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Geomorphic Characteristics of Streams in the Mississippi Embayment Physiographic Region of Kentucky

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Kentucky UNBRIDLED SPIRIT

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Executive Summary

The goals of this project were to develop regional relations for bankfull channel characteristics of the Mississippi Embayment of Kentucky and to assess five biological assessment sites used by the Kentucky Environmental and Public Protection Cabinet (EPPC), Division of Water (DOW). To accomplish these goals, an extensive examination and collection of stream geomorphological characteristics in the Mississippi Embayment of Kentucky was conducted. Data were collected at 37 sites, including five sites used for biological assessment for streams of the region. In addition, supplemental data from the coastal plain region of Tennessee were used to expand the dataset.

Regional geomorphic relations for bankfull channel depth, width, and area were developed based on the dataset for gravel, sand, and silt bed streams. The lack of active stream gauging stations limited the usefulness of this information for analysis of bankfull flow and flow frequency; however, approximations were developed to estimate the bankfull flows. Comparison of the approximations showed that bankfull flows are much less than the 1.5 year flow event developed from annual series analysis.

Information on land-use history, geology and regional history is given to provide a context for the processes driving channel sediment dynamics that are causing instability in the streams of the region. In addition to the conversion of woodland and barrens to agricultural land-use, extensive channelization of the once sinuous channels has affected all streams examined except one 25-mile reach of Obion Creek in Hickman County. Consequently, most streams of the region are deeply incised and many are actively widening. Upland streams continue to incise and appear to be major sources of fine-grained soils (silt and sand) and coarse sediment (gravel). Continued channel incision (bed degradation) may be an important source of sediment from upland streams and gullies. Bank erosion appears to be a significant source of sediment on both low gradient and upland streams. Low gradient streams on wide floodplains are typically aggrading (filling) and attempting to re-meander from their straightened and channelized forms. Aggradation appears to be resulting in a large storage of sediment in the streambed and on newly formed floodplains; well-vegetated banks were observed in most of these straight reaches, and lateral adjustment appears to be propagating upstream and downstream from constructed channel bends.

Morphological data were collected at five biological reference reaches in the Mississippi Embayment. The data indicate that all examined reference reach streams have incised and are moderately or severely entrenched. The data confirm that these biological reference reaches have been affected by extensive channelization of the stream channel networks in which they are located. Although these biological reference reaches may represent the highest quality stream reaches of the region, the habitat has been severely degraded by the effects of channelization.

Recommendations for the applications of the regional bankfull relations for stream morphological assessment and stream restoration design are also provided.

Introduction 1

Stream biological reference reaches have been established throughout the watersheds of Kentucky to assess water quality and aquatic biological communities of the commonwealth (KDOW, 1997). The biological reference reaches typically are located in stream reaches and in watersheds that are considered to be among the highest quality drainage systems of specific river basin management units (RBMUs). The biological reference reach data are used for many purposes including documentation of aquatic species populations, development of water quality and biological indices, and as a measure of the highest water quality resources of the regions where the streams are located. Typical data collected at these reference reaches include detailed chemical and biological data (KDOW, 2002); nonetheless, only the physical data required to conduct rapid biological assessment (Barbour et al., 1999) have been collected at the biological reference reaches. To determine the implications of various physical impacts, specific geomorphologic data are needed to elucidate the effects of flow stresses, sedimentation and other physical habitat factors on biological communities. Additionally, assessment of the causes of change in biological communities at a particular reference reach requires baseline geomorphologic data from which physical changes can be determined. At present, physical data required to assess the current geomorphologic conditions of streams on which biological reference reaches are located have not been reported.

In addition to the lack of geomorphologic data on streams with established biological reference reaches, there is a general lack of information on stream stability and on the characteristics of sediment loads in Kentucky streams. Such data are critical, as sedimentation is cited as one of the most frequent causes of water quality impairment in Kentucky (KDOW, 2004). Ongoing stream restoration efforts intended to improve stream habitat have been conducted without general information on the geomorphic characteristics of streams in various regions of the state. Moreover, as specified by recent US Environmental Protection Agency (USEPA) guidelines (USEPA, 1999), assessment of clean sediment loads is needed for the development of sediment total maximum daily loads (TMDLs).

Among the most useful types of information for assessment of streams are regional channel characteristics relations, often referred to as regional curves. Regional curves that provide geomorphologic characteristics of stream channels are necessary for effective stream evaluation. Furthermore, these regional relations can be used as a basis for some restoration design methods (Rosgen, 1998). At present, stream geomorphic assessment and restoration design in Kentucky is being conducted without the benefit of regional curves for geomorphic parameters.

The purpose of this EPA 319(h) assessment project was to provide the first qualitative and quantitative assessments of stream characteristics in the Mississippi Embayment physiographic region of Western Kentucky. This region is frequently described also by its historical and political heritage as the Jackson Purchase. The original objective of this assessment project was to complete a geomorphic characterization of at least five streams on which biological reference reaches were located. However, objectives were expanded to include the following:

1. Provide an overview of the morphology of regional streams that considers the geologic conditions, the land use, and in particular, the valley use.
2. Provide characteristics of at least five biological reference reaches.
3. Accomplish sufficient data collection and analysis to develop regional relations for geomorphic characteristics of channels in the Mississippi Embayment.
4. Provide some guidelines for the use of the relations.

The first objective was included to provide the necessary context for considering the data collected at particular stream reaches. A summary of relevant regional geology, land use history, and response of stream channels to the historical impacts provides the background information necessary for effective land management, stream assessment, and design of stream restorations. The revised objectives were achieved by completing the following tasks:

1. Develop an overview of relevant geologic and historic land-use factors that influence the stream morphology of channels in the Mississippi Embayment.
2. Complete a reconnaissance of the region to examine the characteristics of stream channels and to determine locations for measurements.
3. Conduct annual series analysis for peak flows for gauged streams of the region using US Geological Survey (USGS) flow gauging station information.
4. Collect measurements of stream cross section characteristics at biological reference streams and other select sites.
5. Conduct analysis to develop regional curves for channel width, depth, and cross section area.
6. Describe how the data could be used for stream assessment and restoration design.

This report summarizes the results of the geomorphologic assessment of streams in the Mississippi Embayment. The report is separated into four sections: (1) a brief description of geologic and historic factors and an assessment of their apparent influence on the response and evolution of observed streams of the Mississippi Embayment, (2) a description of measurement procedures used for this report, (3) an assessment of stream cross sectional morphologic characteristics at select sites and the development of regional geomorphic characteristics, and (4) a recommendation on the use of geomorphologic information for stream assessment and channel design.

Information developed from three other Kentucky Division of Water sponsored 319(h) projects was used in this assessment project. They include (1) *Stream Restoration and Natural*

Channel Design Training Modules for Kentucky Streams, Section 319(h) Nonpoint Source Implementation Program Cooperative Agreement #C9994861-96, KDOW 96-18, (2) *Stream Geomorphic Reference Reaches and Bankfull Regional Curves*, Section 319(h) Nonpoint Source Implementation Program Cooperative Agreement #C9994861-99, KDOW 99-12, and (3) *Obion Creek Stream Corridor Restoration Demonstration Project*, Section 319(h) Nonpoint Source Implementation Program Cooperative Agreement #C9994861-99, KDOW 99-14. Observations, data and aerial photographs obtained through the authors' participation in these EPA and Kentucky Division of Water sponsored projects were incorporated into this project to expand datasets and observations beyond what would have been possible with the funding provided in this project.

Streams of the Mississippi Embayment 2

The Mississippi Embayment is one of five physiographic regions of Kentucky and covers approximately 2300 square miles of land in the westernmost area of Kentucky (Figure 2.1). This region comprises approximately 5 percent of the total land area of the state.

The region is bounded by the Tennessee state line to the south, the Tennessee River (Kentucky Lake) to the east, the Ohio River to the north, and the Mississippi River to the west. Major stream systems tend to flow generally westward to the Mississippi River or northward to the Ohio River. The major stream systems include Bayou de Chien, Obion Creek, Mayfield Creek, and Clarks River (Figure 2.2). The drainage areas of these waterways are shown in Table 2.1.

The terrain is composed mainly of rolling hills and broad flat valleys. The maximum elevation is 590 feet mean sea level (MSL) in Calloway County and the minimum elevation of 280 feet MSL occurs in Fulton County along the floodplain of the Mississippi River.

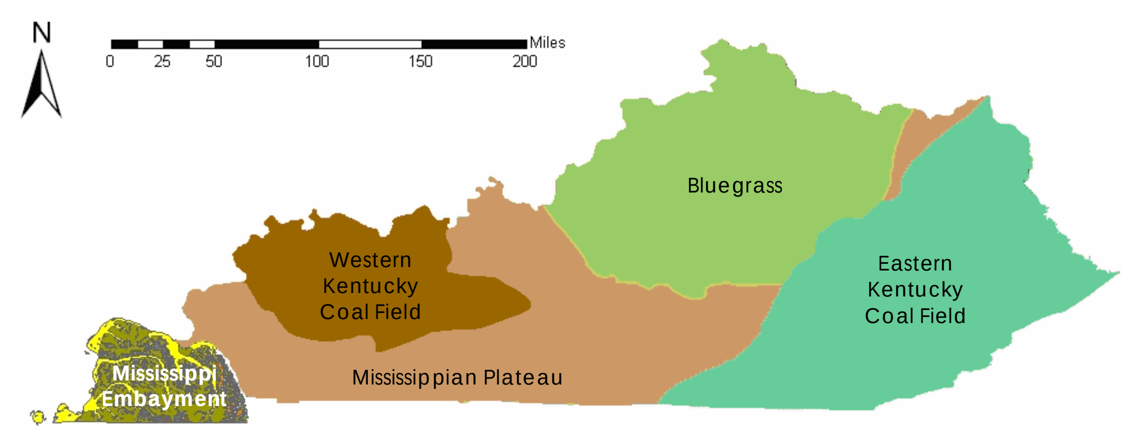

Figure 2.1 Physiographic regions of Kentucky (KGS, 1930).

Table 2.1 Major Waterways in the Mississippi Embayment

Stream Name	Drainage Area (square miles)	Receiving River and Base Level Control
Bayou de Chien	211	Obion Cr (near Mississippi)
Obion Creek	316	Mississippi
Mayfield Creek	435	Mississippi
Clarks River	531	Ohio

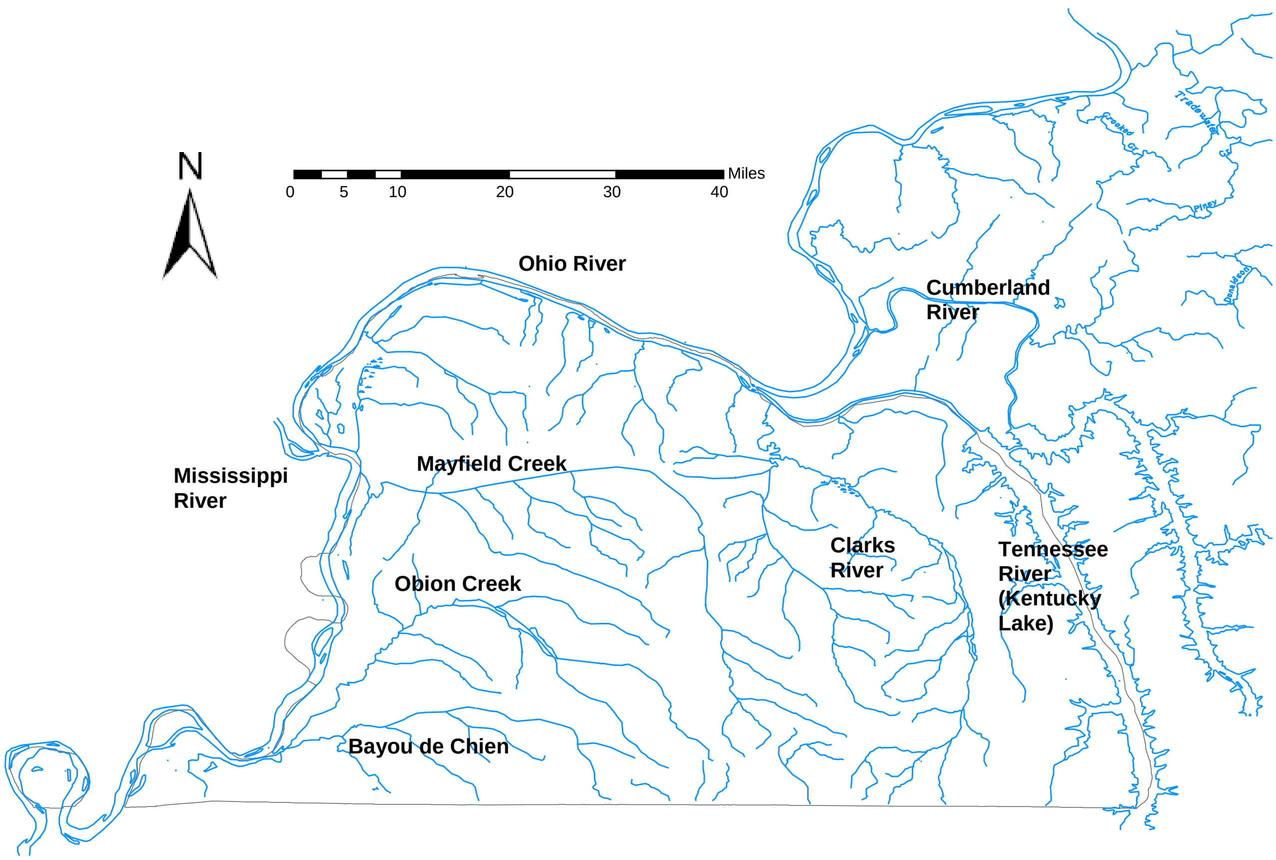

Figure 2.2 Major stream systems of the Mississippi Embayment (Noger, 1998).

2.1 SUMMARY OF REGIONAL GEOLOGY

Although located more than 400 miles from the current shoreline of the Gulf Coast, the Mississippi Embayment is considered the northernmost extent of the Eastern Gulf Coastal Plain physiographic region (see Figure 2.3) of the Southeastern US Coastal Plain (Hupp, 2000; Lawton, 2004). The region is characterized by unconsolidated marine and alluvial (river deposits). As recently as the end of the Cretaceous period (65 million years before present), the Mississippi Embayment was inundated by the northern extension of the present Gulf of Mexico

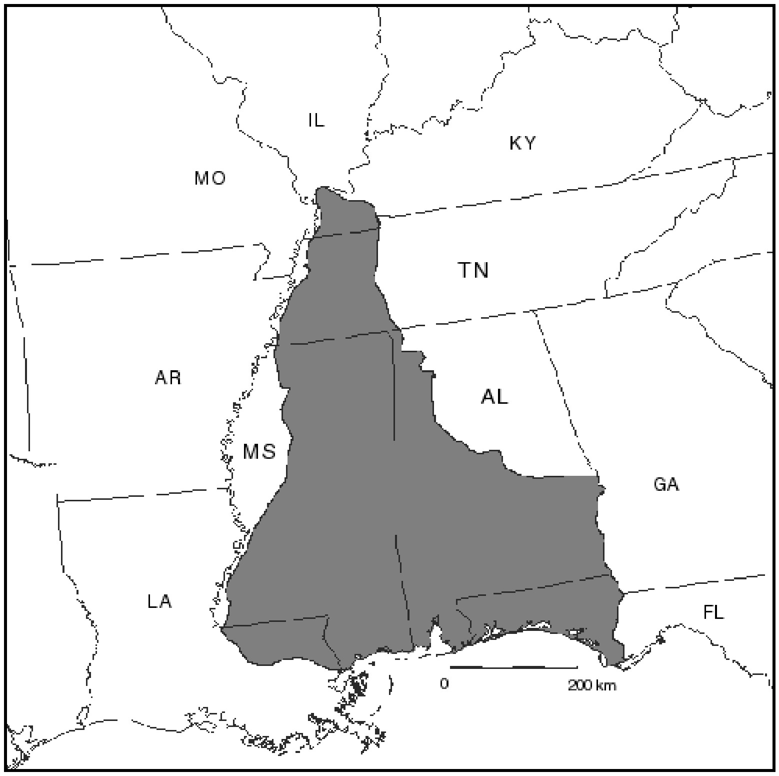

Figure 2.3 Eastern Gulf Coastal Plain physiographic region (Woodrey et al., 1998).

