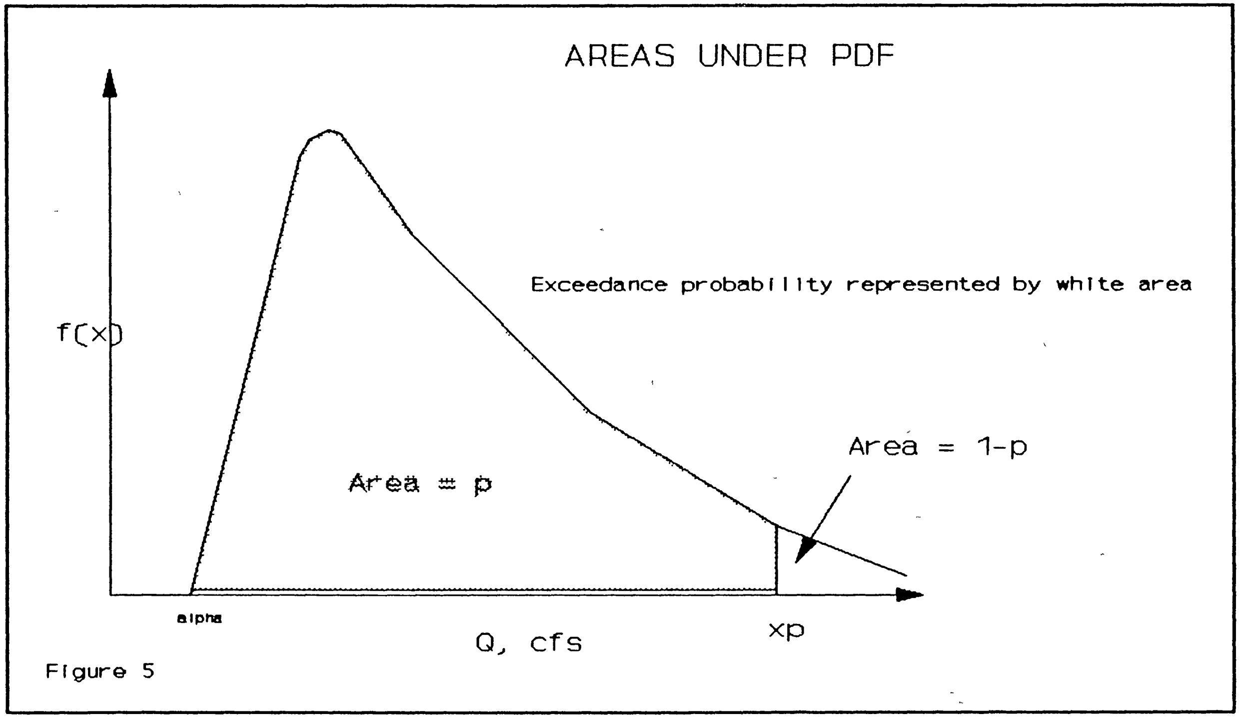
AREAS UNDER PDF
Exceedance probability represented by white area
f(x)
Area = 1-p
Area = p
alpha
xp
Q, cfs
Figure 5

Figure 5.

