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Geomorphic Characteristics of Streams in the Bluegrass Physiographic Region of Kentucky

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Dana S. Kahn Jackman, M.S., ULSI Program Coordinator, prepared Appendix A and Table C.2.

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Executive Summary

Regional geomorphic relations, which describe average bankfull channel geometry and flow as a function of upstream drainage area for streams in a given region, provide a reliable point of reference for assessing stream conditions and evaluating channel dimensions and flow. Data collected from 13 stream-flow gauge sites and 7 ungauged sites were used to develop regional curves for bankfull channel depth, width, area, and discharge for rural, unregulated Bluegrass streams draining fewer than 154 mi^2. The return interval of the bankfull discharge was also estimated for each gauge site with at least 10 years of record of peak annual flow.

An extensive examination and collection of stream geomorphological characteristics in the Bluegrass was conducted. Cross sections and longitudinal profiles were surveyed, and flow and bed sediment data were collected to calculate bankfull parameters and to identify the channel type according to the Rosgen classification system. The effects of geology, historical land-use, and current land use on sediment loads and channel evolution were also considered in stream assessment and in the development of the curves. Humans' historical alteration of watersheds and direct manipulation of streams have led to altered channel geometry, increased sediment transport capacity and load, decreased frequency of floodplain inundation, reduced variability of habitat, reconfiguration of the groundwater-stream interaction, and a decrease in riparian vegetation. Thick alluvial deposits and subsequent channel incision have increased channel bank heights and entrenchment, exposed underlying bedrock in the bed and banks of channels, and inhibited the interaction between the stream bed, the groundwater system, and vegetation.

Bankfull regional curves were derived from collected data by using ordinary least-squares regression to relate bankfull discharge and bankfull channel dimensions to drainage area. Bankfull flow return periods were estimated using a log-Pearson Type III distribution of annual maximum series data. The relationship between bankfull parameters and drainage area in the Bluegrass region is well described by the curves, which explain over 93 percent of the variation within the datasets for bankfull area, width, depth, and discharge. Standard errors are less than 30% for the bankfull geometry and less than 35% for bankfull discharge. On average, the bankfull discharge was found to be approximately half that of the 1.5-year discharge, and no consistent frequency represented the return period of the bankfull flow. Therefore, use of the 1.5-year event for bankfull flow would represent a gross overestimate in all reaches examined in this project; estimates based on morphological features and/or the regional curves would be more accurate.

Introduction 1

The physical characteristics of stream channels strongly influence aquatic and riparian habitat, bank erosion, and sediment loads. Siltation, habitat modification, and flow alteration are the cause of nearly half of the identified stream impairments in the Commonwealth (KDOW 2007), with siltation cited most frequently. These primarily physical causes of stream impairment are all dependent on the presence of riparian vegetation; the entrainment, transport, and storage of sediment; and other geomorphic characteristics of stream channel networks. Changes in these characteristics are a product of complex watershed processes and human modification of the watershed and the stream channel network. Disturbance of streams due to land-use practices such as development, livestock grazing, land clearing, road construction, and channel modification or relocation tend to increase stream peak flow rates, disturb riparian vegetation, and alter stream channel characteristics. The response of many streams to disturbance can be excessive production of sediments through channel incision and subsequent severe bank erosion. In many cases channels incise into bedrock and continue to widen through bank erosion for decades after disturbances have occurred. The disturbances of streams and the associated erosion that continues for long periods can severely degrade stream and riparian habitat not only at the disturbed section of the stream but upstream and downstream as well.

To determine the implications of various physical impacts, specific geomorphic data are needed to evaluate flow stresses, sedimentation, and other physical habitat factors affecting biological communities. In assessing channel stability and habitat, estimates of bankfull flow conditions are particularly useful for

- Classification of the stream reach using the Rosgen (1996) method
- Determination of the degree to which the stream is incised
- Indication of relative bank stability
- Indication of some characteristics of channel pattern
- Indication of the capacity of the channel to transport its supplied load

Evaluation of channel stability is essential for the assessment of sediment loads, which may be needed for development of the sediment total daily maximum loads (TMDLs) required by recent US Environmental Protection Agency guidelines (USEPA 1999). Moreover, geomorphic data from a watershed's streams, including estimates of bankfull parameters, can be used as a basis for the design of stream restorations which physically alter disturbed stream channels in order to improve stream habitat, reduce bank erosion, and reduce sediment loads. In designing stream restorations, estimates of bankfull characteristics are useful for

- Initial estimation of channel geometry for planning of a restoration project prior to detailed morphological assessments required for final design
- Estimation of channel design parameters for sites where morphological characteristics are inconsistent or have not been developed
- Comparison of restoration designs developed using other methods
- Evaluation of restoration designs by permit agencies

Estimates of bankfull parameters may be obtained through direct measurement of similar channels in a watershed or region, or they may be obtained through analytical procedures such as the development of an effective discharge. They may also be obtained through the use of regional curves, which describe average bankfull width, depth, cross-sectional area, and discharge as a function of upstream drainage area for streams in a given region. Given the strong influence of local climate and geology on stream channel form, regional curves are typically developed with respect to physiographic region (e.g., Brush 1961; Harman et al. 1999; Kilpatrick and Barnes 1964; Leopold et al. 1964; McCandless and Everett 2002; Smith and Turrini-Smith 1999; Wolman 1955). While regional curves do not account for all sources of variability in channel characteristics, their formulation does include consideration of geologic conditions, land use, and valley use, and they provide a reliable point of reference for assessing stream conditions and evaluating channel dimensions and flow.

1.1 BACKGROUND

Quantitative geomorphology has been used for over half a century to support the assessment of channels and floodprone areas. Hydraulic geometry relations developed by Leopold and Maddock (1953) described the relationship between channel dimensions and mean annual discharge within specific drainage basins. In the next decade, hydraulic geometry relations, or at-a-station curves, were developed for several geographic regions in the eastern US (Brush 1961; Kilpatrick and Barnes 1964; Leopold et al. 1964; Wolman 1955). After the introduction and deliberation of the concept of a bankfull discharge, whose stage is just contained within the stream banks (Wolman and Leopold 1957; Wolman and Miller 1960), bankfull channel geometry and discharge data were also collected in the early 1970s (Emmett 2004). In the late 1970s, Dunne and Leopold (1978:614) noted the correlation between bankfull channel parameters and drainage area, and they introduced curves describing average bankfull channel dimensions and bankfull discharge as a function of drainage area in "hydrologically homogenous" regions. In the last decade, regional curves have been developed for physiographic regions across much of the US (see NRCS 2007, for example).

1.2 PROJECT PURPOSE AND SCOPE

At present, stream geomorphic assessment and restoration design in Kentucky are being conducted without regional curves; 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. The main purpose of this project was to provide quantitative descriptions (regional curves) that would represent expected values and variation of bankfull flow and channel cross-sectional area, width, and depth in riffles as a function of upstream drainage area in the Bluegrass physiographic region of Kentucky.