(Davis, 1923). The surface of sediments deposited during the Cretaceous period in this coastal environment were later mostly overlain and/or eroded by rivers and streams during the Pliocene and Pleistocene epochs. During the Pliocene, coastal sediments were overlain by a massive deposit of sand and gravel (Lafayette formation). This deposit is considered to be the remnants of a delta created by several ancient braided gravel bed rivers that flowed from the southeast and east toward the ancestral Mississippi River (Potter, 1955). These rivers included the ancestral Tennessee River and the Cumberland-Ohio Rivers. Valleys of the present streams were formed through erosion of these marine and alluvial deposits during the late Pliocene and Pleistocene epochs. A blanket of loess (wind blown sediments) was deposited over the entire region during the Pleistocene. Where it has not been severely eroded, the loess blanket generally thins from about 65 feet along the western edge of the Mississippi Embayment to about to 5 feet along the eastern edge (McDowell, 2001).

Holocene (past 10,000 years) alluvium in the present stream valleys typically consists of a surface deposit of clay, silt, sand, and gravel. Much of the fine-grained alluvium is presumed to be mainly a secondary deposit derived from the erosion of the loess-blanketed uplands. The erosion and redeposition of massive amounts of loess during the Holocene, including the period of human land-use changes, have resulted in stream flow and valley characteristics developed from the transport and deposition of fine-grained sediment (sand, silt, and clay).

With the exception of the easternmost edge of the Mississippi Embayment along Kentucky Lake, the surface geology of the Mississippi Embayment is characterized by Quaternary, Cretaceous, and Tertiary formations. Figure 2.4 and Table 2.2 show the surface geologic map and a description of geologic materials of the Mississippi Embayment, respectively. Continental deposits and loess (QTcl) are the dominant sediments exposed in the region. The lithostratigraphy in

Table 2.2 summarizes the age, sequence, and identifying features of rock and depositional layers in the Mississippi Embayment. Expanded descriptions of the regional bedrock and soil deposits are included in Appendix C of this report.

2.2 LAND-USE HISTORY AND CONSEQUENCES TO STREAM MORPHOLOGY

Prior to extensive European settlement that occurred after the region was purchased from the Chickasaw Indians in 1818 (Davis, 1923), Native Americans are believed to have used fire to maintain prairies (barrens) over most of the uplands of Western Kentucky (Loughridge, 1888). Figure 2.5, a generalized land-cover map of Kentucky representing conditions prior to European settlement, shows the large extent of pre-settlement prairies and wetlands preceding drainage in the late 1800s and 1900s. Forests may have expanded after the land was purchased from Native Americans and the frequency of fires was reduced (Davis, 1923).

Agricultural practices similar to those employed in other parts of the eastern US (Wolman, 1967; Costa, 1975; Jacobson and Coleman, 1986) and midwestern US (Happ et al., 1940; Potter, 1955; Trimble, 1981) during the 19th and early 20th centuries were commonly used in the Mississippi Embayment. Intensive agricultural use of the land without the application of soil conservation practices contributed to extensive upland erosion (Speer et al., 1965). In particular, widespread cultivation of hillsides contributed to severe and extensive hillside erosion during the early part of the 20th century (Davis, 1923; Coleman, 1971). Davis (1923, p. 41) wrote, “in certain sections, one is seldom out of sight of an eroded field.” Photographs of the period indicate

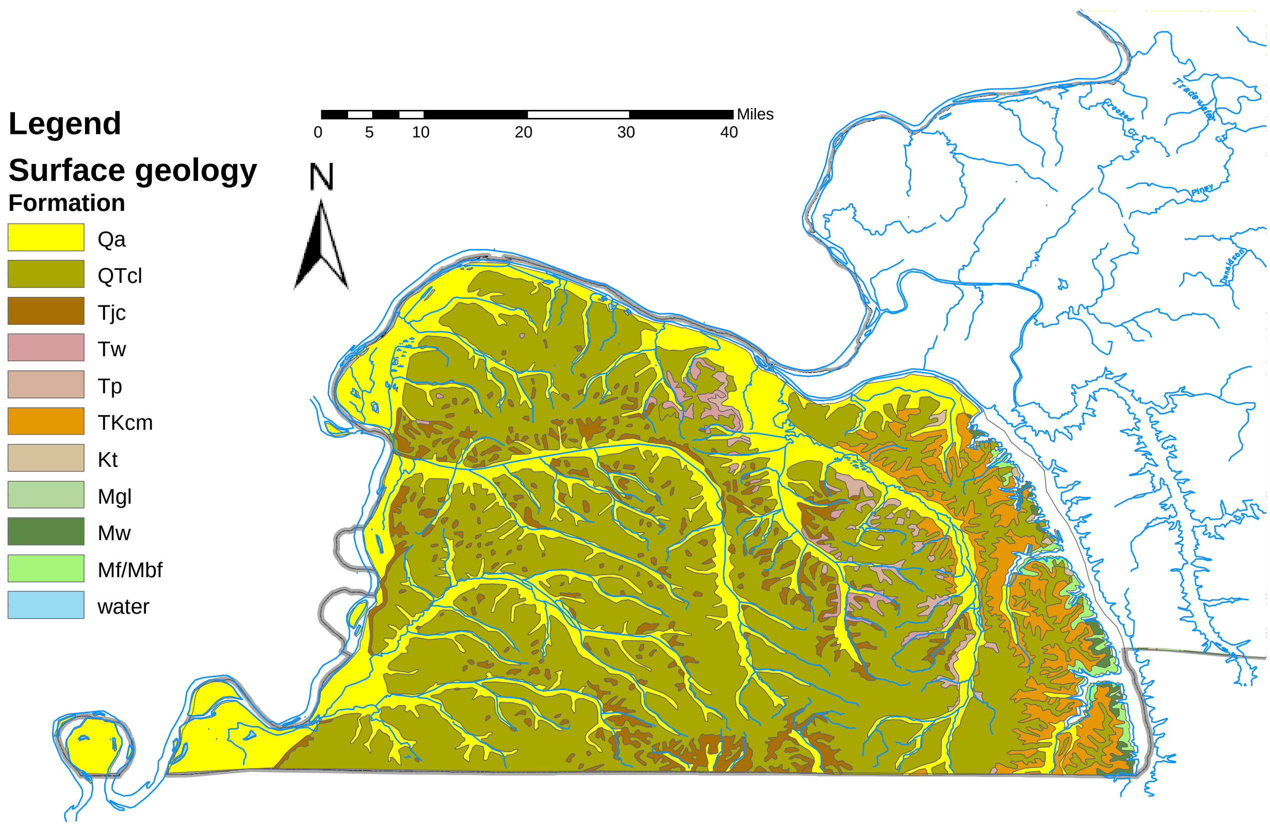

Figure 2.4 Generalized surface geologic map of the Mississippi Embayment (Noger, 2002).

Table 2.2 Summary of Geologic Formations and Key to Geologic Map of Figure 2.4*

<table>
<tr><th>System</th><th>Series</th><th>Formation,
Member and Bed</th><th>Geologic Materials</th><th>Map Symbol</th></tr>
<tr><td rowspan="3">Quaternary</td><td>Holocene</td><td rowspan="2">Alluvium (unnamed)</td><td rowspan="2">Silt, clay, sand, gravel, and, rarely, cobbles and boulders</td><td rowspan="2">Qa</td></tr>
<tr><td rowspan="2">Pleistocene</td></tr>
<tr><td rowspan="3">Continental deposits and loess (various)</td><td rowspan="3">Loess with lenses of sand Graded fan deposit (Lafayette)
Fine to course sand interbedded with silt and clay
Basal cherty gravel</td><td rowspan="3">QTcl</td></tr>
<tr><td rowspan="7">Tertiary</td><td>Pliocene</td></tr>
<tr><td>Miocene</td></tr>
<tr><td>Oligocene</td><td rowspan="2">Jackson and Claiborne Formations</td><td rowspan="2">Jackson: silty clay and clayey silt grading to primarily sand
Claiborne: crossbedded sand with lenses of clayey silt, silty clay and lignite</td><td rowspan="2">Tjc</td></tr>
<tr><td rowspan="2">Eocene</td></tr>
<tr><td>Wilcox Formation</td><td>Crossbedded sand, clay and silt with lignitized plants</td><td>Tw</td></tr>
<tr><td rowspan="2">Paleocene</td><td>Porters Creek Clay</td><td>Clay with interbedded sand
Dikes of glauconite and sand</td><td>Tp</td></tr>
<tr><td rowspan="2">Clayton and McNairy Formations</td><td rowspan="2">Micaceous sand interbedded with clay
Basal cherty gravel and silt</td><td rowspan="2">TKcm</td></tr>
<tr><td rowspan="2">Cretaceous</td><td rowspan="2">Upper Cretaceous</td></tr>
<tr><td>Tuscaloosa Formation</td><td>Cherty gravel with sand, silt and clay</td><td>Kt</td></tr>
<tr><td colspan="5">Unconformity</td></tr>
<tr><td rowspan="4">Mississippian</td><td rowspan="3">Upper</td><td>Ste. Genevieve and St. Louis Limestones</td><td>Sandstone and shale
Chert and oolitic limestone
Fine, fossiliferous limestone</td><td>Mgl</td></tr>
<tr><td>Warsaw Limestone</td><td>Cherty, fossiliferous limestone
Coarse-grained limestone Cherty and argillaceous base</td><td>Mw</td></tr>
<tr><td rowspan="2">Renfro and Muldraugh Members of the Borden Formation and Fort Payne Formation</td><td rowspan="2">Dolomitic siltstone
Cherty, dolomitic limestone
Silty and cherty dolomite
Basal layer of glauconite and phosphatic nodules</td><td rowspan="2">Mf/ Mbf</td></tr>
<tr><td>Lower</td></tr>
</table>

* Refer to Appendix C for Mississippi Embayment lithostratigraphic descriptions.

overland flow erosion and deep gullies in hillsides. Inevitably, sediment eroded from the uplands was deposited at the base of hill slopes, in stream beds, and on valley flats, although studies quantifying sediment transport and storage in western Kentucky have not been conducted to determine the location and extent of alluvial deposits derived from upland erosion after European settlement.

For example, Figure 2.6 shows the exposure of a wooden crossing or primitive corduroy road buried in the sediments on the wide floodplain of Panther Creek, a tributary to the Blood River. A headcut migrating upstream through the deposit exposed the wood structure. The deposition over the structure is approximately 4.5 feet in thickness. The alluvial deposits along the Clarks River near Almo, shown in Figure 2.7, indicate a sequence similar to those found in other

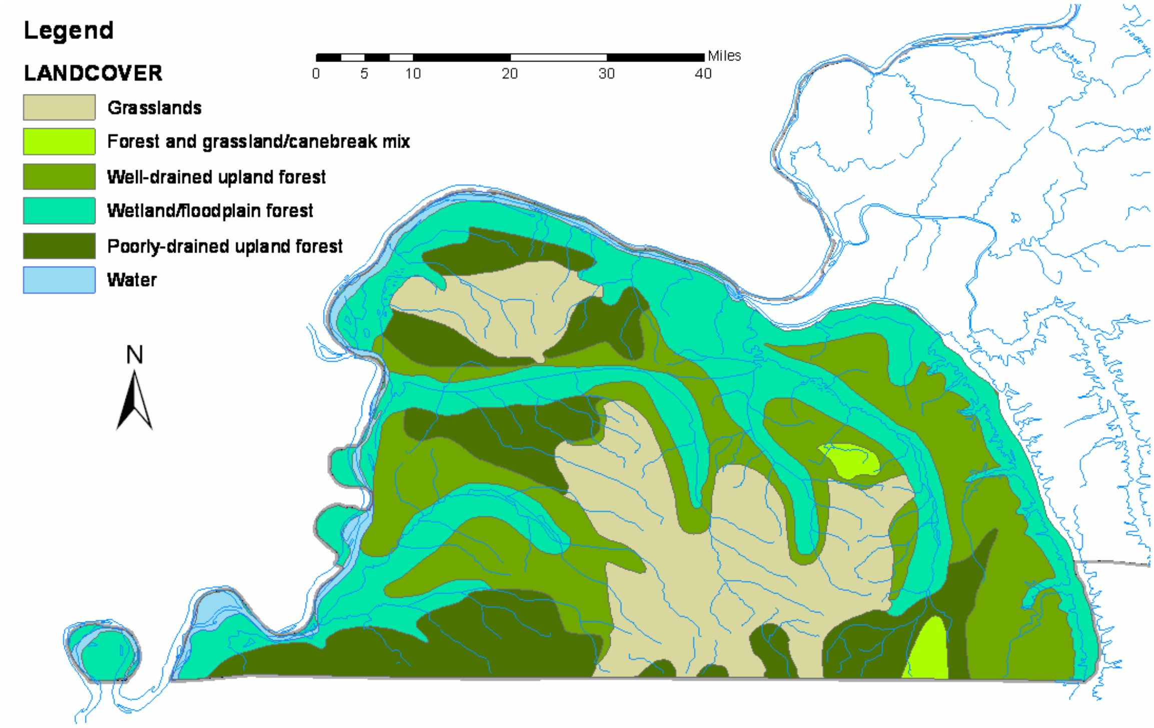

Figure 2.5 Generalized land-cover map of Mississippi Embayment prior to European settlement. GIS coverage provided by Kentucky Nature Preserve Commission—historic land-cover data collaboratively developed by Kentucky Environmental and Public Protection Cabinet, Kentucky State Nature Preserves Commission, Kentucky Heritage Council and the Kentucky Chapter of the Nature Conservancy (Mitchell, 2005).

Figure 2.6 Exposure of a buried wood structure indicating the depth of deposits in the Panther Creek valley, Calloway County.

locations of the midwestern and eastern US—recent alluvium (top brown loose sandy silt) deposited over what appears to be buried wetland soils (gray mottled silty soil) underlain by gravel. Observations made during this assessment indicate that current application of soil conservation practices has reduced the overland component of erosion significantly compared to that of the early part of the 20th century. Still, gullies in upland fields are not difficult to find.

Figure 2.8 shows the regional land-use in 2001. Land use is now predominantly agricultural, with over 52 percent of the region in agricultural production. Remnant forests account for 28 percent of the land use, with lesser amounts of land devoted to other covers.

Figure 2.7 Eroding bank on the Clarks River near Almo, Calloway County.