Three Parameter Lognormal Fit to Systematic Record

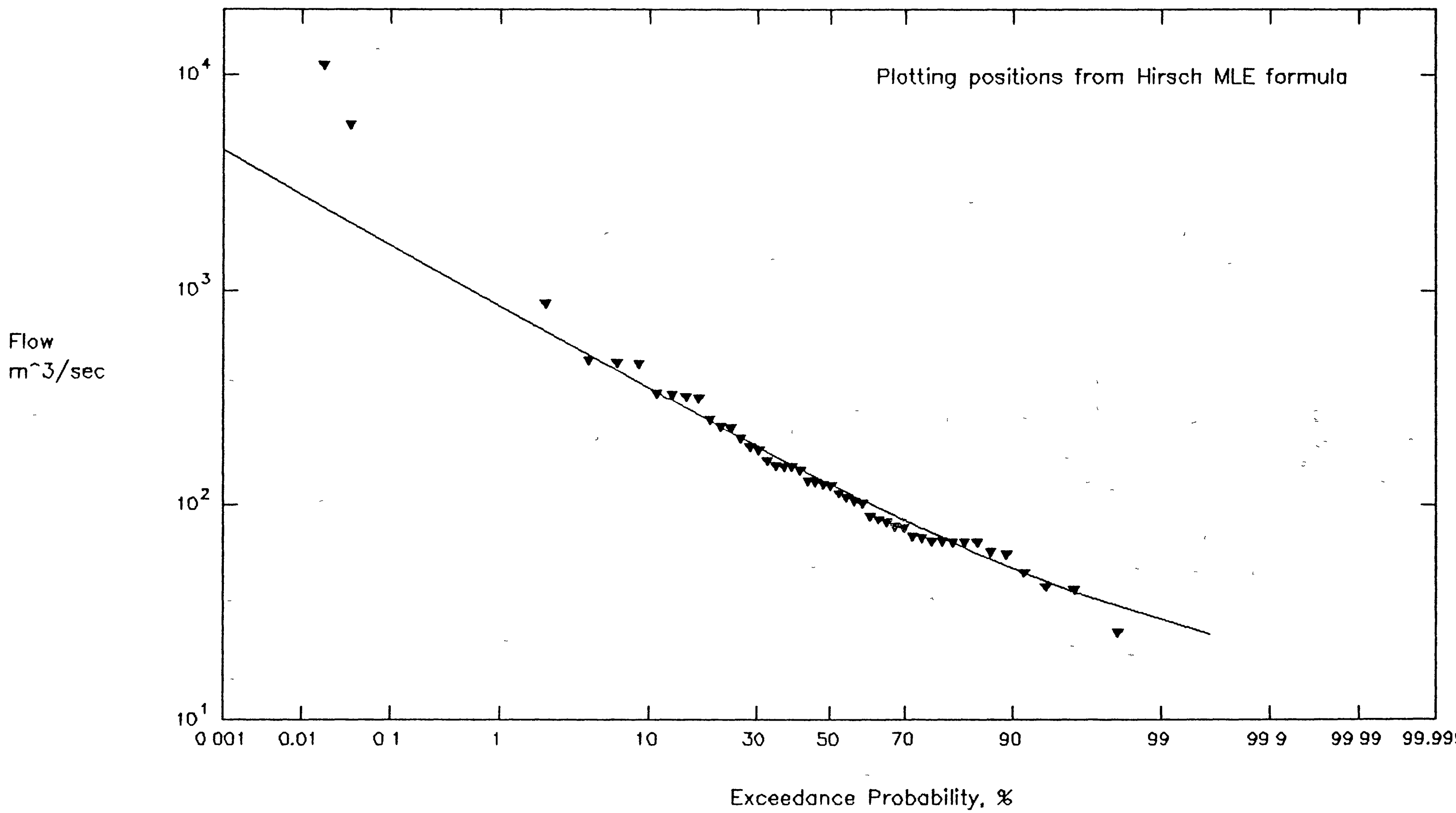

Figure 6

Three Parameter Lognormal Distribution