Data used to develop the regional curves were collected from 20 Bluegrass sites on 16 streams between May 2001 and January 2006. Drainage areas for all 20 sites ranged from 0.25 mi^2 to 154 mi^2. Criteria used to identify suitable stable stream channels for regional curve data collection included a wide range of drainage basin areas within the physiographic region; active stream-flow gauges with long-term hydrological records, preferred in order to determine discharge at the identified bankfull stage; and as many streams as possible having a channel environment that was alluvial, relatively stable, and showed no signs of ongoing rapid morphological change (cf. McCandless and Everett 2002; Smith and Turrini-Smith 1999). Bankfull regional curves for streams draining less than 154 mi^2 were derived from the data by using ordinary least-squares regression to relate bankfull discharge and bankfull channel dimensions to drainage area.

The Bluegrass Physiographic Region 2

Hundreds of years of human manipulation of the Bluegrass landscape and its channels has significantly affected channel morphology; sediment production, storage and yields; floodplain connectivity; and in-stream habitats. Streams throughout much of the region are characterized by low sinuosity, widespread channel incision, high banks that consist primarily of fine-grained layered material with relative small amounts of basal gravel, and/or exposure of bedrock both in the bed and banks of the channel boundary. While the region's streams have experienced similar effects overall, the magnitude of these effects varies depending on the position of the channel within the drainage network, the local susceptibility of the streams and the landscape to erosion of surficial material, and the topographic control of sediment deposition in the channels and on valley bottoms. Consequently, channel characteristics such as degree of channel incision, bed material composition, and bank heights and materials change according to local variations in geology, the effects of glaciations, and historic land use.

2.1 GEOLOGY AND PHYSIOGRAPHY

Structural Geology

The structural geology of central Kentucky is dominated by the Cincinnati Arch (McFarlan 1943:132), the axis of which is oriented in an approximately north-south direction between Cincinnati, Ohio and Lexington, Kentucky. South of Lexington, the structure of the Arch is disrupted somewhat by the east-west alignment of faults and shear zones of the Kentucky River fault system. The general configuration of the Arch is altered in the Jessamine Dome, with limbs descending gently from both sides of the axis. The rock layers dip away from the center of the dome, at an elevation of about 1,000 ft msl, to an elevation of about 850 ft msl at the Ohio River near Cincinnati. The layers dip on average at 20 to 30 ft per mile to the east and west, and at about 10 ft per mile to north and south along the axis.

The Arch formed in a series of episodes of folding and warping that lifted Paleozoic strata far above the elevations at which they had been deposited. Underlying formations were exposed by erosion of the uplifted sedimentary rock layers. Because of the greater uplift at the Jessamine Dome and along the axis of the Arch, the strata exposed in those locations are far older than strata exposed near the outer boundary of the Bluegrass (see Figure C.1 in Appendix C).

Physiographic Sub-Regions

The boundary of the Bluegrass coincides with the exposed Mississippian strata on the flanks of the Arch (Figure 2.1). Within the region, differences in lithology, soil characteristics, and topography distinguish four separate physiographic sub-regions (Table 2.1): the Inner Bluegrass, a gently rolling lowland underlain by Middle Ordovician rocks; the Eden Shale Belt, a rugged transitional region of Kope and Clays Ferry formations; the Outer Bluegrass, subdued hills and lowlands on Late Ordovician, Silurian, and Devonian rocks; and the Knobs, a narrow band of hills bounded by the Muldraughs Hill and Pottsville escarpments of the Mississippian Plateaus physiographic region.

(a)

(b)

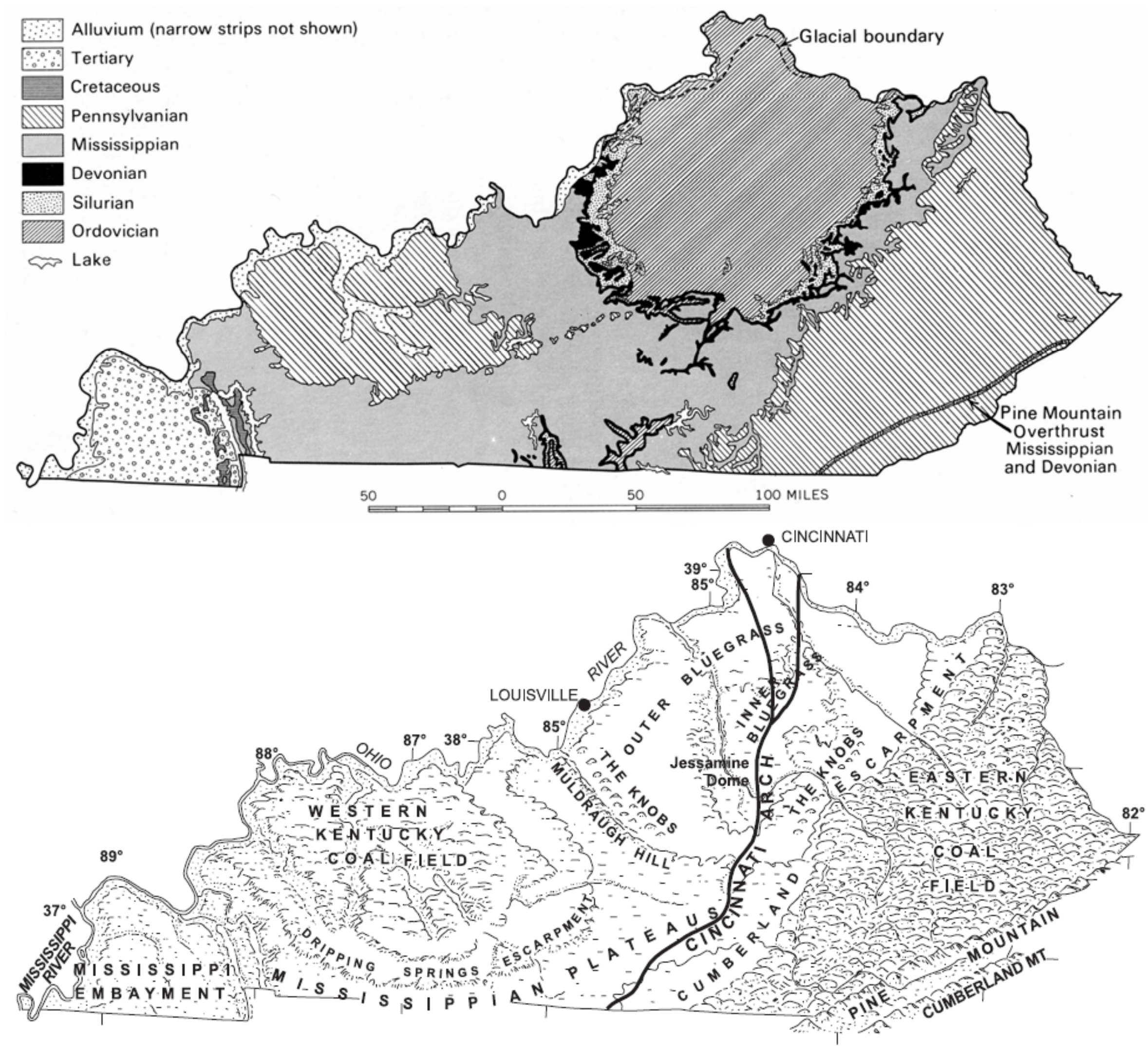

Figure 2.1 (a) Generalized geologic map of Kentucky (after McGrain 1983:12).
(b) Physiographic map of Kentucky (KGS 1980).