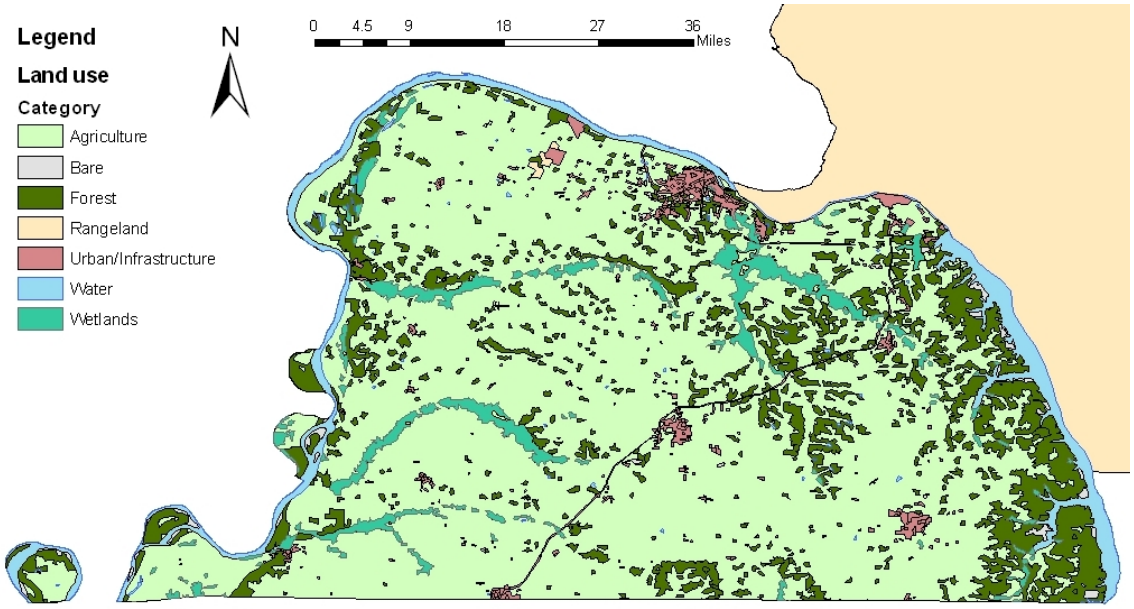

Figure 2.8 2001 land-use map of the Mississippi Embayment (USGS, 2004).

Some of the most fertile soils of the Mississippi Embayment are located in stream and river floodplains. To increase the amount of arable land, stream channelization—including channel straightening, channel enlargement, and channel relocation—was initiated in the late nineteenth century and continued through the middle of the 1900s (Speer et al., 1965). The channelization was intended to reduce the frequency of bottomland flooding and to drain wetlands. Long continuous reaches of sinuous channels, now inactive and disconnected from the currently active channelized stream segments, remain in the large floodplains of Obion and Mayfield Creeks and Clarks River, indicating that streams maintained sinuous patterns until they were channelized.

A striking characteristic of the streams in the Mississippi Embayment is the degree to which these once tortuously meandering streams that flowed through extensive wetlands have been channelized and the associated wetlands drained (see Simon and Hupp, 1992, for information on similar activities in west Tennessee). The channelization is not limited to larger river systems; widespread channelization is indicated on topographic maps and was verified by field observations. Notable exceptions are a 25-mile reach of Obion Creek downstream of Kentucky Highway 307, and sections of Clarks River.

Mayfield Creek provides a good example of the effect of channelization on channel length and stream slope. The sinuous channel of Mayfield Creek prior to channelization formed the boundary of Carlisle and Ballard counties; therefore, it was possible to compare the existing and pre-channelized lengths of Mayfield Creek. In addition, the changes in channel slope were estimated from existing land contours. Upstream of the county boundaries, estimates of the pre-channelized reach lengths were developed from the sinuosity (stream length to valley length ratio) obtained from remnant channels found in aerial photographs of the pre-channelized stream reaches. Figure 2.9 shows the estimated stream profiles for Mayfield Creek before and after channelization. Note that the use of floodplain contours results in a profile that is approximately coincident with the top of the bank above the streambed and does not include fluctuations for topographic variation in the streambed; however, the approximation does provide valuable information about the change in steam length and the overall change in channel slope. Figure 2.9 shows that the length of the main stem was shortened by 35.4 miles and the slopes were increased by 75 percent and 65 percent in the lower and upper reaches, respectively. In addition to the stream morphological implications associated with changes in length and slope, bends that provide form drag on the flow were removed. Removal of bends also tends to cause a general flattening of the streambed as well as a decrease in bed form resistance. These changes lead to a general increase in sediment transport capacity and a tendency for channel bed incision. As a consequence of the effects of channelization, Mayfield Creek is deeply incised, as are all streams examined in the Mississippi Embayment except the few that have not been extensively channelized.

2.3 LOCATION AND POTENTIAL EFFECT OF MILLS AND MILL DAMS

Maps from Kentucky Historical Society holdings (Griffing, 1880) and online sources (Kentucky Land Office, 2005; Utterback, 1998) dated as early as the late nineteenth century were obtained to identify sites where dams may have been constructed or channels may have been modified for milling operations. Figure 2.10 shows the approximate locations of both steam driven and water driven milling operations for saw and grist mills present during the period 1880 to 1885. Extensive settlement of the Mississippi Embayment occurred during the early and mid-1800s; therefore, many grist and saw mills may have briefly existed throughout the region before 1880 but were not counted in this historical inventory.

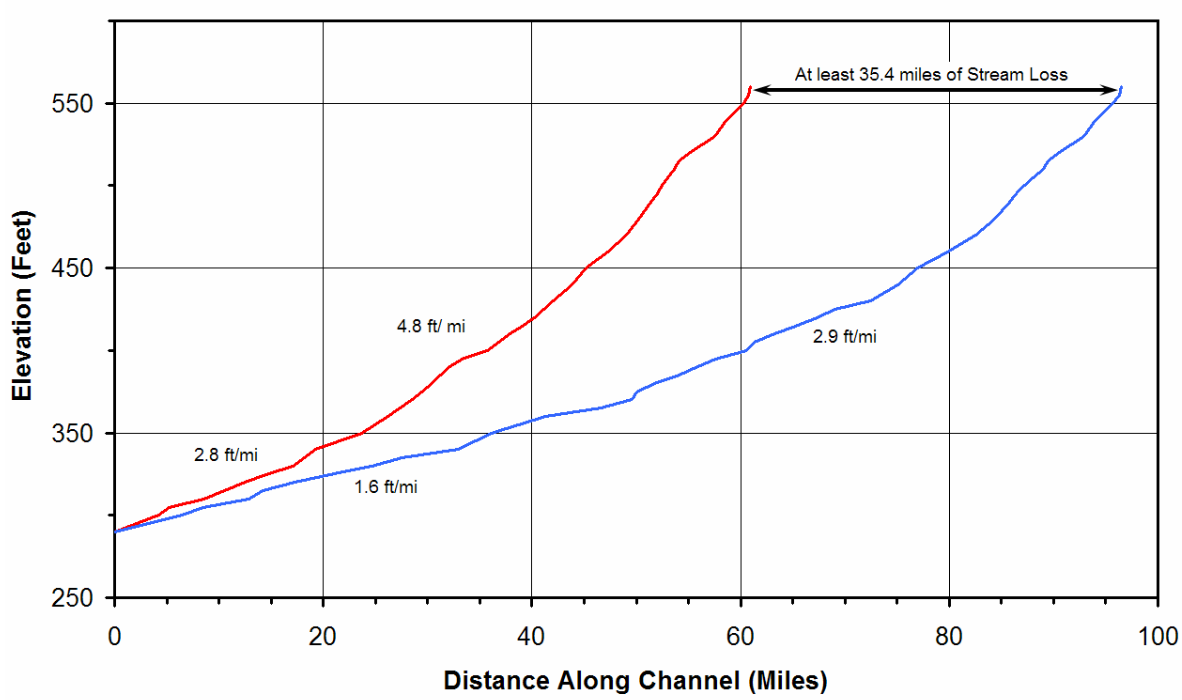

Figure 2.9 Estimated stream profile of Mayfield Creek before and after channelization (Calloway, Graves, McCracken, Ballard and Carlisle Counties).

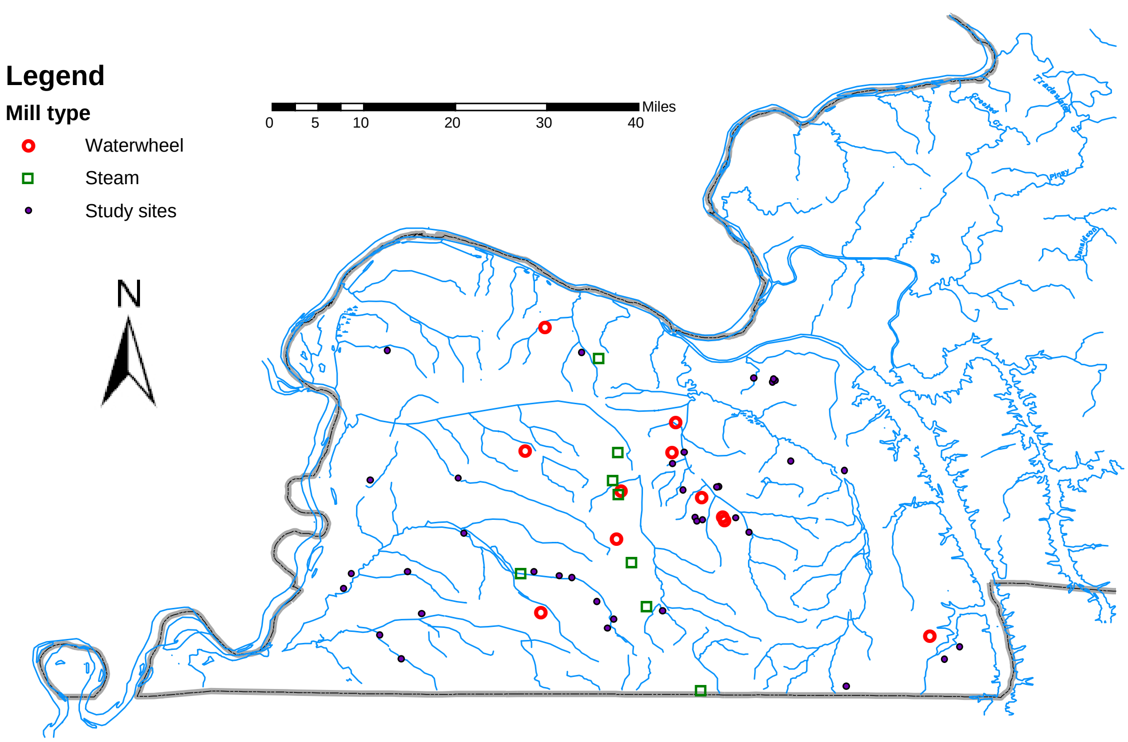

Figure 2.10 Mississippi Embayment mills and geomorphic assessment study sites.

Water driven mills required at least flow diversion by a small weir; however, given the low gradient streams of the region, dams were probably necessary to develop sufficient power. Also during the late 1800s and early 1900s, intensive agricultural activities and lack of soil conservation practices are suspected of causing high sediment loads. The high sediment loads, in combination with backwater effects caused by dams of any size, would have enhanced sediment deposition in channels and on floodplains upstream of the dams. Therefore, floodplain aggradation is suspected on floodplains upstream of mills driven by water wheels. Channelization implemented after mills and milldams were removed, or channelization that bypassed reaches containing milldams, may have caused subsequent channel incision through the milldam backwater deposits as well as through the underlying alluvial floodplain deposits. Valley flat elevations and bank heights may be higher in locations upstream of past milldam locations than in reaches downstream.

In total, 25 mills were identified at 19 locations within the region. Mill types identified by power source are listed in Table 2.3.

Table 2.3 Mississippi Embayment Mill Inventory

Mill Power Source	Mill Usage	Number
Waterwheel	Grist	3
	Saw	4
	Textile	1
	Unknown	8
Steam	Grist	3
	Saw	6

Of the mills identified, three were found to be within one mile downstream of stream measurement sites. Those sites are

- Obion Creek (steam mill on old channel near Baltimore)
- West Fork Clarks River (water wheel on old channel at Kaler)
- Leech Creek (steam mill near the confluence with Mayfield Creek)

Two mills, within 0.5 miles of one another, were identified within 2.5 miles downstream of a fourth (water wheel on the West Fork Clarks River downstream of Duncan Creek). Though mapped together, these mills may have operated at different times.

Valley profiles developed from USGS topographic 7.5 minute quadrangle maps did not show changes in valley slope that would indicate deep deposits on the floodplains near the indicated mill locations. However, the contour intervals of the maps probably were too large to detect changes in floodplain concavity that would form in the low gradient valleys of the region.

2.4 STREAM RESPONSE AND CHANNEL EVOLUTION

Watersheds and stream valleys that have land-use histories similar to those in the Mississippi Embayment of Kentucky have been studied extensively in Mississippi, western Tennessee, and the upper Midwest (see Happ et al., 1940; Simon and Hupp, 1992; Thorne 1999; Potter et al, 2004). Although the geology differs in these regions, the responses of stream channels, as indicated by these studies, appear to be generally applicable to streams of the Mississippi Embayment of Kentucky. Two main responses are evident:

1. Fine grain sediment eroded from upland hillside slopes has deposited in stream valleys, causing general aggradation of stream valley flats and aggradation of some stream channels.
2. Channelization—involving channel straightening, relocation, and enlargement—has caused streams to progress through a series of vertical and lateral channel adjustments. Mechanisms of adjustment include (a) channel incision, (b) bank mass failure and erosion, and (c) lateral bank migration and reformation of the channel floodplain and channel planform pattern.

Many of the larger low gradient streams in wide valley bottoms appear to be in the later stages of adjustment (response 2c, above). In later stages, the bed is aggrading (vertical adjustment), severe bank erosion and lateral migration are progressing, and a new, lower level floodplain is forming. This is shown in Figure 2.11 of Obion Creek and Figure 2.12 of Mayfield Creek. The most severe bank erosion was observed at locations where channel bends were constructed in the channelized (mostly straightened channel) networks. In straight reaches remote from constructed bends, severe bank erosion was not typical in the larger stream channels (shown in Figure 2.13). Well-vegetated banks were observed in most of these straight reaches. Aggradation of beds in channelized reaches appears to be resulting in a large storage of sand and gravel as also indicated in Figure 2.13. Lateral adjustment appears to be propagating upstream and downstream from constructed channel bends.

In smaller headwater streams, channel incision and channel widening are prominent. The effect of channelization of the main stem channels may have (1) decreased the base level near the

Figure 2.11 Late stage channel evolution in Obion Creek downstream of Waggoner Bottom Road, Graves County.

Figure 2.12 Late-stage channel evolution in Mayfield Creek, Graves County.

Figure 2.13 Laterally stable straight channelized reach of Obion Creek, Graves County, downstream of Pryorsburg. Note apparent aggradation of the streambed and storage of sandy gravel in the streambed.

mouths of small tributary streams at their confluences or (2) decreased the length of tributary streams when the main stem was relocated and the tributary confluence was moved laterally. Both effects would produce headcuts that migrated upstream in these tributary channels and caused degradation of the stream bed. In addition, the tributary itself may have been channelized, causing channel incision. Headcuts and general channel incision in these tributaries have propagated upstream where they tend to stall at culverts. Figure 2.14 shows a small tributary channel on the (a) upstream and (b) downstream sides of a culvert. Downstream, the channel is a deep gully and upstream the channel is a relatively small stream in a swale. Recognition of these culverts as grade control structures that prevent upstream migration of headcuts is important to the management of the streams and adjacent infrastructure. Replacement of the culverts with bridges without grade control structures would allow the headcuts to migrate upstream with detrimental effects on upstream infrastructure, increases in bank and bed erosion, and releases of large loads of coarse- and fine-grained sediment to downstream channels. Where culverts are not present to act as grade controls, headcuts have migrated through the channel networks into upland swales and appear to be forming channels where none previously existed.