Fit to Censored Sample

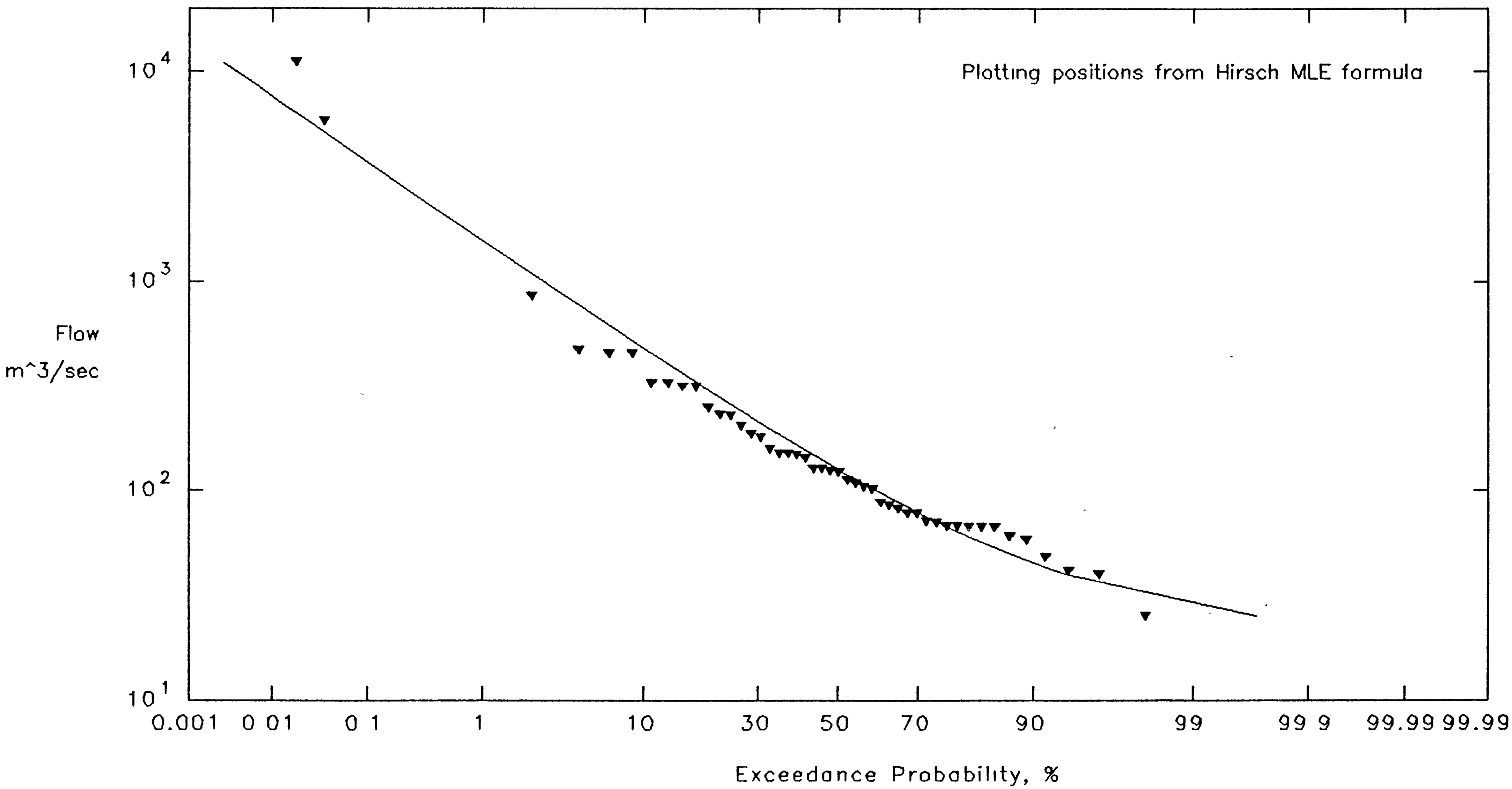

Figure 7

Log Pearson Fit and Plotting Positions – Bulletin 17B