Table 2.1 Characteristics of Bluegrass Physiographic Sub-Regions

Physiographic Sub-Region	Lithology*	Major Soil Units	Soil Thickness†	Topography
Inner Bluegrass	Lexington Limestone (Ol) of Ordovician age	McAfee-Maury (M-M) association, McAfee-Maury-Fairmount (M-M-F) association, and Nicholson-Lowell-Faywood (N-L-F) association	Undulating deep and moderately deep soils high in phosphate (M-M) found on broad gently sloping ridges and somewhat steeper slopes along drainage ways and around sinkholes. Sinkholes are common in this soil unit. Rolling uplands and moderately steep slopes along drainage ways (M-M-F); this soil is well drained and has many sinkholes. Typically deep, gently sloping to sloping, well drained, and moderately well drained soils found on broad upland ridges (N-L-F).	Very low relief with broad gently sloping ridges and steeper areas around abundant shallow sinkholes. Highest elevation is 1070 ft above sea level and the lowest elevation occurs at the normal pool depth of the Kentucky River at 550 ft above sea level.
Eden Shale Belt	Ordovician limestone and shales interbedded with some siltstone (Kope, Okc, and Clays Ferry, Ocf, Formations)	Faywood-Eden-Lowell (F-E-L), Eden-Lowell (E-L) association	Shallow to moderate soil depths on steep slopes (F-E-L) and variable on ridgetops (E-L). Soils generally well drained with dominantly clay subsoil. Soils may be moderately deep on floodplains and terraces of larger rivers.	Highly dissected area with steep convex hillsides, long narrow v-shaped valleys and rounded ridgetops. The highest elevation is found in Bath County at approximately 1000 ft. Ridge tops of 900 ft are typical elsewhere with valleys commonly 150 to 300 ft below.
Outer Bluegrass	Limestones, dolomites, and shales of Late Ordovician and Silurian age (primarily Oaf, Ob, Od, Odc)	Nicholson-Lowell-Faywood (N-L-F) association, Shelbyville-Lowell-Faywood (S-L-F) association	Deep to moderately deep, well drained soils with clayey subsoil (N-L-F) over limestones, and shallow to moderately deep, somewhat excessively drained soils (S-L-F) over shales. Soils developed on some Silurian carbonate rocks are nearly as rich as those of the Inner Bluegrass.	Rolling, undulating hills of low to moderate relief, with elevations typically between 800 and 900 ft above sea level. Jeptha Knob in Shelby County is an exception and the highest elevation at 1188 ft.
Knobs	Thick shales (with thin siltstone and sandstone inclusions) of Devonian age (New Albany shale, MDnb) or Mississippian age (New Providence shale, MDbb) and the edges of thick layers of Mississippian limestone strata (Msh)	McGary-Markland-Lawrence (M-M-L) association, Huntingdon-Lawrence-Newark (H-L-N) association and Rockcastle-Colyer-Trappist (R-C-T) association.	On stream terraces, soils are deep, somewhat poorly drained to well-drained, and nearly level to gently sloping (M-M-L). Similar soils found along Rolling Fork (H-L-N). In the upland portion of the Knobs, the soils are shallow, excessively drained, and gently sloping to steep (R-C-T).	Individual knobs are characterized by symmetrical concave-upward slopes which rise gently out of the bottomlands or surrounding plains. The slopes steepen upward into cliffs on knobs with resistant caprocks. Knobs that have lost their protective caps have rounded crests. Well-developed knobs may be nearly circular or elliptical in plan view. Elevations from 520 to 1575 ft above sea level.

* Stratigraphic units and their lithologies are described in Appendix C.

† Depth of soils over bedrock, as determined by USDA soil surveys. Very deep = >60 in over bedrock; Deep = 40-60 in; Moderately deep = 20-40 in; Shallow = 10-20 in; Very shallow = <10 in.

Sources: Hall et al. 1980; McDonald et al. 1983; McDonald et al. 1985; Odor et al. 1968; Preston et al. 1961; Richardson et al. 1982; Sims et al. 1968;Weisenberger and Isgrig 1977; Weisenberger et al. 1963; Zimmerman 1966.

The Inner Bluegrass is characterized by gently rolling topography developed in thick layers of residual soils formed from in-place weathering of limestones, dolomites, and shales (Sims et al. 1968). Deeply entrenched streams such as the Kentucky River flow through gorges carved in resistant rock units like Lexington Limestone and the massive limestones of the High Bridge Group. The Lexington Limestone consists mostly of very fossiliferous and fossil-fragmental limestone with minor amounts of shale (Cressman 1973); in contrast, the High Bridge Group consists of sparingly fossiliferous and micrite-rich limestone (Cressman and Noger 1976). These units are among the most karst-prone in the Bluegrass, and sinkholes, formed by dissolution in carbonate rock layers, are concentrated primarily in this sub-region (Figure 2.2). Subsurface channels are present where joints or solution cavities form in soluble limestone or dolomite, but outside the Inner Bluegrass the development of karst topography or extensive subsurface channel networks tends to be limited by interbedded shale. This is especially the case in the Eden Shale Belt, where the prevalence of impermeable shale strata ensure that sub-surface drainage does not develop.

The boundaries of the Eden Shale Belt (also known as the Eden Hills or Hills of the Bluegrass) have been varyingly defined according to numerous criteria including geology, topography, soils, vegetation, and others (e.g., W. Andrews, pers. comm.; Davis 1927; Woods and Omernik 2002). For the purposes of this report, the region has been defined as that underlain by the Okc and Oc members of the Kope and Clays Ferry formations (see Figure C.1 and Table C.2 in Appendix C). These strata are of Ordovician age, but they are significantly different in lithology from the strata of the Inner Bluegrass. The rock layers of the Eden Shale Belt consist mostly of interbedded shales and limestones. These strata are both thinner and more erodible than the layers of limestone and dolomite in the Inner Bluegrass. Dissection by streams has occurred to a high degree in the Eden Shale Belt, with little flat land present in the sub-region. The residual soils developed from the interbedded shales and limestones are cut by steep-sided narrow valleys that contrast sharply with the more subdued landscape of the Inner Bluegrass with its gentler rolling hills (Figure 2.3).