Upstream migration of the headcuts and subsequent degradation and widening of the channel appears to be a significant source of both fine-grained sediments (clay, silt and sand) and underlying coarse-grained sediment (sandy gravel). In some of the gullies observed, several feet of fine-grained sediment were eroded in the channel bed before deeper gravel material was exposed. This exposure indicates that prior to deep channel incision, the beds of small tributaries were composed of silt or sand and therefore were not sources of gravel. Channel incision may have changed some of the tributaries' sediment loads from low supplies of fine-grained sediment to high supplies of both fine-grained and coarse-grained sediments.

In many tributaries, the change in sediment load characteristics from a composition of mainly silt and clay to one high in silt, sand, and gravel can have significant implications for the long term stability of main stem channels. An example is Obion Creek, which was channelized over its entire length upstream of the Graves County/Hickman County line and remains in a mainly sinuous form for much of its length downstream of the line. Upstream the channel has a gravel bed with most tributaries incised into gravel. Downstream the channel is formed in sand and silt. Observations during the late nineteenth century (Woolman, 1892) indicated that Obion Creek then was mainly a silt bed stream with gravel only near the mouth of small tributaries.

Today, the channel network upstream of Kentucky Highway 307 transports a bedload consisting of small to medium sandy gravel. Downstream of Bug Road the bed material transitions to sand and silt. The current transition from a gravel bed to a bed of sand and silt occurs in the reach between the confluence of Brush Creek and Bug Road and has been a cause of substantial stream instability for decades. The transition from gravel bed to silt and sand bed occurs in the same reach where the upstream channelized reach of Obion Creek transitions into the downstream sinuous channel that has not been channelized. A large debris jam (approximately 1.5 miles in length) upstream of the Highway 307 bridge completely blocks the channel, forcing flow onto the floodplain and causing the formation of hundreds of small anabranching channels. Gravel is stored in the channelized reaches upstream of the debris jam. Observation of remnant historic channels in floodplains during this assessment project indicates sinuous single-thread silt bed channels, as shown in Figure 2.15, whereas the present multiple-channel network is anabranched in the transition.

(a)

(b)

Figure 2.14 Small unnamed headwater tributary of the west fork of Mayfield Creek near the intersection of Kentucky Routes 80 and 384 in Graves County (a) upstream of pipeline and culvert and (b) downstream of pipeline and culvert. Note undermining of waterline in (b).

Figure 2.15 Remnant reach of pre-channelized Obion Creek upstream of Kentucky 307 bridge, Hickman County.

Measurement of Bankfull Flow Channel Geometric Characteristics

3

The main objective of the field data collection phase of this project was to obtain bankfull characteristics of channels over a broad range of channel conditions throughout the Mississippi Embayment. When bankfull conditions can be identified at gauging stations, discharge can be related to the bankfull stage and a frequency can be estimated for the bankfull flow event. Stain lines on bridges with co-located gauging stations were examined to determine if bankfull flow could be related to the stain lines. However, the general lack of gauging stations in the region and the lack of unambiguous depositional features that would clearly indicate bankfull conditions at the few existing gauging stations necessitated collection of most of the data at un-gauged sites.

3.1 IDENTIFICATION OF BANKFULL FLOW CONDITIONS

Several methods have been used to identify indicators of bankfull flow conditions (Williams, 1978; Leopold, 1994; Pruitt et al., 1999; Smith and Turrini-Smith, 1999; Harman et al., 2002; Doll et al., 2003; McCandless, 2003; Sweet and Geratz, 2003). In this project, the determination of bankfull flow conditions was limited to that proposed by Dunne and Leopold (1978): the flow that completely fills the channel so that its surface is level with the active floodplain. The active floodplain is the flat portion of the valley adjacent to the channel that is constructed by the present river in the present climate and is frequently inundated by the river (Dunne and Leopold, 1978) at intervals of 1 to 2 years. The “present river” and “present climate” are of particular importance in defining the bankfull level and the active floodplain; if the river incises, it may abandon the floodplain, which becomes a low terrace. Thus, distinguishing the active floodplain from low terraces is critical to identifying the bankfull stage.

The active floodplain is well defined for streams that are not incised. For example, Figure 3.1 shows a cross-section of Obion Creek downstream of any major channelization. At this site, the active floodplain is the valley adjacent to the channel (the “valley flat”) and the definition of bankfull is unambiguous. Some remaining sinuous active channel reaches and sinuous reaches abandoned and disconnected by channelization projects indicate that the valley flat (locally called the first bottom) represented an active floodplain prior to channelization.

Determinations of bankfull flow, the active floodplain, and geometric characteristics of all but a few streams in the Mississippi Embayment were complicated because of channel response to extensive and intensive human disturbance, primarily channelization. Streams previously channelized and incised often form smaller channels in fine-grained deposits within the channelized, typically widening outer channel as shown in Figure 3.2. The fine-grained depositional feature is considered to be a developing, embryonic active-floodplain. Although this embryonic floodplain is unlikely to be fully developed, it was the only consistent feature that could be identified in many channels. This fine-grained depositional feature was considered to be the best-available representation of the active floodplain. Hupp (1988) and Osterkamp and Hupp (1984) have a different interpretation of what they have termed an in-channel shelf vegetated mainly by brushy vegetation. Hupp (1999) stated that processes forming the fine-grained shelf are not conducive to the formation of extensive floodplains. According to Hupp (1999), these benches are formed by flows of 5 to 25 percent flow duration and the level of the bench approximates that of the mean annual flow in many perennial streams. However, Hupp (2000) later states that streams in the coastal plain physiographic regions access their floodplains every year for prolonged periods, sometimes for months. The field data collection phase of this project observed that woody vegetation, although apparently young, was present at and below the levels of these benches.

Where the channel has widened significantly and the bed showed no indications of rapid elevation change, frequently only one main flat fine-grained depositional feature was observed. Nevertheless, where either backwater effects exist from downstream obstructions or constricttions, or where evidence of rapid bed elevation change was present, multiple flat depositional features were observed. In some cases, gradually sloping benches were present. Sites with multiple or sloping benches were avoided.

Bankfull indicators were evaluated at selected flow gauging stations currently operated by the USGS Kentucky Water Science Center. Annual series peak flow data and stage-discharge

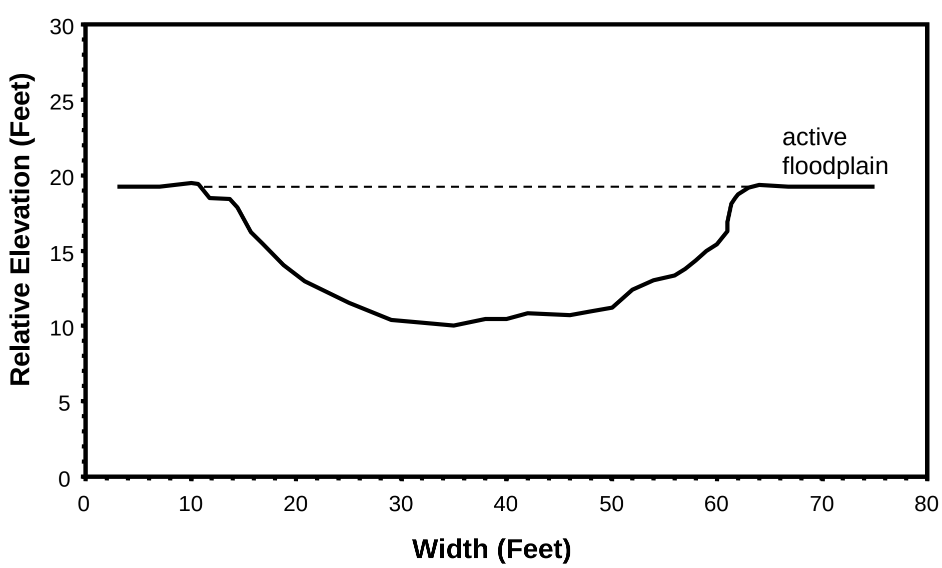

Figure 3.1 Cross section of Obion Creek, Hickman County, where the valley flat is the active floodplain (bankfull level indicated by dashed line).

relations developed for these sites were used to evaluate channel geometry, flow, and the frequency of specific flow conditions. Yet changes in channel geometry by bridge maintenance dredging, debris blockage and removal, and/or channel aggradation caused frequent shifts in gauging station rating curves. These changes in inferred geometry limited the number of gauges that could be used to obtain reliable estimates of stage discharge relations in the range of expected bankfull conditions. At other sites, only inconsistent indicators of bankfull flow could be identified near the gauging stations. As described in later sections, an evaluation of bankfull indicators was conducted at four gauging stations; the results of those evaluations, however, led to the conclusion that the indicators at those four gauging stations were also unreliable.

In order to expand the dataset of bankfull channel cross-sectional geometric characteristics, an approach was used in which bankfull cross sectional characteristics were measured at many un-gauged reaches where bankfull conditions were well defined. A description of the data collection methods at gauged sites and un-gauged sites is provided in subsequent sections.

3.2 SITE SELECTION FOR REACH ASSESSMENT

USGS Gauging Stations

Site information for all USGS stream flow gauging stations in the Mississippi Embayment region was compiled prior to site visits to determine which stations (1) had sufficient annual peak series data (ten or more continuous years) for conducting flood-frequency analysis, (2) had a stable stage-discharge relationship over the period of record used for flood-frequency analysis, and (3) were located on sites with public access. These criteria reduced the number of possible sites from 16 to 8. Four of these stations subsequently were eliminated because the gauges had been discontinued and because benchmarks, which are required to reference survey data with gauge records, could not be located. The final list of sites used is presented in Table 3.1.

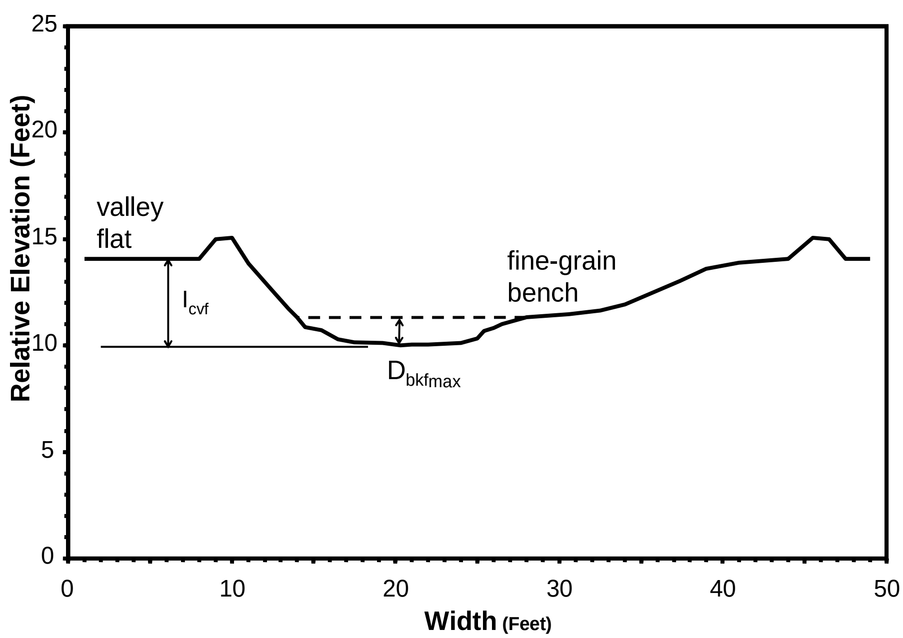

Figure 3.2 Cross section of Grindstone Creek, Calloway County (bench and bankfull level indicated by dashed line).

Table 3.1 USGS Gauging Stations Used in Study

Stream Name	USGS Gauge ID	Drainage Area (mi^2)	Period of Record
Bayou de Chien	07024000	68.7	1985–present
Massac Creek	03611260	14.6	1985–present
Obion Creek	07023500	36.8	1964–1983
West Fork Clarks	03610545	68.7	1969–1983

All stream gauging stations were located on channelized reaches and at bridges. As a consequence of the effects of channelization and of bridges, evidence of consistent and reliable bankfull flow conditions was not observed during reconnaissance. As a result, data collection at gauging stations and from the USGS was limited to assessing the significance of stain lines on bridges and scour lines along banks, assessing the frequency at which the valley flat elevation is flooded, and developing regional flood frequency characteristics.

Un-Gauged Reaches

Extensive review of topographic maps and aerial photographs was performed to identify reaches where channels had some curvature that would enhance channel widening processes and the formation of consistent bankfull features. Once such reaches were identified, reconnaissance of potential reaches was conducted to determine if suitable conditions did indeed exist. These potential reaches were found to be remote from vehicle access, often requiring several thousand feet of foot travel. Survey sites on previously altered, un-gauged streams of this project were found to be associated with locations where the channel was constructed significantly wider than the undisturbed channel or where bank erosion had occurred, causing substantial widening. In either case, the wide conditions of the channel caused the formation of a consistent depositional feature in the form of a fine-grained bench.

A search was conducted for reaches which, based on a review of USGS 7.5 Minute Quadrangle Topographic maps and aerial photographs, may not have been altered. Maps display indications of numerous abandoned and inactive reaches adjacent to active, channelized reaches. However, many of these segments were found to have been filled since the date of the mapping.

Stream reaches where data were collected could be separated into the following four categories:

- **Active non-incised sinuous reaches –** These reaches do not appear to have been altered or affected directly by channel modifications on other segments of the same stream. Fine-grained benches lower than the surrounding valley flat were not observed.
- **Abandoned non-incised sinuous reaches –** These reaches are remnants from local channel modifications that did not appear to be altered. Fine-grained benches lower than the valley flat were not observed at these sites.
- **Channelized and widening reaches –** These reaches were found to have formed smaller channels and embryonic floodplains (one or more fine-grained benches) within larger channels in reaches that have incised and that are widening in response to direct channelization. The elevation of the embryonic active floodplain was lower

than the surrounding valley flat and was therefore considered incised with respect to the valley flat.

- **Reaches affected by channelization and widening reaches –** These are reaches located upstream of directly modified reaches which have formed smaller channels and embryonic floodplains (one or more fine-grained benches) within larger channels in reaches that have incised and are widening in response to downstream channelization. These streams also were considered incised with respect to the adjacent valley flat.

3.3 DATA COLLECTION

USGS Gauging Stations

Data on stream reaches in the proximity of USGS gauging stations were collected using the methods detailed below. Survey data were collected using a conventional survey instrument (Topcon GTS-226 total station). Details of data collection in addition to those listed here are given in Harrelson et al. (1994):

1. Gauging information (Form 9-207) was obtained from the USGS Kentucky Water Science Center to determine the station stage-discharge relation, gauge height of benchmarks, and other station details.
2. Annual flood series data were obtained from the USGS Kentucky Water Science Center or from the Center's online datasets.
3. Possible bankfull indicators, tree lines along the banks, stain and scour lines on bridge piers, and USGS benchmarks were identified and marked for survey.
4. One stream cross-section was surveyed upstream of the gauging station and the adjacent bridge at a high point in the bed profile visually determined to be stable. Cross-section surveys spanned from left to right top of bank, and bankfull indicators and other features were noted.
5. Possible bankfull indicators and tree lines identified in the vicinity of the cross-section, as well as prominent stain and scour lines on bridge piers, were surveyed.
6. Bed sediments were assessed visually to estimate the median grain diameter category (silt, sand, or gravel).
7. Collected survey data were stored on a hand-held data logger during field activities and then transferred to a spreadsheet software program for analysis.

Un-Gauged Streams

The remoteness of locations where apparently stable bankfull indicators were identified meant access was limited for transporting conventional survey equipment that could be used to perform detailed surveys of channel geometry. An alternate survey technique was developed to measure channel geometry, utilizing light weight equipment which could be transported over the long distances required to reach the survey sites. This method allowed field personnel to identify and measure bankfull geometry during a single visit, eliminating the need for follow-up visits and potential inefficiency of field activities. The method employed provides data only at a station. Figure 3.3 shows the site locations where cross-sectional data were collected.