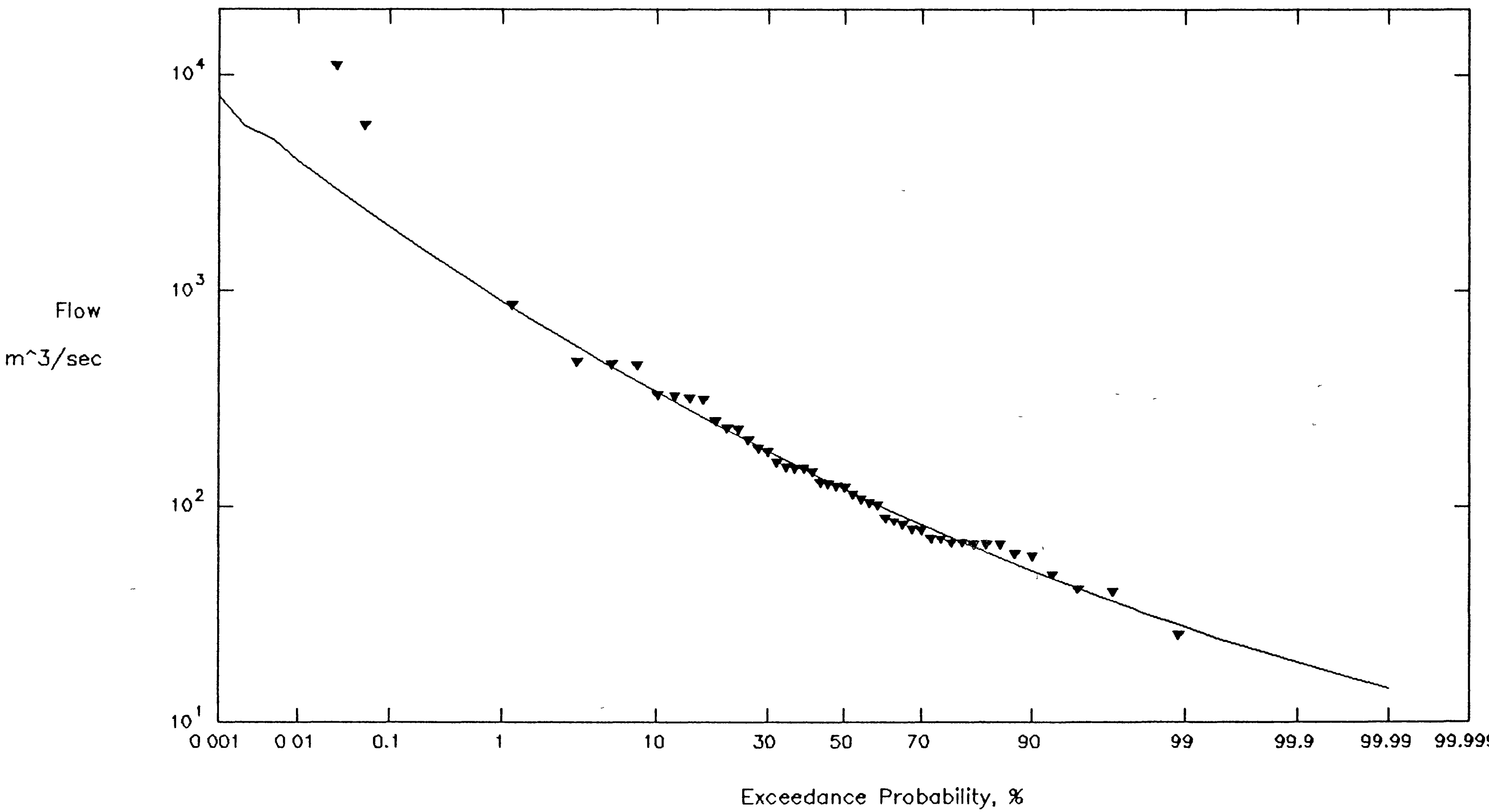

Figure 8

Hirsch Plotting Position Formula Based on Adjusted Weibull Equation