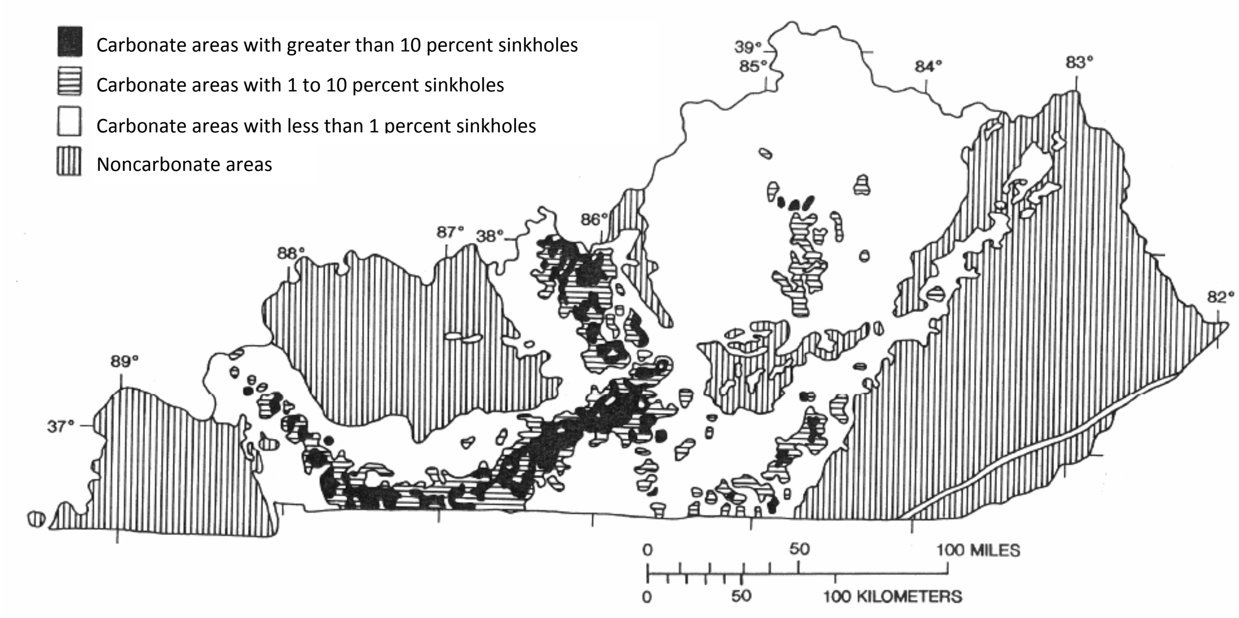

Figure 2.2 Generalized carbonate areas and surficial karst development in Kentucky (from Crawford and Webster 1986).

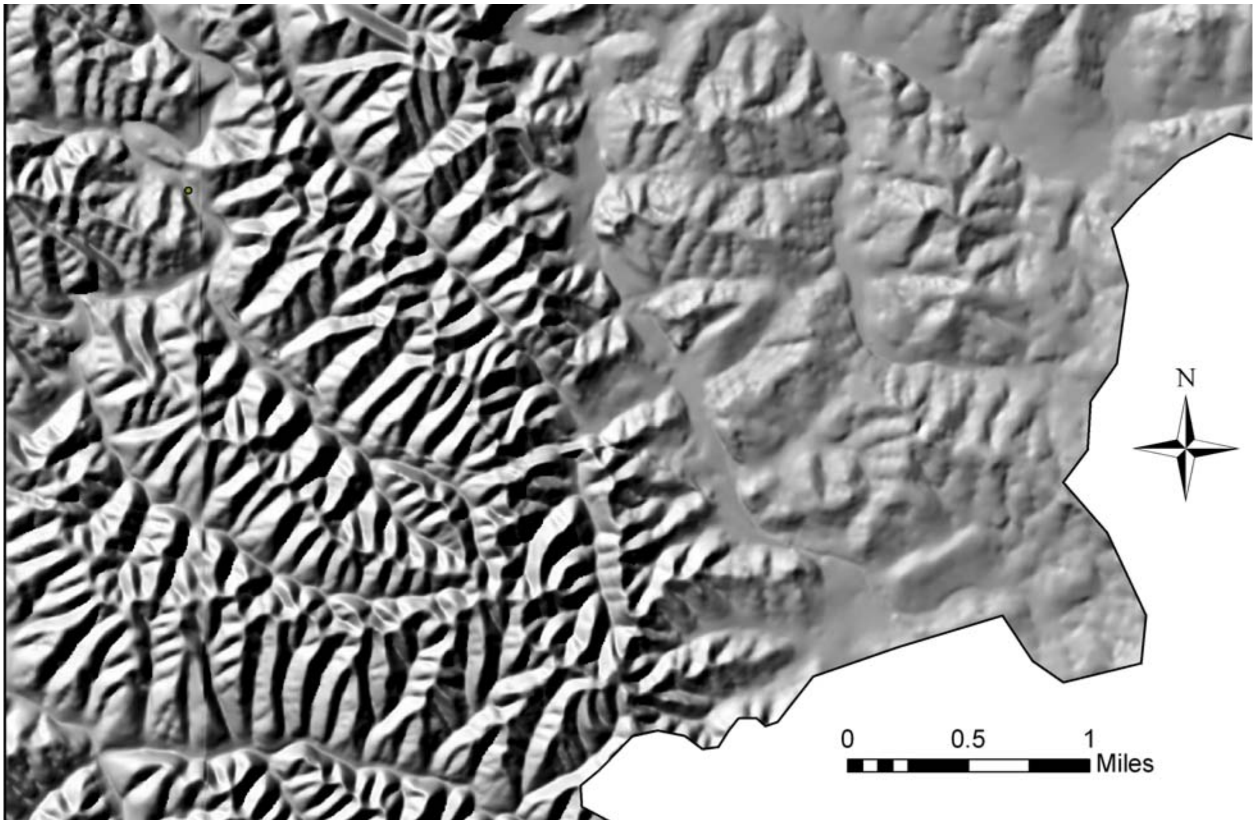

Figure 2.3 Contrast in topography between the Eden Shale Belt (left) and Inner Bluegrass (right) in Benson Creek watershed.

The topography of the Outer Bluegrass, where underlain by Ordovician rocks, is similar to the Inner Bluegrass, typically with low-to-moderate relief and soil depths ranging from thick over limestones to thin over shales. Where Silurian and Devonian carbonate rocks are exposed, the terrain is very similar but with fewer hills and more flat land. The Silurian strata consist of dolomites, limestones, and shales (minor components, in general) that are significantly different in properties from the younger Devonian fossiliferous limestones and thick shales that crop out farther away from the Inner Bluegrass. The soils developed on some Silurian carbonate rocks may be nearly as rich as those of the Inner Bluegrass. Unstable hillslopes, with small, low-angle landslides, are a characteristic of areas underlain by Silurian shales, which contain abundant swelling clays. The outer edges of the Outer Bluegrass typically consist of lowlands or gently rounded low hills. The elevations in the Outer Bluegrass vary from about 1000 ft msl in Garrard and Madison Counties to about 500 to 550 ft msl in Spencer and Nelson Counties. The highest point is at Jeptha Knob in Shelby County, with an elevation of 1176 ft msl.

Bordering the Outer Bluegrass is the Knobs sub-region, formed by erosional outliers developed in thick, silty Devonian shales with thin sandstone inclusions (New Albany Shale) or Mississippian-age shales (New Providence Shale) and the edges of thick layers of Mississippian limestone strata. The Knobs contain hundreds of isolated hills formed from the New Albany and New Providence shales. Where the shales are capped by thin, resistant layers of siltstone or sandstone, the hills are almost flat-topped. When erosion and weathering undermine the cap-rock layers, the hills become conical; without the cap-rock layers, the hills become more rounded. Local relief in the Knobs varies from 100 ft to 500 ft. The edges of the Mississippian limestone layers form long escarpments or cuestas (edges of slab-shaped rock masses that slope gently in one direction, leaving steep faces exposed on the sides opposite to the gentle slopes). On the eastern side of the Bluegrass region, the Mississippian strata are thinner. The escarpment there virtually merges with the western edge of the Eastern Coal Field (primarily Pennsylvanian sandstones, shales, coals and siltstones), and sediment loads in the streams in this area appear to be relatively high (Figure 2.4).