Cross-sectional measurements at un-gauged stream sites were performed at riffle crests for gravel-bed streams or at straight channel segments on silt-bed and sand-bed streams. The following procedures were used in this assessment project to conduct a "rapid measurement":

1. Steel reinforcing bars were driven into the ground at the valley flat elevation at or near the top of bank where the cross-section was to be surveyed.
2. A string line was pulled taut across the channel between the cross-section markers, set to a level horizontal plane using a line level. The taut line established a horizontal datum to which all elevation data were referenced.
3. A graduated survey tape was strung parallel to the datum line, with zero set at the left bank (facing downstream).
4. The cross-section was measured by noting the cross-channel station and measuring the vertical distance from the datum using a graduated tape. Distance, elevation, and point description data were recorded by a second survey crew member.
5. Photographs of the surveyed cross-section and study reach were taken.
6. A visual determination of the class of median bed surface grain size was also performed to provide data for stream classification using the Rosgen (1996) method.

Elevation measurements of local channel and valley slope with the accuracy required could not be obtained without the use of survey equipment; hence, local measures of channel and valley slope were not obtained where the rapid measurements method was used. Without accurate estimates of local friction slope, methods based on friction slope such as the Manning Equation are unreliable.

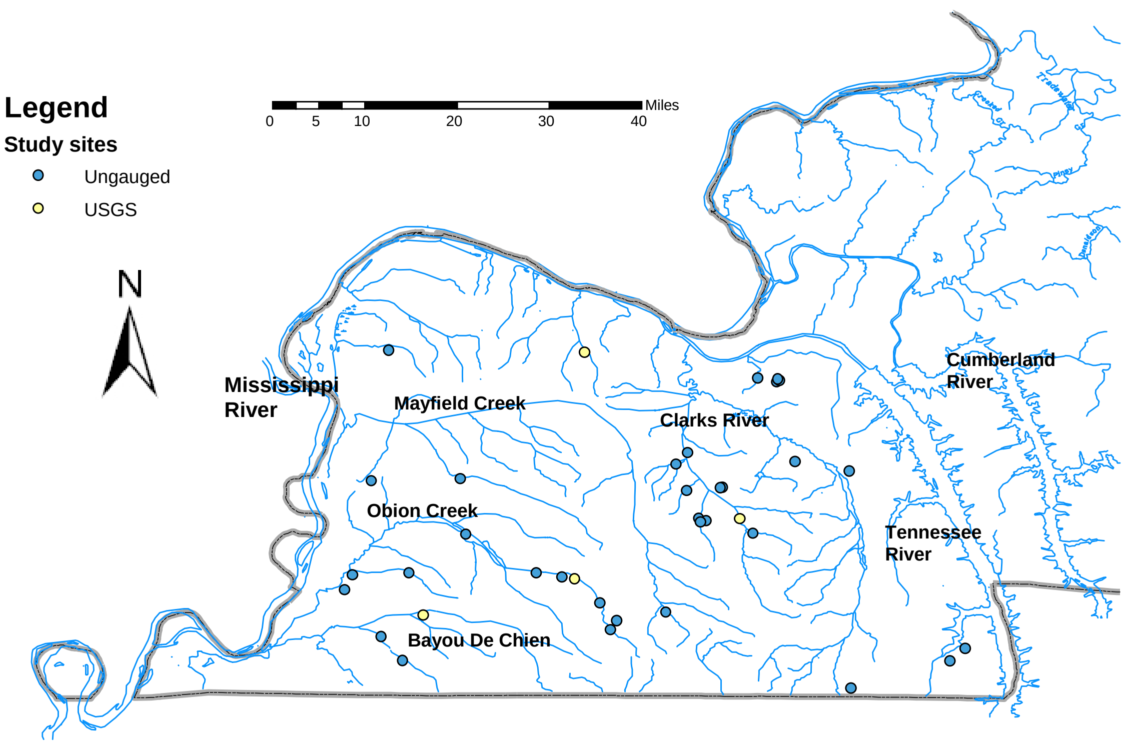

Figure 3.3 Study sites within the Mississippi Embayment.

3.4 DATA REDUCTION

USGS Gauging Stations

Collected survey data were adjusted for the gauge datum using information from USGS Form 9-207 for each gauge. The station stage-discharge rating table then was used to determine the discharge associated with the elevations of several suspected indicators of bankfull conditions—indicators such as the lowest level of tree growth, stain lines on bridges, or scour lines along banks.

Annual flood series data were analyzed to estimate the return period of discharges associated with the elevation of suspected bankfull indicators and also with the top of bank. Discharges associated with several return periods were determined and compared to estimated bankfull discharges as a function of contributing drainage area.

Return periods were estimated using the Log-Pearson Type III method, a method used extensively in engineering for estimating flood frequency (USIACWD, 1982). Flood-frequency analysis was conducted using a spreadsheet in accordance with the Log-Pearson Type III Method.

Channel cross section area, width, and mean depth associated with the top of bank, and elevations of bankfull indicators and elevations of stain lines on bridge piers were computed using the field survey data. In combination with discharge measurements obtained from stage-discharge relations of the gauging station, these data were used to estimate mean flow velocities.

Local valley slope and valley bottom width were determined from USGS 7.5 minute quadrangle topographic maps for each site. Local valley slope was determined by measuring the down-valley distance between adjacent contour lines. Valley bottom widths were determined from the cross-valley distance between contours where a significant increase in ground surface gradient was observed, indicating valley hillside slopes or slopes extending to terraces.

Un-Gauged Streams

Data obtained from the rapid measurement method were reduced to a local coordinate system and channel cross section geometric parameters were computed using a simple spreadsheet analysis program. These basic data and parameters include

- Channel area
- Width
- Mean depth (area divided by width)
- Maximum depth
- Floodprone width (measured at twice maximum depth)
- Entrenchment ratio (floodprone width divided by bankfull width)
- Bank height ratio (see comments below)

See Rosgen (1996) for a detailed description of each parameter. Appendix D provides the data from each ungauged site used in the analysis provided in Section 4.

Valley bottoms in the Mississippi Embayment were observed to be very flat and wide. Where valley flats were determined to be the active floodplain, the floodprone width was estimated to be greater than 10 times that of the channel. An example is Obion Creek downstream of the 307 bridge in Hickman County, where the valley bottom width is on the order of 5000 feet and the channel width is less than 50 feet. In incised channels where the elevation prescribed for measuring the floodprone width was lower than the valley flat, the width was measured in the field.

A parameter titled relative incision, R_{cvf}, was developed here to characterize the degree to which the top of the bank for the incised bankfull channel approaches the surrounding valley flat, assumed to be the elevation of the active floodplain prior to channelization activities. Relative incision is defined here as the ratio of the height of the valley flat from the stream bottom, I_{cvf}, relative to the maximum depth of the channel at bankfull, $D_{bkf,max}$, as indicated in Figure 3.4. A relative incision of unity would indicate that the active floodplain is the valley flat, whereas a relative incision of 2 would indicate that the embryonic floodplain is at an elevation approximately equal to the maximum depth (relative to the bankfull stage) in the channel cross section. Where the relative incision was greater than 2.0, the floodprone width was measured; otherwise, the floodprone width was considered greater than 10 times the width of the channel.

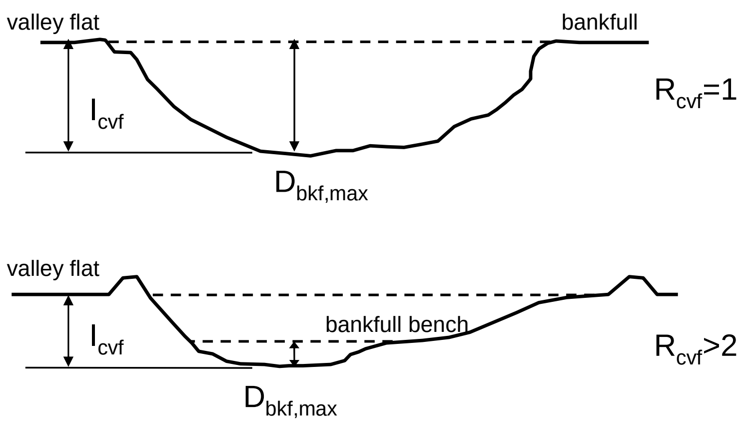

Figure 3.4 Relative incision.

Bankfull Geometric Characteristics of Channels

4

4.1 BANKFULL DISCHARGE

USGS Gauging Stations

Four gauging stations in the Mississippi Embayment were visited to determine what, if any, significance is associated with stain or scour lines on bridge piers. Bridge stains or bank scour lines have been used (D.L. Rosgen, 2005, pers. comm.) as an indicator of the bankfull flow level. When measured at a gauging station, these data can be used to determine the associated discharge from the stage-discharge curve for the gauge. Often these indicators are used as secondary or confirmatory indications that the bankfull level has been identified appropriately using robust morphologic features.

A summary of the scour line survey measurements and data analysis at each gauging station is presented below in Table 4.1. These data reveal that scour or stain lines were found to be associated with the stage at which flow reaches the valley flat elevation. The valley flat level represents the dominant change in the stage-discharge relationship on these incised channels;

Table 4.1 Summary of Scour Line Analysis at USGS Gauging Stations

Stream Name	USGS Gauge ID	Drainage Area (mi^2)	Feature Associated with Scour Line	Corresponding Discharge (cfs)	Corresponding Return Period (years)
Bayou De Chien	07024000	68.7	valley flat	1060	1.035
Massac Creek	03611260	14.6	valley flat	2084	2.22
Obion Creek	07023500	36.8	valley flat	4009	1.55
West Fork Clarks	03610545	68.7	valley flat	7058	3.9
			left bank change in slope	983	1.004

increases in discharge are coupled with only minor changes in stage when the flow is distributed over a wide valley flat. This phenomenon causes suspended sediments and floating debris to remain at this stage for a wide range of flows above that which exceeds the top of bank. The lack of significance associated with staining on piers below the top of bank is attributed to the lack of a significant break in the stage-discharge relationship for flows that do not reach the valley flat. A scour or stain line can develop below the top of bank when a depositional feature of sufficient width to invoke a break in the rating curve develops, a condition which is associated with latter stages of channel evolution.

The frequency with which flow reaches the stain or scour lines identified during this study is associated with the degree to which the channel is incised relative to the valley flat. This incision may take the form of direct channel alterations, which often produce deepened and enlarged channels, or incision associated with downstream bed degradation which has propagated into the study reach. The high frequency with which the discharge reaches the valley flat on Bayou de Chien, which appears on maps and aerial photographs to have been channelized, suggests that 1) the constructed channel was not over-excavated to a high degree, or 2) the bed has aggraded to the point at which further aggradation would result in overbank floodplain construction or channel avulsion.

In contrast, the relatively low frequency at which flow reaches the valley flat at the West Fork Clarks River site, which also appears to have been channelized based on review of maps and photographs, suggests that the channel was excavated to a much greater degree relative to the undisturbed channel depth, or significant bed aggradation is not yet occurring. However, survey data suggest that a lower stain line is associated with a break in slope at the left bank. This situation suggests the possibility that the depositional feature associated with this stain line is of sufficient width to invoke a break in the stage-discharge relationship.

In addition to evaluation of stain lines on bridge piers, the relative elevation of woody vegetation growth on the stream banks was investigated to determine if these elevations are associated with a consistent frequency of inundation, below which flows are too frequent to allow vegetation development. Analysis of this potential bankfull indicator did not yield meaningful or consistent results and thus is not described further herein; this finding was also documented by Williams (1978).

The valley flat level is not considered to be an active morphologic feature at the gauging sites studied herein, largely because of prior channel alterations. The result of prior alterations is high variability in the frequency associated with the stain or scour lines observed at the bridges. However, two scour lines—one on Bayou de Chien and the other on the lower line at the West Fork Clarks River—appear to be associated with flows similar to the bankfull flows estimated for the un-gauged bankfull measurement sites, as discussed below.

Un-Gauged Streams

Where bankfull channel characteristics were collected at gauging stations, the return period of the bankfull flow can be estimated; however, unreliable bankfull indicators at gauging stations prevent direct use of the gauge data to estimate flow or return intervals. To provide some indication of bankfull flow return interval, flow was estimated at each of the un-gauged sites. Estimates of bankfull flow discharge were developed using the bankfull area measured at each ungauged site (see Appendix D) and estimates of the cross section average velocity based on the bed material type as given in Table 4.2. These estimated flows were compared to flows for several different return intervals obtained from curves of predicted flow as a function of drainage area. Vesely (in preparation) found good correlation between average bankfull flow velocity and bed material size class in the Southeastern US Coastal Plain. He recommended the use of Table 4.2 to provide estimates of bankfull flow when other methods were not available.

Table 4.2 Estimated Average Channel Velocity for Bed Materials in the Southeastern US Coastal Plain (Vesely, in preparation)

Bed Material	Average Channel Velocity at Bankfull Conditions (feet per second)
Silt	1.5
Sand	2.0
Bimodal gravel and sand	2.5
Gravel	3.5

Comparisons of flows associated with the various stain or scour lines and the estimated bankfull discharges are shown in Figure 4.1. Bankfull discharge estimates associated with the two aforementioned Bayou de Chien and West Fork Charles River scour lines are, for the same drainage area, close to the bankfull discharge estimates based on morphologic features. Mean velocities associated with the stain line at Bayou de Chien and the lower line at West Fork Clarks River, both bimodal bed sediment streams, are 2.5 and 2.6 feet per second, respectively.

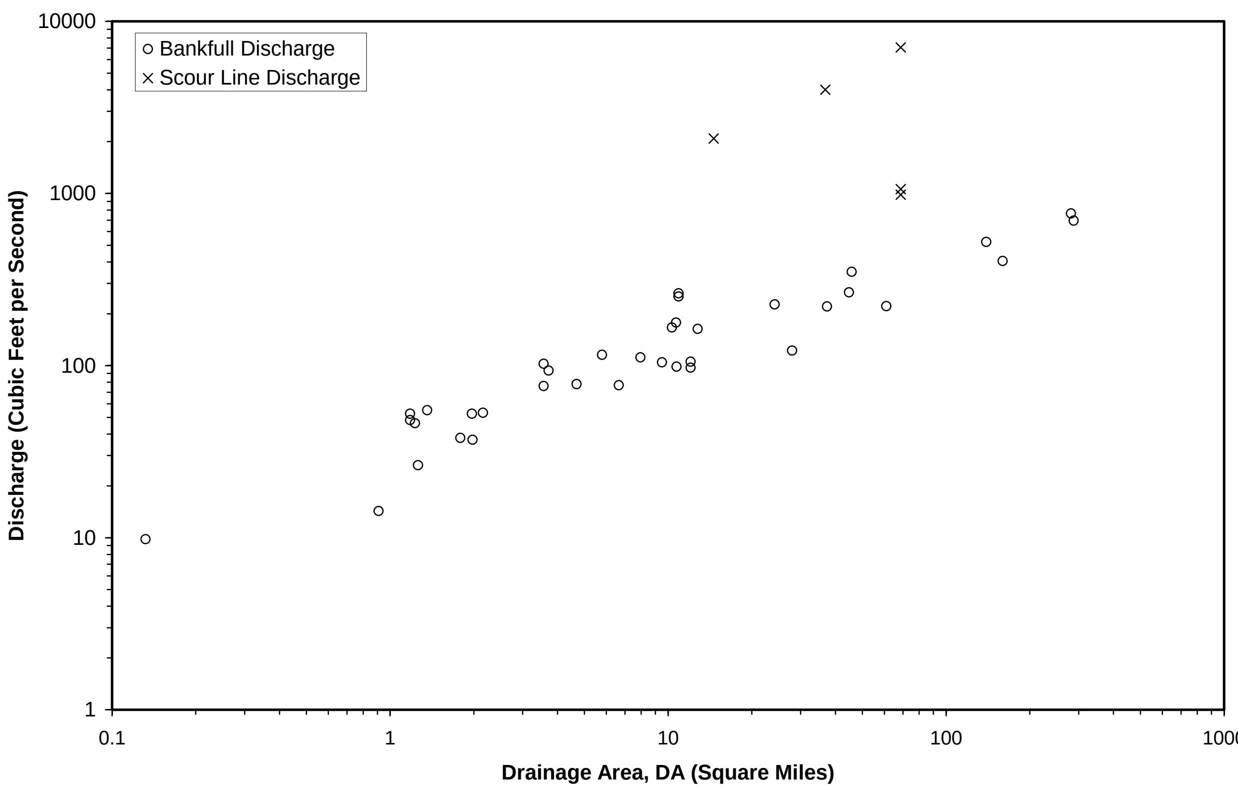

Figure 4.1 Bankfull and scour line discharge as a function of drainage area.