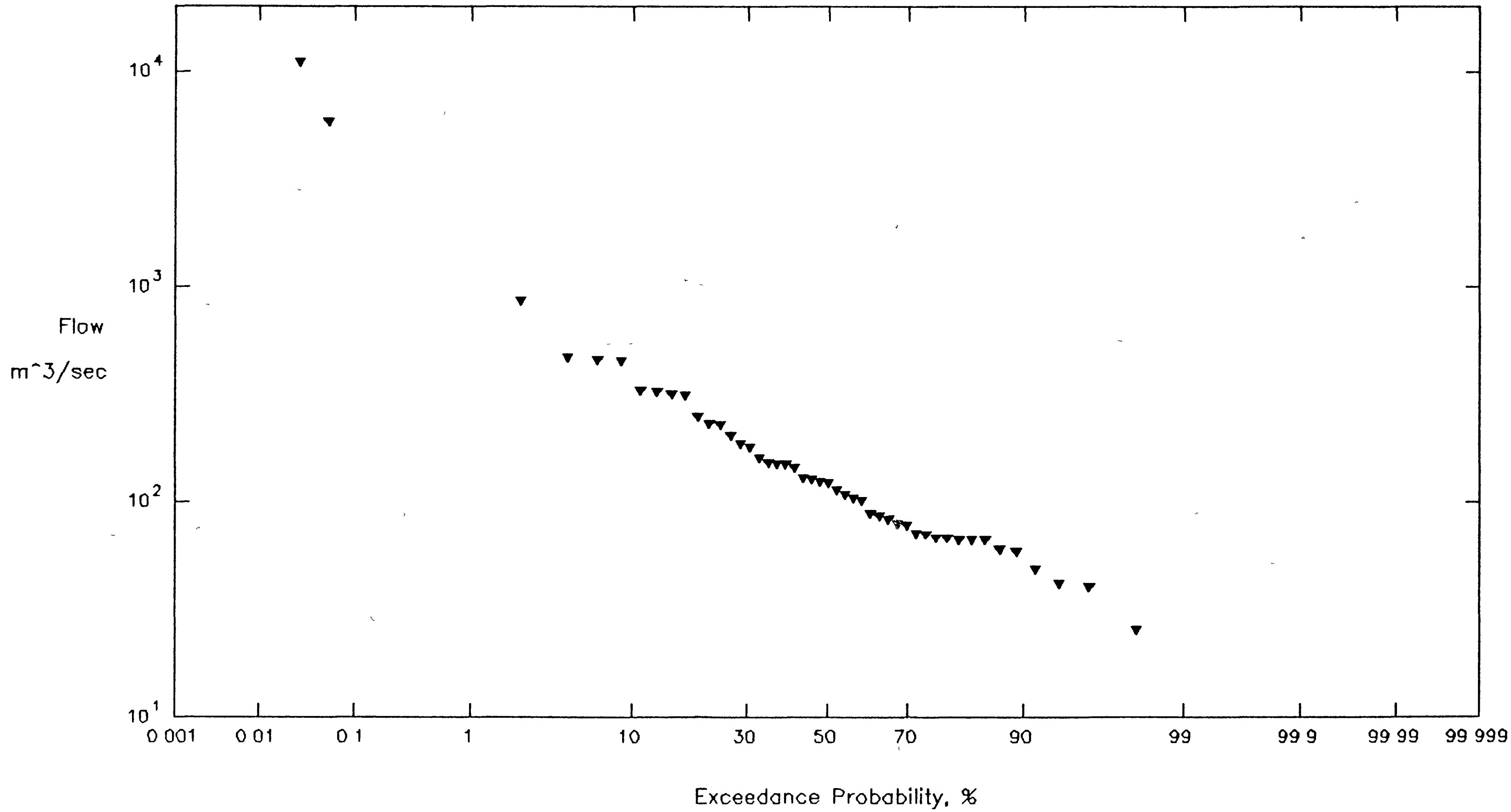

Figure 9

Hirsch Plotting Position Formula Based on Maximum Likelihood Estimator

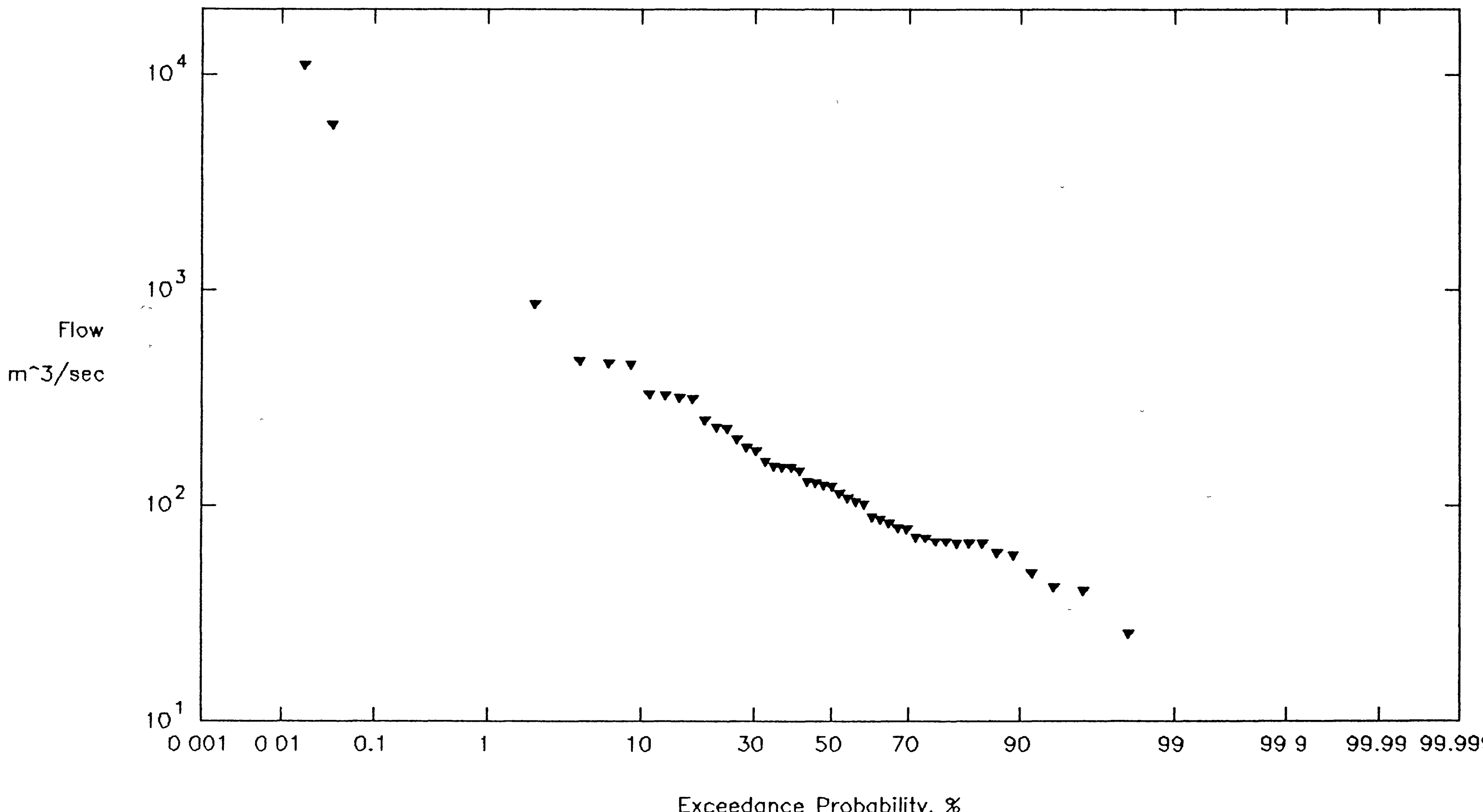