Glaciation and Impacts of Climatic Change

Most of the Bluegrass region was not directly affected by the advance of continental ice sheets southward during the Pleistocene Epoch, at the beginning of the Quaternary Period about one million years before present. The glacial sheets' damming of ancestral north-flowing rivers did, however, dramatically alter the region's drainage network, including the Ohio River and all streams that flowed to the north and northeast. Prior to glacial advance, drainage northeast of the mouth of the Kentucky River (e.g., along the preglacial Licking and Big Sandy rivers) occurred to the northeast and then into the preglacial Teays River valley that extended westward across Ohio, Indiana, and Illinois to the present location of the Mississippi River (Figure 2.5). Blockage of the Teays River drainage by ice and ice-contact deposits diverted those waters southeastward and created the precursor of the modern Ohio River.

Flow to the newly formed Ohio River, with a contributing drainage area more than 50 times that of its ancestral river, bypassed the previously northward, longer route of the Teays, and the Ohio incised. Further incision was caused by the meltwater and sediments released to the Ohio by retreat of the Wisconsinan ice sheet. The incision of the Ohio River below its pre-glacial level

Figure 2.4 Rock Lick Creek in the eastern Bluegrass region. The higher sediment load and, in particular, abundant sand-sized material (see inset) is characteristic of stream reaches that have headwaters in the Eastern Kentucky Coal Field region.

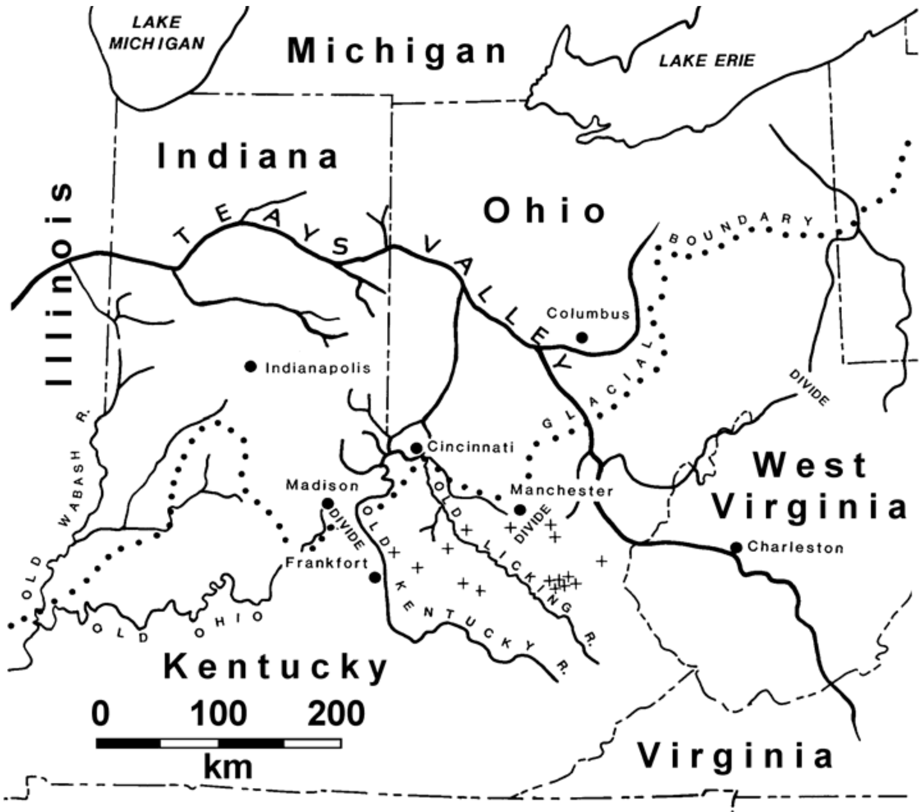

Figure 2.5 Pre-glacial drainage of the Kentucky River and its tributaries (modified from Teller and Goldthwait 1991).

affected the longitudinal profiles of all of its Bluegrass tributaries. The incision lowered the base level of the Kentucky River, causing a wave of incision that propagated upstream on the Kentucky River and into each of its tributaries.

The incision of the Ohio River also created large-scale locally steep reaches, or geological knickpoints, in the longitudinal valley profiles of tributary streams. These knickpoints represent active zones of channel incision into the bedrock that have lowered the elevation of the valley bottoms relative to the ridge tops by 200-300 ft, creating features such as the Red River Gorge (Andrews 2004). Other tributaries of the Ohio River such as the Salt River were similarly affected. A geological knickpoint in the Salt River (Figure 2.6) divides the longitudinal valley profile into three distinct sections. Section A is downstream of the knickpoint, and hence has experienced considerable stream erosion since the Pliocene-Pleistocene transition (1.2 Ma). Section B is the reach which is currently incising into the landscape, producing relatively high rates of bedrock breakdown and initiating bed degradation of tributaries (Schumm et al. 1984). Section C, above the steepened reach, is the reach that may not have been affected by the base-level change of the Ohio River and as a result is less incised into the landscape. Although Section C may not have been affected by base level changes in the Ohio River, some evidence indicates that parts of Section C were captured from the Kentucky River drainage. Paleovalleys in the present Benson Creek and upper Salt River watershed have been identified as possible spillways for overflow from the dammed ancestral Kentucky River (Andrews 2004), which flowed into the ancestral Salt River system.

Different forms of stream capture may have occurred at other locations in the Bluegrass. As a river incises into the landscape, it can capture nearby drainages if the drainage divide is lowered