4.2 DEVELOPMENT OF 1.01- AND 1.5-YEAR RETURN INTERVAL CURVES

Using data from all USGS gauging stations in Kentucky with more than 10 years of record, frequency analysis based on the annual maximum flood record was conducted using the Log-Pearson Type III distribution (McCuen, 1998) as described in *Guidelines for Determining Flood Flow Frequency* (USIACWD, 1982). Flows corresponding to the 1.01- and the 1.5-year events were estimated for gauging stations across Kentucky and for the five eligible stations within the Mississippi Embayment (real time stations—Massac, Bayou de Chien, and Clarks at Almo; inactive stations —Obion at Pryorsburg and West Fork Clarks at Brewers). Using all the gauging stations in Kentucky, polynomial regression based on the method of least squares (Neter and Wasserman, 1974) was used to develop power functions (see Table 4.3) from the gauging data for specific return periods, $Q_{t\text{-return}}$, in the following form:

$$Q_{t\text{-return}} = a\, DA^{b} \qquad (1)$$

The variable DA (mi^2) is the drainage area, and *a* and *b* are a coefficient and exponent, respectively, determined from the regression analysis.

Table 4.3 Regression Equations of 1.01- and 1.5-Year Events Based on Gauge Data

Region	Regression Equation	Coefficient of Determination, R^2	Standard Error*, S_e
Kentucky	$Q_{1.01} = 38.3\ DA^{0.79}$	0.87	149.0%
	$Q_{1.5} = 152\ DA^{0.71}$	0.94	56.9%
Mississippi Embayment	$Q_{1.01} = 76.7\ DA^{0.68}$	0.89	65.7%
	$Q_{1.5} = 265\ DA^{0.62}$	0.97	25.7%

Figure 4.2 clearly indicates that the return interval for bankfull flows is substantially less than 1.5 years. The 1.01 year event tends to form an upper limit. One reason for the relatively small channels and low flows may be the extremely well developed floodplains, small sediment sizes, and assumed low bedload sediment loads.

4.3 BANKFULL GEOMETRY

The characteristics of bankfull channel cross section area, top width, and depth collected in this assessment project were examined with respect to the drainage area of the watershed contributing to the channel at the location of the observations. The curves relating bankfull channel cross sectional characteristics and the contributing drainage area are collectively referred to as bankfull regional curves. Curves for gravel-bed, sand-bed, and silt-bed streams were developed separately. Data from western Tennessee by Smith and Turrini-Smith (1999) were included in the analysis for sand-bed and silt-bed streams. Polynomial regression based on the method of least squares (Neter and Wasserman, 1974) was used to develop power functions of the following form:

$$Y_{BKF} = a\, DA^{b} \qquad (2)$$

The variable Y_{BKF} represents the following bankfull parameters: flow area, A_{BKF} (ft^2), channel bankfull width, W_{BKF} (ft), or average flow depth, D_{BKF} (ft). The variable DA (mi^2) is the drainage area. Table 4.4 provides the results of the regression analysis for each, and Figures 4.3 through 4.5 show plots of the resulting power curves and data from which they were developed.

Gravel-bed streams were found for watershed areas in the range of 1 to 40 square miles, sand-bed streams were found for watershed areas from 3 to 2000 square miles, and silt-bed streams were found for watershed areas from about 0.9 to 900 square miles. The range of these

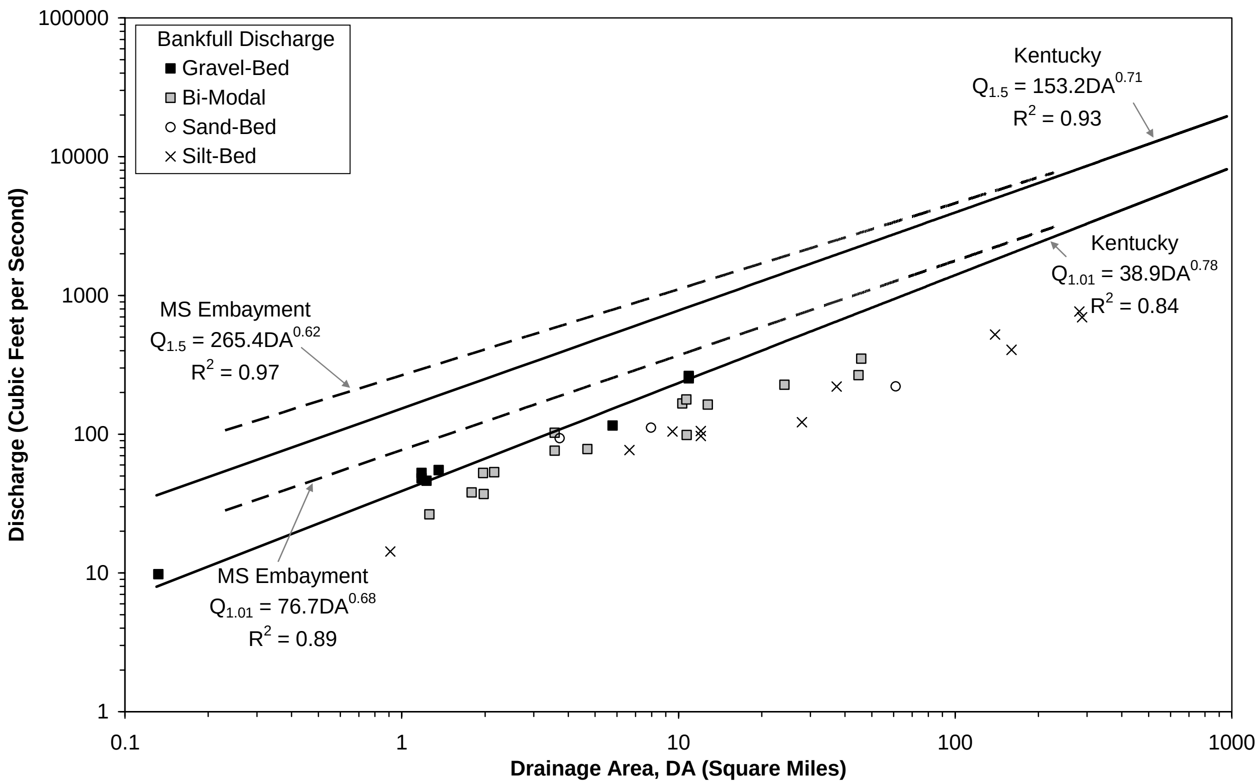

Figure 4.2 Regression Curves for Q1.01 and Q1.5 Derived from Gauges Across Kentucky and from the Mississippi Embayment, with Estimated Bankfull Flows from the Mississippi Embayment.

Table 4.4 Regression Equations of Channel Bankfull Characteristics for Streams of the Mississippi Embayment of Kentucky

Bed Material	Regression Equation	Coefficient of Determination, R^2	Standard Error*, S_e
Gravel bed	$A_{BKF} = 12.1\ DA^{0.64}$	0.93	21%
	$W_{BKF} = 12.1\ DA^{0.41}$	0.81	21%
	$D_{BKF} = 1.00\ DA^{0.23}$	0.48	28%
Sand bed	$A_{BKF} = 16.7\ DA^{0.57}$	0.91	41%
	$W_{BKF} = 10.5\ DA^{0.34}$	0.90	26%
	$D_{BKF} = 1.60\ DA^{0.22}$	0.79	26%
Silt bed	$A_{BKF} = 13.1\ DA^{0.63}$	0.93	31%
	$W_{BKF} = 9.47\ DA^{0.35}$	0.92	19%
	$D_{BKF} = 1.38\ DA^{0.28}$	0.83	23%

* transformed from the log10 domain as a percentage of the mean according to Tasker (1978).

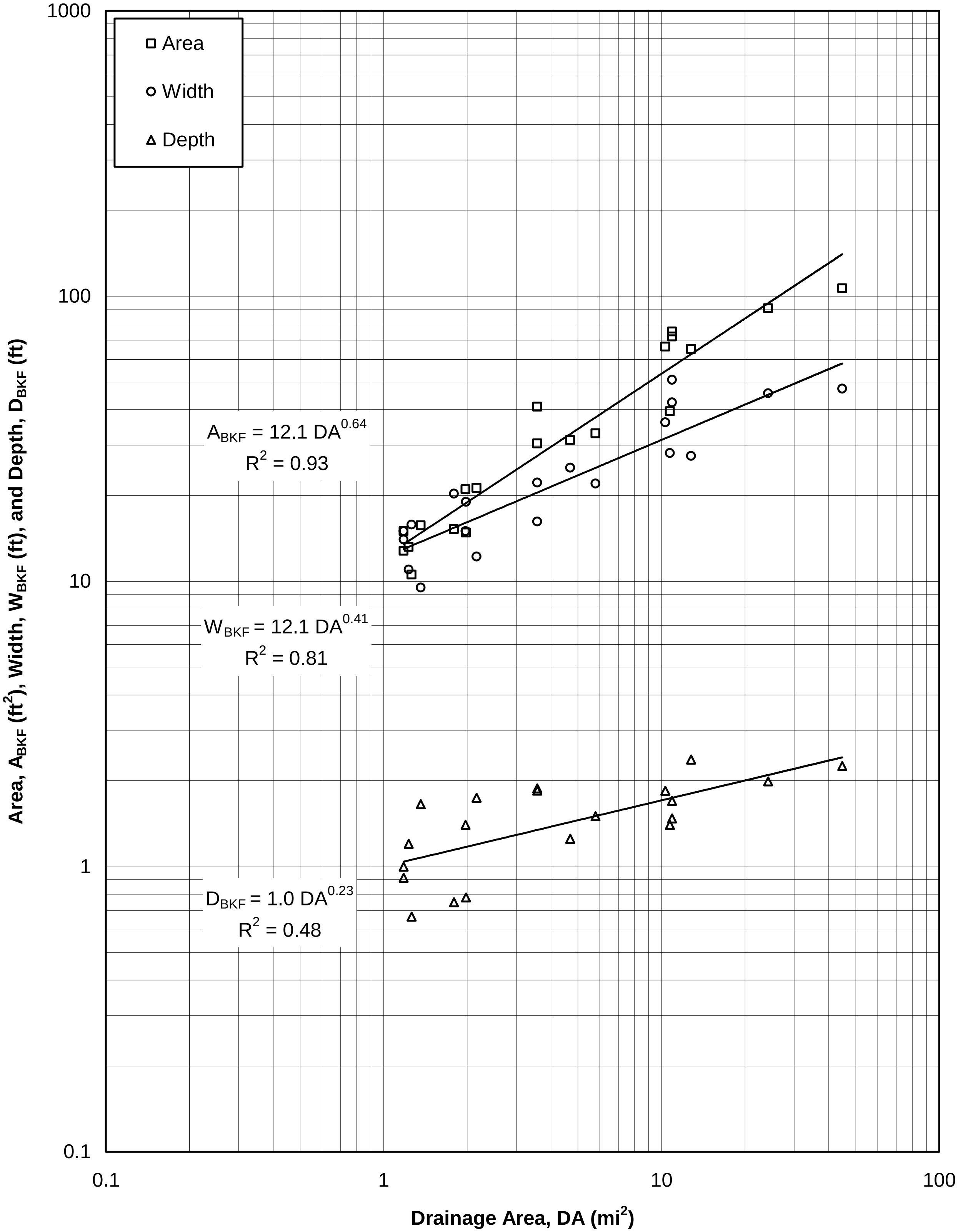

Figure 4.3 Bankfull cross-sectional characteristics of gravel bed streams in the Mississippi Embayment of Kentucky.

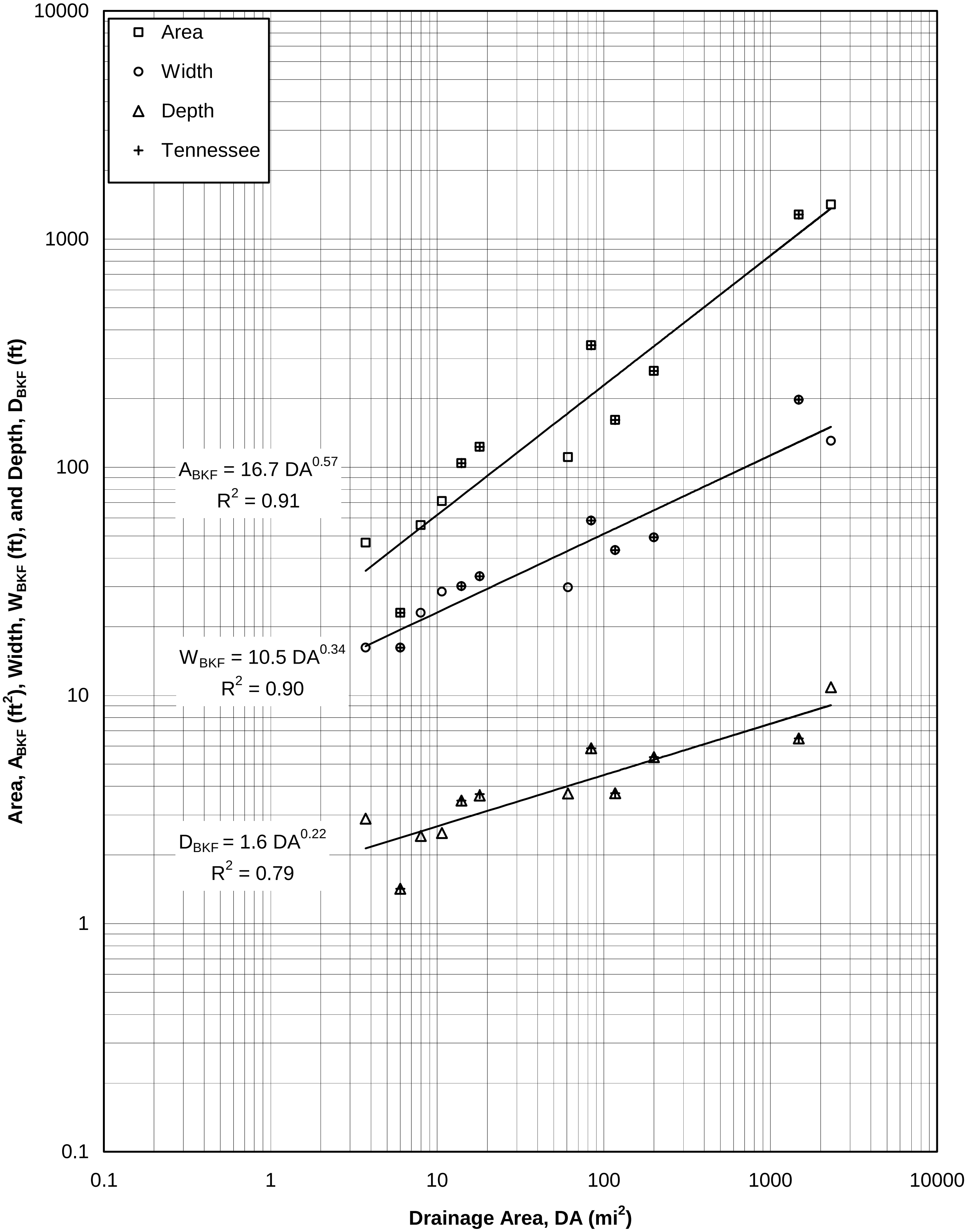

Figure 4.4 Bankfull cross-sectional characteristics of sand bed streams in the Mississippi Embayment of Kentucky and western Tennessee.