Figure 10

Plotting Positions from Hirsch MLE Formula

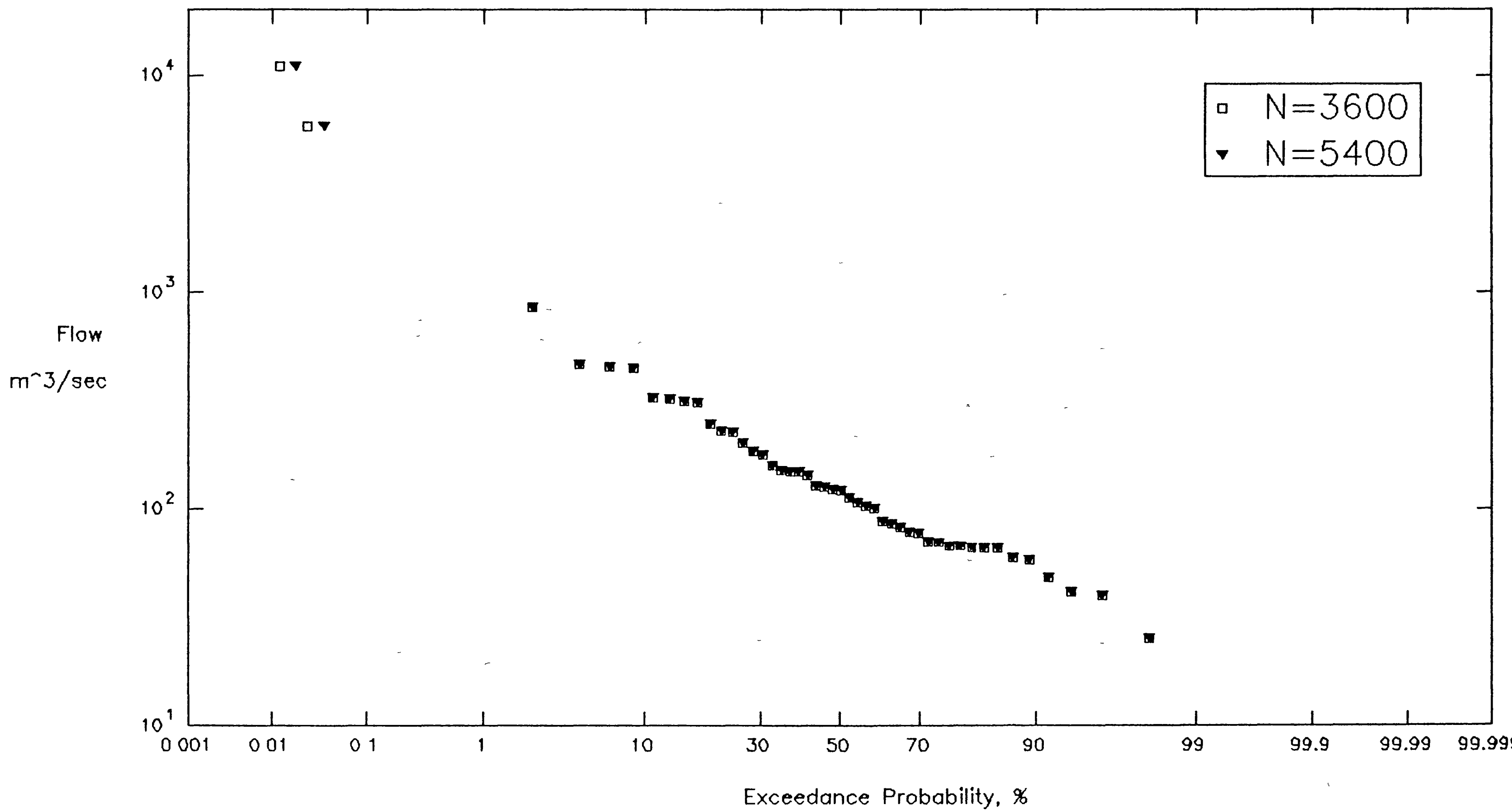

Figure 11

Effect of Changing Threshold