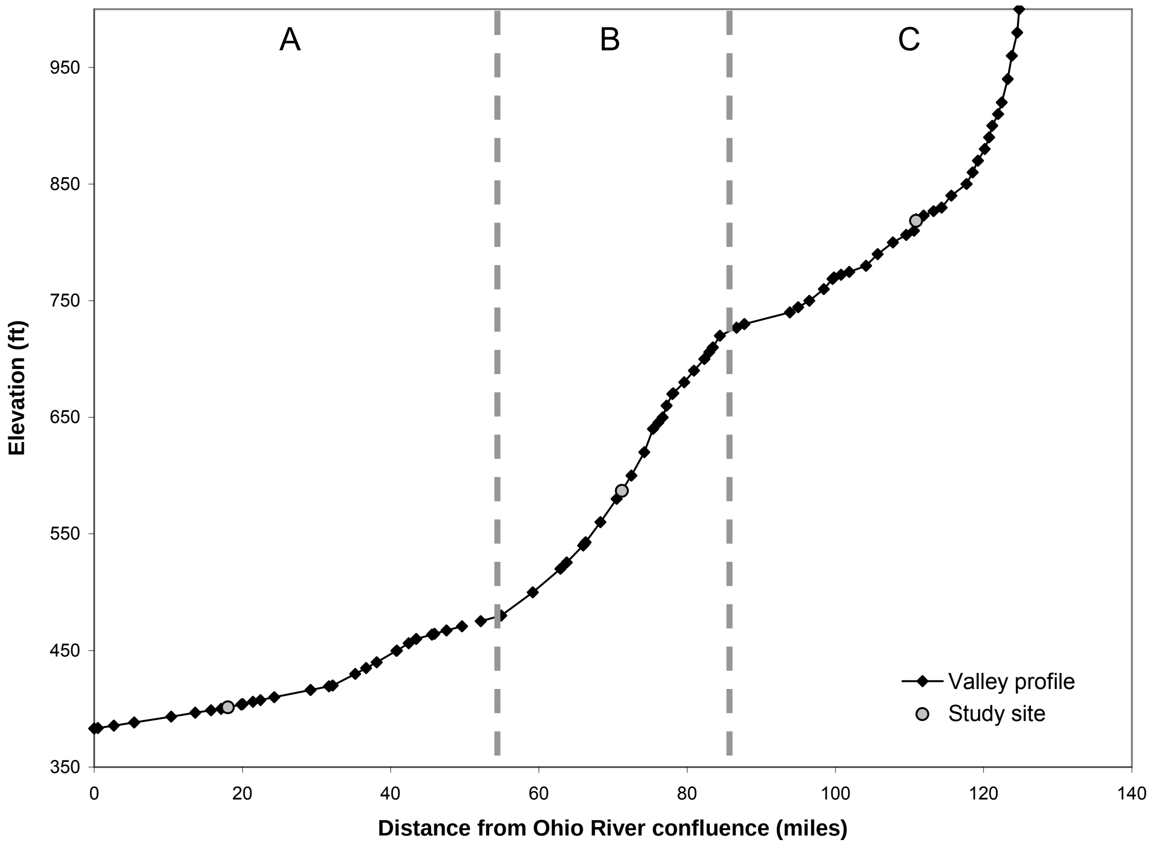

Figure 2.6 Longitudinal valley profile of the Salt River showing steepened reach, or geologic knickpoint.

relative to the adjacent watershed. Hence, the drainage network may have been significanty rearranged since the downcutting of tributaries to the Ohio River began. In the Bluegrass, the capture of an early tributary of the Kentucky by the Salt River system has been identified by a sharp bend in the Salt River near Lawrenceburg (Leverett 1929). This type of stream capture, or piracy, has been well documented in the Kentucky River basin in the Eastern Coal Field (Outerbridge 1987). Evidence of similar piracy is suggested by valley widths and drainage divide elevations on topographic and hillshade maps of many streams within the Bluegrass region (Figure 2.7).

2.2 LAND-USE HISTORY

Present-day stream characteristics, morphological change, and evolutionary trends may be more heavily influenced by continuing effects of historic land use than by present land use. In southern Appalachia, for example, the effects of the "ghost of land use past," including legacy sediments from past farming, caused biodiversity in forested streams on previously cultivated lands to closely resemble biodiversity of streams on currently cultivated lands. Land use dating back nearly five decades was found to be more reliable than current land use in predicting contemporary biological stream diversity (Harding et al. 1998). Likewise, Jacobsen and Pugh (1997) found that channel migration increased in intensively farmed areas compared to undisturbed stream sites. Thus, while many legacy effects may not be readily apparent, recognition of them is important for understanding stream morphology. In the Bluegrass, the most persistent legacy effects can be traced to land use changes introduced during the last 250 years (Table 2.2), though

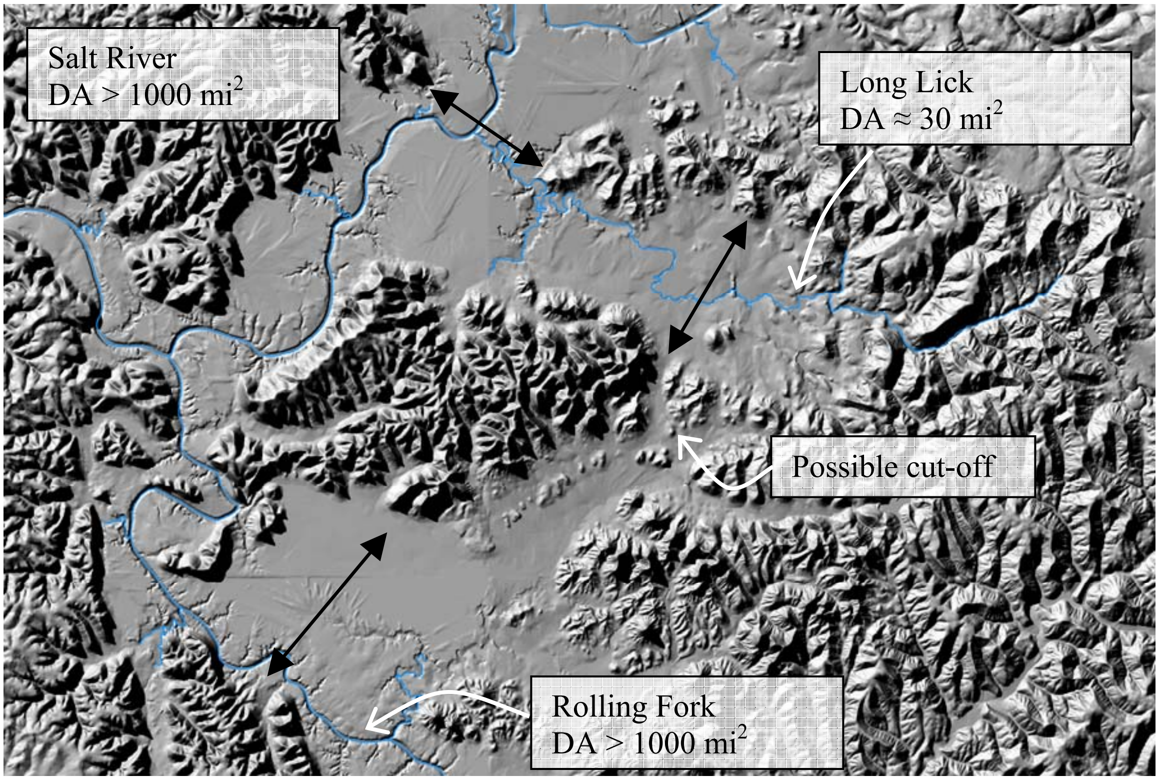

Figure 2.7 Evidence for changes to the drainage system near Shepherdsville. Long Lick Creek drains less than 30 mi^2 but has a valley width approximately equal to that of the Salt River and Rolling Fork. The hillshade map reveals relatively low ground on the southern drainage divide of Long Lick Creek, which may have been the course of a much larger stream.

that period represents only a small fraction of the time humans have been modifying the region's landscape. (See Appendix D for a detailed account of Bluegrass land use history).

Agriculture and Natural Resources

Approximately 3000 years ago, Native Americans in the Bluegrass began to build earthworks and cultivated some crops, though they relied heavily on gathering and hunting (Railey 1996). As they became more sedentary, their effects on the land became more significant. Native American practices of land clearing, plant cultivation, and setting of forest fires are thought to have affected vegetative composition of previously forested areas throughout the Southeast (DeVivo 1991). For more than 700 years before Europeans began to settle Kentucky, Fort Ancient groups in the Bluegrass built villages and practiced swidden horticulture, using fire to clear forested land in floodplains, where they cultivated primarily maize, beans, and squash. Fire was also used extensively for hunting, for warfare, and for improving pasturage for game (Pyne 1982; Williams 1989).