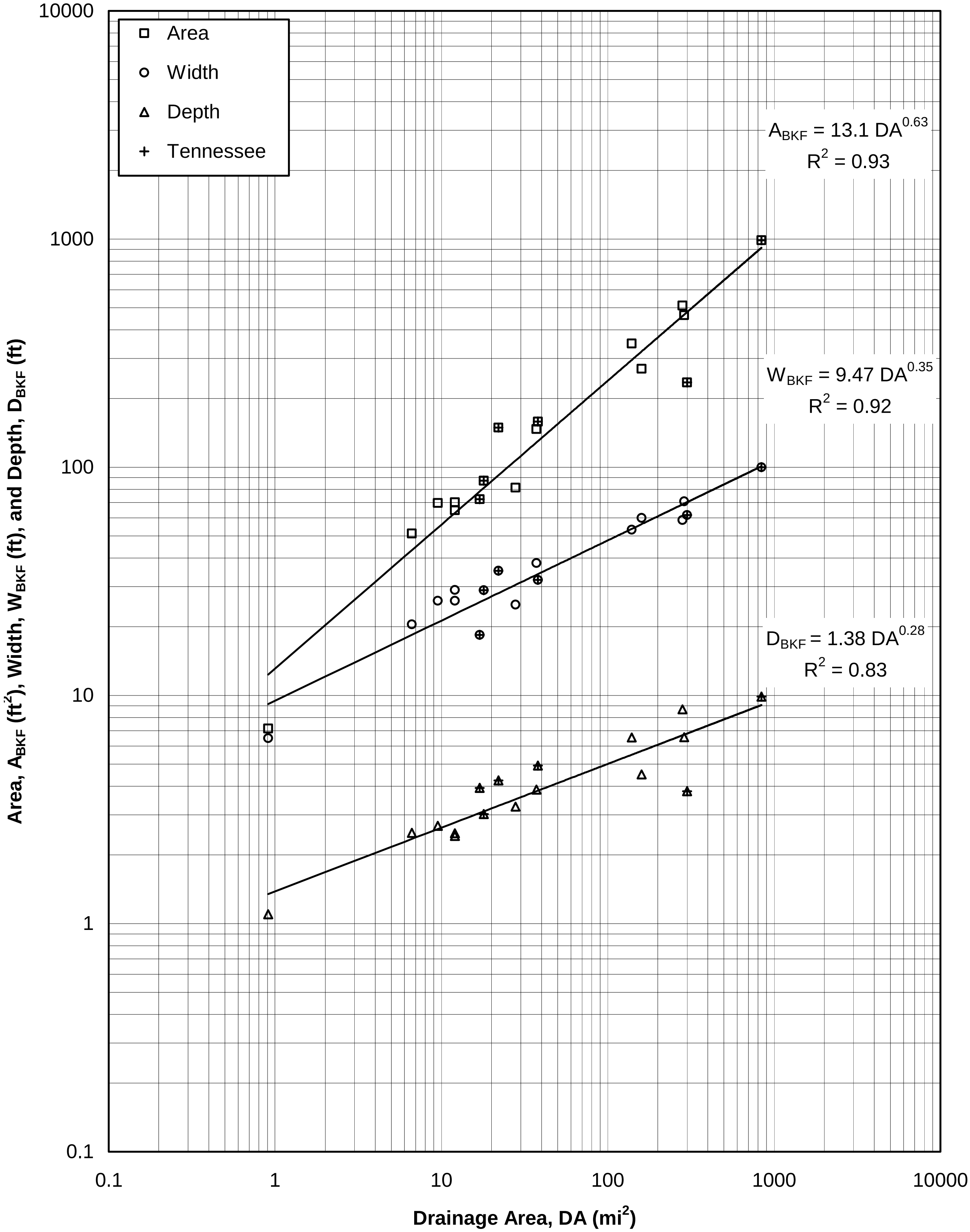

Figure 4.5 Bankfull cross-sectional characteristics of silt bed streams in the Mississippi Embayment of Kentucky and western Tennessee.

data should be considered a minimum range rather than a maximum range for streams with each type of bed and is primarily a function of the abundance of streams with a particular bed material. In several locations, the bedload was gravel moving over a subsurface of fine-grained and apparently cohesive material such as clayey silt.

The large number of gravel-bed streams with watersheds in the 1.0 to 10 square mile range examined in this project include streams that have upstream reaches cutting through a layer of gravel (Lafayette or other formation). These streams have incised, either naturally or because of channelization, through the blanket of loess and into the gravels. The Lafayette formation is a massive layer of gravel and sand which is thought to be a delta deposit of the ancestral Tennessee River and the Cumberland-Ohio Rivers (see Section 2, Figure 2.4 and Table 2.2). Other small streams, primarily those draining into the modern Tennessee River (Kentucky Lake) and the Clarks River are incised into basal cherty gravel and silt of late Cretaceous age. Unlike the situation in streams that transport gravel derived from local weathering of bedrock, the gravels derived from the Lafayette formation have been transported and sorted previously; therefore, cobbles and boulder size material found in these streams have come from riprap protection or other sources of imported rock.

Morphological Assessment of Biological Reference Reaches | 5

The Kentucky Division of Water (KDOW) has established 35 biological reference reaches in the Mississippi Embayment, broadly distributed across the region. Channel geometry was measured at five of these biological reference reaches to provide morphologic data that may be used by KDOW for establishing an association between channel morphology and biological indices. The five reaches examined were selected to provide data for a wide range of contributing drainage areas, and to be broadly distributed across the region. The list of the selected biological reference reaches and a summary of morphological data are provided in Table 5.1.

5.1 DATA COLLECTION AND REDUCTION

Channel measurements were obtained at riffle crests or local topographic high points of the bed at the biological reference sites. Unambiguous bankfull indicators were not present on any of the reaches, which is an indication of instability at all sites. To obtain an estimate of cross-sectional area in the biological reference reach, bankfull area was approximated using one of the following: (1) measurements of bankfull area on the same stream but upstream or downstream of the biological reference reach; (2) measurements of bankfull area from an abandoned channel that may have been cut-off from the current active channel during channelization; or (3) equations that express regional relations developed in Section 4 of this report. Other channel parameters of Table 5.1 were derived by identifying the bank elevation at which the cross-sectional area of the biological reference reaches would be equal to the bankfull area determined as described above.

Channel relative incision, R_{cvf}, is the ratio of channel incision, I_{cvf}, to the maximum depth in the channel cross section at bankfull discharge, D_{max} (see Figure 3.4 for graphical definition of variables). The relative incision represents the degree to which the channel has incised compared to the valley flat. A relative incision of 1.0 indicates that the top of the bank, the valley flat, and the bankfull stage are all at approximately the same elevation. Relative incision ratios greater than 1.0 indicate that the channel has incised compared to the valley flat and that the level at which an active floodplain is forming is lower than the valley flat. The entrenchment ratio, E, has been used by Rosgen (1996) to classify streams according to the available width of floodplain above the bankfull stage for frequent floods that are currently building the active floodplain. The entrenchment ratio, E, is the ratio of the floodprone width, W_{fp}, to the channel bankfull width, W. The streams were classified using the parameters of Table 5.1 according to the Rosgen classification system (Rosgen 1996).

In addition to channel cross section characteristics, parameters descriptive of the valley setting also were measured. Valley width, W_v, channel sinuosity, K, and valley slope, S_v, were obtained from a combination of measurements based on aerial photographs taken in the 1990s and from USGS 7.5 minute topographic maps.

5.2 ASSESSMENT OF STREAM MORPHOLOGY AT BIOLOGICAL REFERENCE REACHES

The well-developed, wide valleys of this coastal plain region of Kentucky naturally supported sinuous stream channels. Measurement of remnant channel reaches and stream-based property boundaries established prior to major channelization of streams indicate that stream sinuosity may have exceeded 1.5 for streams in the Mississippi Embayment. According to the Rosgen valley classification system (Rosgen 1996), all of the valleys would be classified as type VIII or type X valleys which support sinuous E- and C-type streams. The data from Table 5.1 show sinuosity of less than 1.2 for all but one of the streams investigated in this study, typical of previously channelized streams. The lack of sinuosity in these streams may play an important role in the low variation of pool depth and the lack of general channel complexity. High channel complexity is typical of high quality stream habitat.

Relative incision greater than 2.0 for all streams indicates that these streams are deeply incised compared to their valley flats. As a consequence of the deep incision, all streams are moderately (B stream types) or severely entrenched (F and G stream types). The low sinuosity and high entrenchment results in boundary shear stresses on the order of 3 to 6 times those that would occur under natural conditions for flows that reach the top of the banks. The confinement of moderate size flood events to the channel, the increased depth of the flood flows caused by channel incision and the increase in channel slope due to channel straightening contribute to the increase in boundary stress for these streams. In addition, form drag associated with channel bends and bed undulations caused by sinuous planform is probably much less than in natural non-entrenched and sinuous planform streams. The mobility of surface sediment that affects the frequency of bed movement, and the capacity of the channels to convey sediment, have increased substantially, because both are sensitive to increases in boundary stress. Although trees on straight channel reaches appear to stabilize the banks in the biological reference reaches, severe bank erosion is occurring where channels are actively incising upstream, and near channel bends upstream and downstream of the biological reference sites.

Table 5.1 Stream Morphological Characteristics and Classification for Selected Biological Reference Reaches of the Mississippi Embayment

Stream Name	Biological Station ID	DA (mi^2)	K	S_v (ft/ft)	R_{cvf} I_{cvf} / D_{max}	A_{bkf} (ft^2)	W (ft)	D (ft)	D_{50} (mm)	W/D	E	Stream Type (Rosgen 1996)	Channel Alterations and Channel Evolution
Shawnee Creek	07002001	10.6	1.40	0.0031	2.3	66.5*	32.7	2.03	9.9	16	1.5	B4	Extensive planform redeveloping in previously channelized reach
W. Fork Mayfield Creek	07006001	44.2	1.13	0.0010	2.1	175.1*	40.8	4.29	4.5	10	1.2	F4/G4c	Extensive channel network channelization with only some local planform redevelopment
Obion Creek	07014002	60.8	1.01	0.0012	4.3	110.6†	57.4	1.93	8.0	30	1.1	F4	Extensive channel network channelization with only minor planform redevelopment
W. Fork Clarks River	09010009	3.59	1.01	0.0033	5.2	29.8‡	29.2	1.02	12.5	29	1.1	F4	Extensive channel network channelization with only minor planform redevelopment
Grindstone Creek	09016010	1.35	1.16	0.0099	3.6	14.7‡	20.1	0.73	22.0	28	1.4	B4	Extensive channel network channelization with only minor planform redevelopment

Variables:
DA = drainage area (mi^2)
K = channel sinuosity
S_v = valley slope
I_{cvf} = elevation difference of valley flat from streambed (ft)
D_{max} = local maximum depth at bankfull flow (ft)
A_{bkf} = bankfull flow area (ft^2)
W = channel bankfull top width (ft)
D = channel average bankfull flow depth (ft)
D_{50} = mean particle size of bed material in riffles
E = Entrenchment Ratio

Notes:
* based on nearby measurement of active channel
† based on nearby measurement of inactive channel
‡ based on Section 4 regional relation

Application of Regional Geomorphic Relations 6

Estimates of expected channel dimensions and bankfull flow are useful for the assessment of channel stability and habitat and are critical for the design of channels for stream restorations. Estimates of bankfull parameters can be obtained from measurement of channels in the watershed, from measurement of similar channels in the region, or through analytical procedures such as the development of an effective discharge (Biedenharn et al. 2000; Copeland et al. 2001; Soar and Thorne 2001). In channels undergoing rapid change, however, bankfull indicators at a site may not be apparent or may be ambiguous. In those cases, regional curves may be useful for estimating bankfull flow and channel geometric characteristics for a particular watershed size.

6.1 STREAM STABILITY AND BASIN SEDIMENT ASSESSMENT

In assessing channel stability and habitat, an estimate of bankfull flow conditions is particularly useful for

1. classification of the stream reach using the Rosgen (1996) method
2. determination of the degree to which the stream is incised
3. indication of relative bank stability
4. indication of some characteristics of channel pattern
5. indication of the capacity of the channel to transport its supplied load

The regional curve equations and statistics provided in Table 4.4 and the plots provided in Figures 4.3–4.5 permit estimates of channel characteristics for streams of the Mississippi Embayment of Kentucky and indicate the variability of those channel characteristics. Some data from the Mississippi Embayment region of Tennessee for larger sand-bed and silt-bed rivers were used to develop the relations for Kentucky; therefore, the sand-bed and silt-bed relations may also be useful for Tennessee. Although many differences exist among the highly modified stream networks of the Mississippi Embayment, relations between watershed area, channel bankfull flow, and channel dimensions are reasonably reliable, with standard errors typically less than 30 percent for channel cross-sectional area, channel width, and channel average depth. Local watershed and channel conditions, however, may cause channel bankfull flows and bankfull dimensions to differ significantly from those estimated from equations reported in this project. Therefore, examination of bankfull conditions on the stream of interest should be conducted, and the results should be compared to the regional relations provided in Section 4. Channel dimensions outside the range of those provided here should be examined carefully to determine the cause of the variation.

Those conducting stream assessments in the Mississippi Embayment should consider the geology, the rich land-use history, and the current land use. The cross-sectional dimensions of a channel are the product of many complex geomorphic processes, including the transport of sediment and channel evolution after disturbance. A combination of geologic factors, the sequence and magnitude of land-use activities, and the sequence of channelization of the stream networks all have significant effects on sediment loads and channel evolution. Land use affects the hydrologic conditions that generate the flows and sediment loads carried by streams. In the Mississippi Embayment, channel networks are continuing to evolve in response to altered flow and sediment loads and the effects of extensive channelization.

In-channel sediment dynamics (erosion, transport and storage) should be considered in any assessment of in-stream habitat, channel stability, or sediment load in the Mississippi Embayment. Those conducting an assessment of sediment loads of the region should consider the contribution of both fine-grained sediments (sand, silt, and clay) and coarse-grained sediment (gravel) from the streambanks of both lowland and upland streams and gullies (see Figures 2.11–2.13). Channel lateral migration in wide-valley and low-gradient reaches was apparent at many locations and is a source of mostly fine-grained sediment (sand and silt). Gravel and sand, however, are accumulating in the bed and on newly formed floodplains within some channels. The channel bars storing gravel and sand deflect flows toward banks, causing bank erosion and further development of bends. The problem of bank erosion and lateral instability of channels should be expected to increase as these straightened channels redevelop planform curvature.

Gullies are a source of both coarse and fine sediments. Although improved agricultural practices appear to be reducing overland sediment runoff and grade control structures are preventing or reducing the occurrence of gullies in upland swales, many deep gullies still exist in upland areas (Figure 2.14). These gullies have migrated upstream and appear to have extended the channel network upslope into upland swales where channels may not have been present prior to channelization.