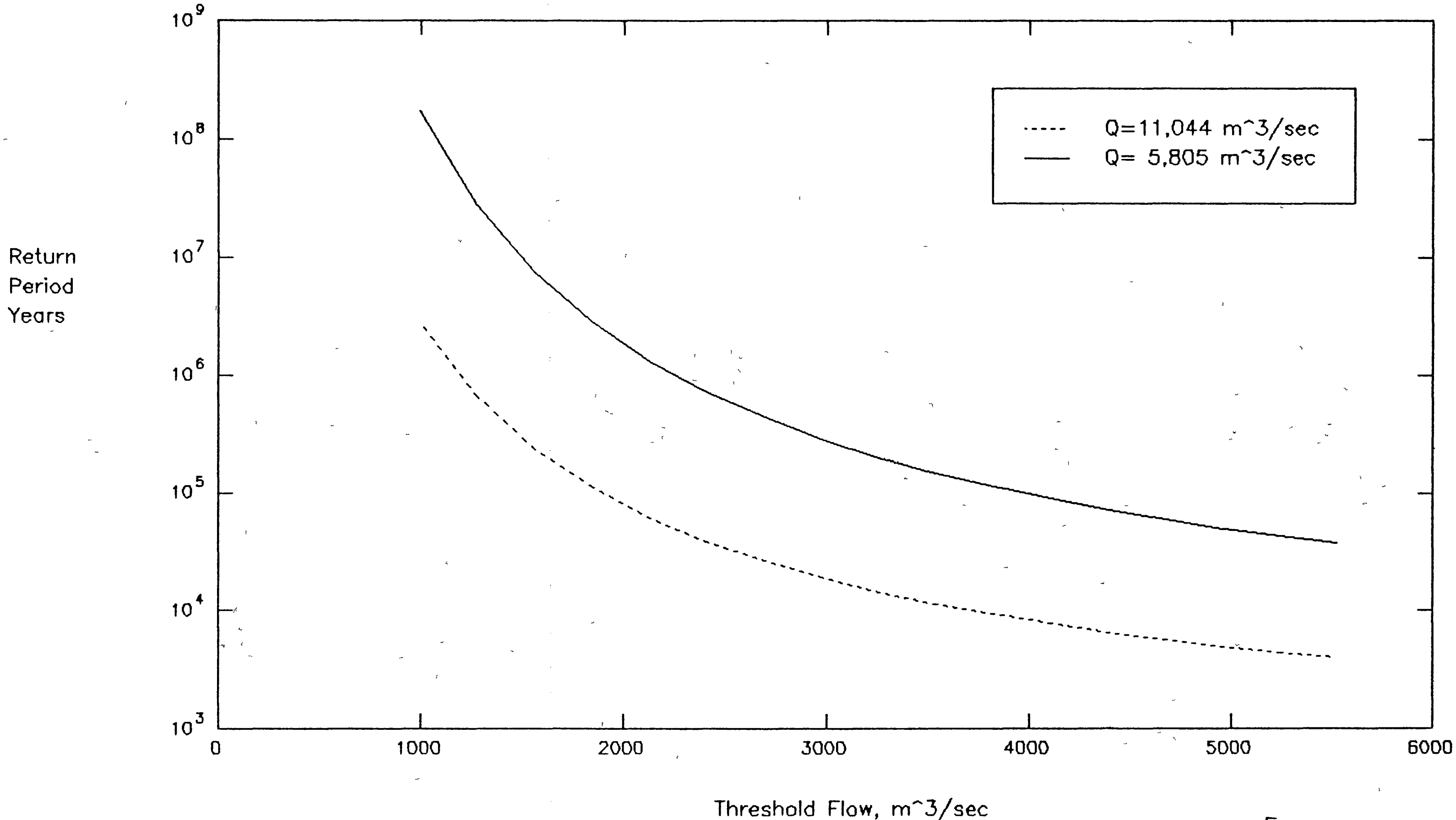

Figure 12

Effect of Changing Length of Record

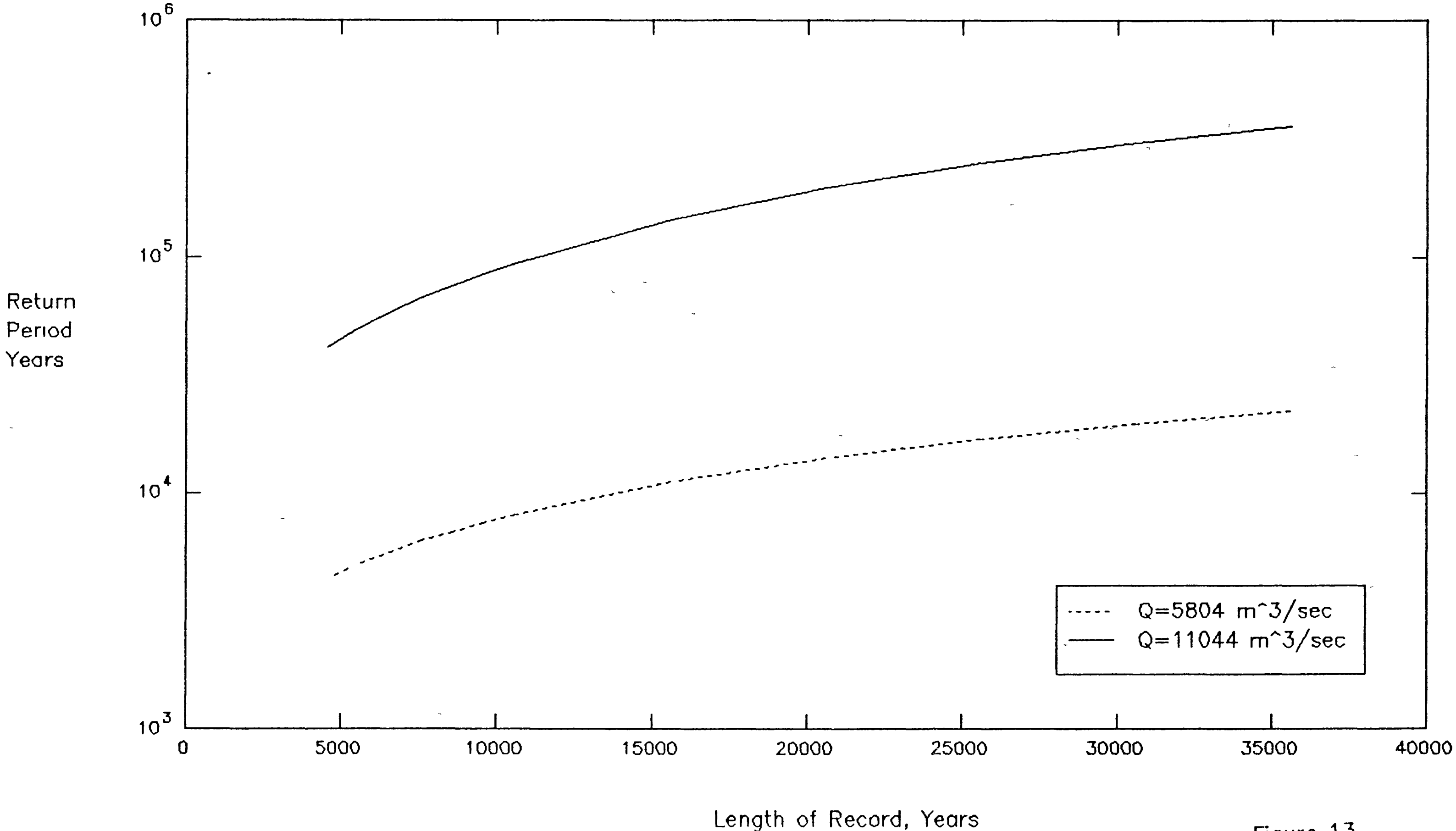

Figure 13

VITA

Kay C. McQueen

Candidate for the Degree of

Doctor of Philosophy

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