Native peoples continued to thrive in the area until their populations were decimated by diseases introduced by European colonists in the East. The rapid, dramatic decline in population reduced the area under cultivation, and abandoned fields were colonized by opportunistic successional vegetation (Delcourt et al. 1993). Inner Bluegrass vegetation patterns at the time of Euroamerican settlement were so peculiar that Braun (1950) described the area as more anomalous than any other vegetative region in the eastern US. While the forests of the Outer Bluegrass were probably quite dense, as much as half of the Inner Bluegrass was savannah-woodland, cane,

Table 2.2 History of Bluegrass Land Use and Floods, c. 1000–1940 CE

Time ⟶	Pre-1770	1770-1790	1790-1820	1820-1865	1865-1890	1890-1920	1920-1940
Floods			1817, flooding of Kentucky River	1848, flooding of Lulbegrud (Clark & Montgomery cos.), Boone, Benson, Valley (Fayette, Franklin, Hardin cos.), and Elkhorn creeks 1858 flooding of Elkhorn Creek & Kentucky River	1872, Kentucky River rose 15 ft in 6 hours; largest flood of the river since 1817; Eagle Creek (Gallatin, Carroll, Owen, Grant, counties) rose 4 ft higher than any time on record	1905, flood waters cut channels around Locks 9 & 10 of KY River 1906, KY River at Frankfort discharge measured at 10,800 cfs at gauge height of 8.12 ft.	
River Use & Management	Dense beaver populations (60-400M in North America c.1600) c.1750s-60s, most beavers extirpated from KY for fur trade	1783, 1st KY water-powered gristmill built, Lincoln Co. 1787, first exports to New Orleans markets via KY, OH, and MS rivers	Construction of dams for water-powered industries Extensive use and modification of rivers as trade routes Ohio River becomes primary route for immigration into BG	c.1840, >1300 mills (~700 dams) in BG	c.1880, ~250 waterwheels (~150 dams) in BG Decline of river traffic/ commerce Sawmill boom on KY River & tributaries from clearing in EKY	c.1900, 4:1 ratio of steam engines to waterwheels	
Agriculture	c.1000, swidden horticulture and densely populated villages in river floodplains c.1600s, buffalo enter BG	Emphasis on hunting, little agriculture Elimination of buffalo	Rapid increase in acreage of crops, pasture Open-range grazing of livestock	~3.3M BG acres "improved" by 1850 Increased livestock production Farmland consolidation c.1850, independent drainage projects common	~4.8M BG acres "improved" by 1880s, when acreage begins to decrease Subdivision of large estates into smaller farms	c.1900, "improved" acreage in BG peaks at ~5M BG soils depleted; farming efficiency begins to decline c.1912, drainage districts organized for coordination of extensive drainage projects	c.1920, marginal lands abandoned (esp. in ESB) c.1930, soil exhaustion throughout BG prompts changes in land management c.1920, >⅓ Jefferson Co. in drainage enterprises
Forestry	c.1600s, native popl. decline; expansion of successional vegetation in formerly cultivated fields c.1000, clearing/burning of forest by natives for agriculture	BG >99% forested at beginning of settlement	Clearing/burning of forest and cane for agriculture and charcoal production Culling of trees for home use and market			c.1910, in most BG counties, only 5-6% of land still forested	c.1920, expansion of successional vegetation in formerly cultivated areas (esp. in ESB)
Mining			Mineral mining: salt, iron, clay	Decline of mineral mining BG quarries producing almost 50% (by value) of KY stone		c.1900, stone production increases for road construction	
Urban/ Inter-urban		c.1775, first settlers establish stockaded communities	BG population increases from ~73k to ~340k	1840s, limited railroad construction begins—78 BG miles completed by 1850	Railroad expansion	c.1900, increased road construction	

and meadows of grass and clover (Braun 1950; Campbell 1980). Though richly vegetated, the Bluegrass land claimed by pioneers in the 1770s was not the pristine wilderness they assumed it to be.

Pioneers erected stations and forts, beginning with Harrodsburg and Boonesborough in 1775 (Clark 1992), in defensible locations near permanent sources of fresh water that would be accessible during raids by Native Americans. Regions outside the Bluegrass saw few settlements until after 1795 (Gray 1933:863), but by 1800, the Commonwealth's population reached 220,955 and included settlers in all regions of the state east and north of the Cumberland and Tennessee Rivers (Clark 1992:156; US Census 1801). The Bluegrass population had reached 177,782; by 1810 it had reached 268,631 and accounted for two-thirds of the population of the entire state.

The period from about 1790 to 1820 brought significant changes to the Bluegrass landscape, as settlers commenced clearing large acreages for cultivation and pasture and developed mining and manufacturing industries. The navigable Kentucky River connected Bluegrass farmers with an extensive external trade network through the New Orleans seaport (Clark 1992:175), and market demands largely influenced the selection of crops that would be produced by Bluegrass farms. Early Bluegrass agriculture was broadly based on grains and livestock for both subsistence and surplus trade; hemp and, to a lesser extent, tobacco were also grown as cash crops (Hopkins 1951:27; Mitchell 1978).

Though most Bluegrass farms produced some combination of grains, hemp, and livestock (Mitchell 1978), disparities in the amounts of land and labor to which farmers had access resulted in sometimes radical differences in their land use and consequent effects on the landscape. Yeoman farmers, with little cash, relatively small acreages, and few or no slaves, relied on shifting (slash-and-burn) cultivation, which maximized the short-term return they would get for their time and toil (Otto & Anderson 1982; Williams 1989:60-63). Slash-and-burn methods cleared fields ten times faster than clear-cutting and were the most expedient way to bring forested areas under cultivation. Some large trees were chopped down for use as building logs, fences, or fuel; most were girdled and left to deaden in the new fields. Small trees and underbrush were cut and grubbed out by hand and then burned, releasing crucial nutrients into the soil and killing insect pests (Williams 1989:60-63). By planting crops in these "deadenings," farmers were able to avoid the much more intensive labor and time required to fell the trees and uproot the stumps.

Despite the advantages slash-and-burn methods afforded farmers, the practice was profligate in its use of the land and its resources. Shifting cultivation required that a large proportion of land be left fallow, so less than one-third could be cultivated at any given time. Moreover, new patches had to be created annually; without the addition of fertilizers, the crops quickly leached nutrients, and the deadenings were only productive for a few years. The root networks and stumps in the deadenings required that farmers use hoes or, in larger fields, light, maneuverable plows. This precluded the use of deep plowing, which could have extended the life of the soil by bringing low soil layers and their nutrients up to the crop zone and creating large furrows that would have slowed erosion. Side roots rotted away within two years, and the stumps rotted in less than seven; when the fields were abandoned, the soils eroded badly before they were reclaimed by shrubs and trees (Otto & Anderson 1982:137,142; Trimble 1974; Williams 1989).