Where small streams and gullies are crossed by roadways, culverts tend to limit the depth and extent of upstream channel degradation (see Figures 2.14a and 2.14b). Backwater effects from bridges, confluences, and debris blockages can affect channel bankfull geometry enough to make channel dimensions inconsistent with the regional curves. Many small dams also exist in the uplands of the Mississippi Embayment, and bankfull dimensions may vary downstream of these dams, where the hydrology and sediment load characteristics have been altered.

While a lack of gauging station information in the Mississippi Embayment limited the analysis of flow frequency, Vesely and Parola (in preparation) used the data from seven different studies across the coastal plain of the eastern US and showed approximately the same result: bankfull discharge is less than that of the 1.5-year event estimated using the annual series method (USIACWD 1982) for the same drainage area. In the Mississippi Embayment of Kentucky, bankfull flows appear to be less than that of the 1.01-year event (based on annual series). Use of the 1.5-year event, therefore, would represent a gross overestimate of bankfull flow in all cases examined in this study.

6.2 RESTORATION DESIGN

In designing stream restorations, bankfull characteristics estimated from the bankfull relations given in Section 4 of this report are useful for

1. initial estimation of channel geometry for planning of a restoration project prior to detailed morphological assessments required for final design
2. estimation of channel design parameters for sites where morphological characteristics are inconsistent or have not been developed
3. comparison of restoration designs developed using other methods
4. evaluation of restoration designs by permit agencies

Because regional curves provide regional estimates of bankfull parameters that broadly describe stream conditions, they do not include specific conditions that would form channels at specific sites. Therefore, while regional curves provide a means of checking the reasonableness of channel design dimensions and flows, they are not a means of design verification. On the other hand, designers should provide justification for channel dimensions that are outside the range of the data provided in Section 4.

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Appendices

Mississippi Embayment Lithostratigraphic Descriptions

C

Lithostratigraphic descriptions provided in the following table are excerpted from McDowell, R.C., ed. 2001. The Geology Of Kentucky—A Text To Accompany The Geologic Map Of Kentucky. USGS Professional Paper 1151-H. Prepared in cooperation with the Kentucky Geological Survey. January.

System	Map Code	Formation, Member and Bed	Description
Quaternary	Qa	Alluvium *(unnamed)*	Alluvium occurs throughout Kentucky and is shown along most of the larger streams and tributaries... It is particularly extensive along the Ohio River and its tributaries in western Kentucky and in the Mississippi Embayment. As shown on this map, alluvium also includes sediments mapped on the geologic quadrangle maps as (low) terrace and floodplain deposits, and in western Kentucky as outwash deposits. Small areas of low-lying glacial deposits, such as lacustrine and eolian sediments, are also included locally. Alluvium consists of boulders, cobbles, pellets, sand, silt, and clay in various proportions; it is as much as 200 ft thick along major rivers. Most alluvium is Holocene, but some is late Pleistocene.
	QTcl	Continental deposits and loess *(various)*	Continental deposits mapped separately and with loess are extensive and mappable only in far western Kentucky in the Mississippi Embayment… West of the Tennessee River (Kentucky Lake), in the Mississippi Embayment region, continental deposits and loess were combined into a single unit. The continental deposits consist mainly of a basal gravel grading upward into sand with interbedded silt and clay. The gravel is made up of subangular to subrounded chert pebbles, cobbles, and boulders with smaller amounts of rounded to well-rounded quartz and quartzite pebbles. The sand is composed dominantly of fine to coarse grains of quartz with minor amounts of chert and, locally, mica and is yellowish orange to reddish brown. The continental deposits may represent two periods of deposition: Miocene(?) and Pliocene deposits occur on the higher elevations, and Pleistocene deposits are inset at lower elevations. Included in the continental deposits is a sequence commonly referred to in the southeastern region as "Lafayette Gravel," a vast, complex Pliocene alluvial fan composed of sediments transported from a southeastern source and deposited by the ancestral Cumberland and Tennessee Rivers. Parts of this fan were dissected and the gravels redeposited during the Pleistocene. Loess in the Mississippi Embayment region consists of windblown silts assigned to three Pleistocene formations separated by unconformities marked by buried soils. The formations are the Peoria Loess (Woodfordian Substage of Wisconsinan), the Roxana Silt (Altonian Substage of Wisconsinan), and the Loveland Loess (Illinoian). The Peoria Loess is characteristically pale yellowish gray and is as much as 65 ft thick along the Mississippi River. The Roxana Silt is reddish brown and contains lenses of sand in the lower part; it is as much as 20 ft, but generally is less than 5 ft thick. The Loveland Loess is grayish orange and less than 10 ft thick; it has been recognized only in small areas west of Paducah. The windblown silt was probably derived from glacial outwash in the Ohio and Mississippi Valleys to the north and west.

System	Map Code	Formation, Member and Bed	Description
Cretaceous / Tertiary	Tjc	Jackson and Claiborne Formations	The Claiborne and overlying Jackson Formations (middle and upper Eocene) are combined on the map to form a single unit. In the Mississippi Embayment, beds of Oligocene age are included in the uppermost part of the Jackson Formation… The Claiborne Formation is composed of sand containing lenses of clayey silt, silty clay, and lignite. The sand is white, light gray, and brown and weathers yellowish orange to reddish brown; it is composed of well-sorted, angular to rounded, fine to medium grains of quartz and minor amounts of muscovite and chert. Bedding is thin to thick, and crossbedding and cut-and-fill structures are common; in places, angular to rounded clasts of clay are present. Clayey silt and silty clay are light gray to black, brown, and olive gray, and weather yellowish orange, red, and white. Dark varieties are generally lignitic, and lignite occurs locally in beds generally less than 5 ft thick. The Jackson Formation consists of two facies, fine and coarse. The fine facies, composed mainly of silty clay and clayey silt, grades northward and eastward into the coarse facies, a sequence of sand and lenses of silty clay. The silt and clay are olive gray to light green and light gray to black and are locally very sandy and micaceous. Some clay samples contain pumiceous glass of volcanic origin. Sand is moderate gray to light gray and brown and weathers yellowish orange to reddish brown. It is composed of fine to very coarse grains and in places contains pebbles of quartz with minor amounts of white, light-gray, yellow, and, less commonly, black chert. Angular to rounded pebbles to boulders of clay occur locally. The sand is thin to thick bedded with common crossbedding and cut-and-fill structures.
	Tw	Wilcox Formation	The Wilcox Formation, of early Eocene age, is composed of interbedded sand, clay, and silt. The sand is light gray and brown and weathers yellowish orange to reddish brown. It is composed mostly of fine to medium quartz with minor amounts of chert and muscovite and rare glauconite, biotite, and feldspar; sorting is poor. Bedding is thin to thick, and crossbedding and cut-and-fill structures are common. The sand is usually clayey or silty and in many places contains locally derived angular to rounded pebbles, cobbles, and boulders of clay. These coarse sediments occur mostly near the base of the formation in channels eroded into underlying units. "Sawdust sand," the most distinctive rock type in the formation, is composed of fine to medium grains of quartz, white chert, and kaolinite which impart a speckled appearance. This lithotype is dominant in some areas and absent in others. The silty clay and clayey silt are light gray or brown to black and weather yellowish orange to white. Kaolinite and illite are the dominant clay minerals. Marcasite and pyrite nodules are locally present. In many places lignitized plant material is present, and lignite lenses occur sparsely. The thickness of the Wilcox is extremely variable because of the irregular erosion surface on which it was deposited and because of extensive postdepositional erosion.

System	Map Code	Formation, Member and Bed	Description
	Tp	Porters Creek Clay	The Porters Creek Clay of Paleocene age is divisible into three units: interbedded sand and clay in the upper and lower parts separated by a thicker dominantly clay unit in the middle. The clay is light gray to black or brownish gray. It is characteristically faintly mottled and slightly to very sandy, and it contains fine muscovite flakes and rare glauconite, biotite, and glass shards. Typically, the clay is brittle and breaks with a conchoidal fracture. In the upper and lower units, the clay contains carbonized, silicified, and rare pyritized fragments of wood. The sand is olive gray, medium to dark gray, and bluish gray and weathers yellowish orange or reddish brown. It is composed of fine to medium, angular grains of quartz and minor amounts of muscovite, glauconite, magnetite, and other minerals. In places the sand is cemented with silica into a resistant orthoquartzite. The presence of glass shards suggests a volcanic origin for part of the sediments. Vertical clastic dikes of glauconitic and micaceous sand, mostly less than 2 ft wide, occur in many places in the Porters Creek Clay. They probably resulted from local seismic activity. The high degree of weathering of these dikes, and their location at higher, drier elevations, suggest that they are pre-Pleistocene in age. Fossils are rare except for palynomorphs, which indicate a marine environment, probably a warm, shallow epeiric sea, with a brackish, nearshore deltaic environment to the northeast, where a major river may have entered the sea.
	TKcm	Clayton and McNairy Formations	The McNairy Formation (Upper Cretaceous) and the overlying Clayton Formation (Paleocene) are combined on the map as a single unit. These two formations are separated by a regional disconformity that is marked by distinct faunal and floral changes. However, because of lithic similarity and poor exposures of the formational boundary, they cannot be distinguished in the field in most places. The sequence consists mainly of light to dark-gray, fine to medium (rarely coarse) sand that weathers to yellow or reddish brown. The sand is interbedded with gray, black, or brown clay, a few lenses of chert gravel and silt near the base, and sparse lignite. The sand, dominantly angular to subangular quartz, is generally micaceous and locally contains pebbles and cobbles of clay. Bedding ranges from thin to thick, and crossbedding and cut-and-fill structures are common. *Ophiomorpha* are locally abundant in the sand. Clay, commonly micaceous, occurs in fine laminae to thick beds which contain leaf imprints or marcasite concretions in many places. Sand is dominant in the south, but the clay content increases progressively northward, and near Paducah the unit is mostly clay. The basal contact is an unconformity with as much as 150 ft of relief on the underlying Tuscaloosa Formation or Paleozoic rocks. Paleontological evidence indicates that the McNairy Formation was deposited in a marine to freshwater deltaic environment, and predominance of freshwater over marine palynomorphs suggest that the Clayton Formation is deltaic or lacustrine. Pollen studies indicated that the climate was warm temperate to subtropical.

System	Map Code	Formation, Member and Bed	Description
	Kt	Tuscaloosa Formation	The Tuscaloosa Formation of Late Cretaceous age occurs mostly just east of the Mississippi Embayment, along the Tennessee and Cumberland Rivers (Kentucky Lake and Lake Barkley), where it overlies Mississippian rocks. It is composed of light-gray gravel with scattered lenses of sand, silt, and clay; sand and silt are dominantly chert. Bedding is typically indistinct, but crossbedding occurs locally. The gravel consists of rounded chert and rare orthoquartzite clasts generally less than 4 inches in diameter. The formation rests unconformably on a paleokarst surface having a local relief of about 100 ft and represents fluvial deposits in which the original bedding has been locally modified by leaching of the subjacent carbonate rocks. The unit apparently extends downdip into the subsurface no more than 3 or 4 mi, where it is overlapped by the McNairy Formation. The configuration of the unit suggests deposition in a narrow trough opening to the south. The thickness of the Tuscaloosa ranges from 0 to 180 ft.
Mississippian	Mgl	Ste. Genevieve and St. Louis Limestones	These limestones constitute the bulk of the strata of Meramecian age and underlie broad karst plains in western, west-central and south-central Kentucky. In western Kentucky, this map unit includes the Salem Limestone of Illinois and Missouri at the base. …The St. Louis Limestone of western Kentucky is about 500 ft thick and is divided into two informal members separated by a zone of abundant chert. It is a very fine-grained, somewhat cherty, argillaceous and dolomitic limestone with some beds of skeletal limestone, formed on a shallow-marine shelf, and is characterized by the corals *Acrocyathus proliferus* and *A. floriformis* in the lower part. The lower contact is rarely exposed, and the underlying Salem Limestone, part of which is lithologically similar to the St. Louis, is included with this map unit in western Kentucky. The Salem Limestone in this area is about 120 ft thick and is composed of dark-gray, crossbedded skeletal limestone and fine-grained argillaceous limestone with some oolitic limestone at the top. A 10- to 20-ft-thick zone of extremely cherty limestone occurs near or at the top of the St. Louis Limestone in western Kentucky. The overlying Ste. Genevieve Limestone is from 190 to 320 ft thick and is divided into three members. The basal Fredonia Limestone Member, thickest of the three, is a very light gray, crossbedded and massive, oolitic to skeletal limestone characterized by the crinoid *Platycrinites*. The overlying Rosiclaire Sandstone Member… is composed of calcareous sandstone and shale, and the Levias Limestone Member is an oolitic to skeletal limestone similar to the Fredonia. The top of the Ste. Genevieve Limestone is placed below the sandy and silty fine-grained limestone of the Renault Limestone. The rocks of the Ste. Genevieve formed as sandbars and shoals on a shallow-marine shelf which supported an abundant fauna.

System	Map Code	Formation, Member and Bed	Description
	Mw	Warsaw Limestone	The Warsaw Limestone of Trigg and Lyon Counties and adjacent areas of western Kentucky is a light-gray, coarse-grained, largely crinoidal-bryozoan limestone, about 150-300 ft thick, which crops out mainly along the Cumberland and Tennessee Rivers. It overlies the Fort Payne Formation, is overlain by the Salem Limestone, and is correlated with the Ullin and Harrodsburg Limestones of southern Illinois and west-central Kentucky. The Warsaw Limestone in western Kentucky is commonly cherty and argillaceous at its base; this inner part is similar to but coarser grained than limestone of the Fort Payne Formation. The remainder of the Warsaw Limestone is composed of crossbedded, skeletal limestone with scattered chert nodules and abundant fossils…The Warsaw Limestone of western Kentucky was deposited on a shallow-marine shelf and in troughs within this shelf…The Warsaw, like most of the Upper Mississippian limestones of western Kentucky, is poorly exposed and is identified principally by a thick, reddish-brown, cherty soil.
	Mf/ Mbf	Renfro and Muldraugh Members of the Borden Formation and the Fort Payne Formation	Rocks included in this map unit overlie Lower Mississippian detrital rocks and record a major shift in sedimentary environments from basinal and deltaic to shallow-marine carbonate near the end of Early Mississippian time. The Muldraugh and Renfro Members are uppermost units of the Borden Formation, whereas the Fort Payne Formation overlies the Borden Formation along the delta front and the Chattanooga Shale elsewhere. The lower contact of unit Mbf is marked by a thin layer of glauconite and phosphatic nodules, which indicate a hiatus in sedimentation. The upper contact is gradational and in places intertonguing with Lower and Upper Mississippian limestone, dolomite, and shale...The Fort Payne and Muldraugh are Early Mississippian in age and the Renfro is Early and Late Mississippian. Rocks forming this map unit commonly have many small caverns and sinkholes and are overlain by cherty soils. …Outcrops of the Fort Payne Formation are also present along the Tennessee and Cumberland Rivers in western Kentucky…The Fort Payne Formation is as much as 660 ft thick in south-central and western Kentucky, where it overlies the Chattanooga Shale. Gray to black dolomitic siltstone and cherty, dolomitic limestone of the Fort Payne were deposited as basin fill adjacent to and southeast of the Borden deltaic sediments. …The Muldraugh Member of the Borden Formation also overlies Borden detrital rocks; it is considered to be a thinned lateral equivalent of the Fort Payne Formation. The Muldraugh Member, like the Fort Payne, is a silty and cherty dolomite, but it contains smaller bodies of crinoidal limestone and some silty shale.