Landscape changes also occurred with the rapid development of industries based on natural resources. In the late 1700s, Bluegrass entrepreneurs began drilling for salt, mining and processing iron ore, mining clay, quarrying limestone, and cutting timber for internal markets and for export (Clark 1992). Clear-cutting for manufacturing, mineral processing, and agriculture, and overgrazing of forest vegetation by free-roaming livestock took a heavy toll on the Commonwealth's forests. By 1850, more than 80 percent of the region was in farms, and

59 percent (approximately 3.3 million acres) of that land was classified by census takers as “improved.” Improved lands included land under cultivation; cleared or tilled land, whether fallow or in pasture; orchards; nurseries; vineyards; gardens; and land on which buildings had been constructed. In the next 10 years, improved land in farms totaled almost 4 million acres, or 68 percent of farm land (US Census 1853, 1864; n.b., these figures were collected by county and therefore are only a close approximation of the Bluegrass region).

The continued use of fire for clearing lands for agriculture caused the loss of thousands of additional acres. In 1880 alone, 10 documented wildfires burned more than 556,000 acres of woodlands in the state. Nearly half of those fires had started as part of land clearing efforts (Sargent 1884:491). Hogs, too, were still being cited in the 1880s as a potential factor in the loss of white oaks in Kentucky (Sargent 1884). The number of improved acres decreased in many Bluegrass counties in the 1880s, but land clearing continued throughout the remainder of the century. By 1900, the amount of improved land in farms peaked at more than 80 percent (about 5 million acres).

Extensive land degradation was noted by William Linney in his surveys of selected western, southern, and eastern Bluegrass counties from 1882-1887. Just two decades later, an inventory of Kentucky’s remaining forestry resources revealed that only 39 percent of the state remained in forest. The survey, begun in 1907, blamed practices dating back more than 100 years for the needless destruction of former stands and the debilitated fertility of the remaining forests (Hall 1909). Less than 14 percent of the Bluegrass region was forested by the early 20th century; most of the region’s counties had been almost completely denuded, with less than 6 percent of their land still in forest (Barton 1919).

Modification of Drainage Networks

The activities of Euroamericans affected not only the physical landscape but also the drainage networks of the Bluegrass almost immediately following the beginning of settlement in Kentucky. The removal of beavers, construction of milldams, channel modifications, and drainage enterprises all affected the hydrology and geomorphology of Bluegrass watersheds.

Removal of Beavers

One of the earliest changes Euroamericans introduced to Bluegrass channels, as elsewhere (e.g., Wohl 2005), was the removal of beavers from the area in the 1750s and 1760s (Cline 1974). By constructing dams, canals, and other structures, beavers effect extensive hydrogeomorphological alterations of drainage networks, both in riparian areas and in stream channels. The cumulative effects of beaver habitat modification undoubtedly created drainage networks that were substantially different from those without beavers. The geomorphic consequences of their rapid removal following European contact, however, remain relatively unknown. The incision of streams into the impounded sediment and their subsequent erosional down-cutting have been attributed to the removal of beaver (Parker et al. 1985), as have lower groundwater levels and a change in flow regime from perennial to ephemeral (Pollock et al. 2003).

Mills, Water-Power & Industry

Construction of small dams for water-powered mills promptly followed the introduction of agriculture to the Bluegrass. The first milldam to be authorized by a Kentucky county court was built on the Dix River in 1783 (Verhoeff 1917:18). By 1795, when most of the population was still restricted to the Bluegrass, a British visitor reported that the state already had a thousand mills (Winterbotham, as cited in Hunter 1979:3).

Water was used to power not only gristmills but also, in some cases, sawmills, tanneries, fulling mills, carding mills, iron furnaces and forges, distillery mills, and mills producing paper, gunpowder, and linseed (flax) oil (Hunter 1979). By 1810, Bluegrass counties had over 1600 distilleries and a wide assortment of other industries. Gaines (1905:3) estimated, based on county records, that more than 80 gristmills and sawmills were established in Scott County between 1776 and 1820—approximately 1 mill for every 177 county inhabitants (US Census 1821).

Along with gristmills, sawmills were considered to be essential to new communities and quickly followed—or on occasion even preceded—the establishment of water-powered gristmills. Sawmills provided the materials for board floors, frame houses and barns, furniture, and other goods necessary for permanent settlement. Pairing grist- and sawmills allowed the miller, who was often also a farmer, to make more efficient use of his water resources and his time, especially when the areas served by the mill were still so sparsely populated that the gristmill was underutilized (Hunter 1979).

By 1840, the Bluegrass had more than 1300 mills. By 1880, however, the number of mills had declined by more than 60 percent, though their number remained high in many areas, with mills located approximately every half-mile on some sections of streams. This decline in the number of mills was due largely to the growth of cities and the consolidation of the milling industry as large “merchant mills,” which produced flour and meal for sale in the market, became more common (Hunter 1979). Eventually, water-powered mills would also be replaced by steam-powered mills.

Channel Maintenance

Prior to Kentucky statehood, Virginia laws governed the modification of navigable channels and gave the county courts the authority to regulate the improvement of streams. Laws governing the improvement of navigable streams were substantially similar to those governing road improvements, empowering the courts to levy taxes and conscript labor crews for open-channel work (Verhoeff 1917:19). Following statehood, a version of the Virginia law governing the improvement of streams was not adopted until 1816. Virginia’s custom of passing special legislative acts to establish public ferries was also perpetuated in Kentucky (Verhoeff 1917:19).

Ferry landings, fish traps, fish dams, milldams, timber booms, and other obstacles were added to streams that in their natural state were already not particularly conducive to navigation. Flow varied enough to render even the largest streams impassable for several months each year. Islands, rocky shoals, debris snags, accumulations of gravel and sand, and overhanging trees all blocked potentially navigable channels (Verhoeff 1917:12-13). Nevertheless, any stream which could carry a flatboat during a period of high flow could be considered navigable (Robertson 1914).

Early efforts to make the streams more navigable to the rafts and flatboats that transported logs and goods to markets included both open-channel work and construction of slack-water systems. Open-channel work focused on removing or reducing channel obstructions. Labor crews snagged the channels to remove debris, removed vegetation from the banks, and constructed wing-dams, dikes, and training walls. The streams required constant maintenance to maintain navigability (Verhoeff 1917:12-13). Beginning in the late 1880s, however, river commerce noticeably declined. By that time, extensive railroad networks had been constructed through the state and transportation of goods by rail was more economical than by river. Thereafter, the improvement of rivers for navigation received much less attention than it had in the ante-bellum period (Raitz 1980:35).

Drainage

Water management efforts in frontier Kentucky focused mainly on manipulation of surface waters, especially wetlands and small streams. Kentucky is one of only ten states to have lost at least 70 percent of their original wetland acreage. Based on soil surveys from the 1970s, approximately 1,566,000 acres (6.1 percent) of Kentucky's 25,852,800 acres are estimated to have been wetlands at the time of first settlement (KSWCC 1982). By the mid-1980s, only 300,000 wetland acres remained—a statewide loss of 81 percent (Dahl 1990). Of the 125,000 acres of wetlands estimated to have been in the Bluegrass at the time of settlement, 92,000 acres (73.6 percent) had been drained as of 1978 (KSWCC 1982). Agricultural development was responsible for most of the loss, as wetlands were drained, filled, or otherwise converted to cropland.

Extensive cutting of bottomland timber began with the arrival of pioneers, and wide-scale drainage projects were carried out in some areas of the Bluegrass as early as the 1790s to prevent disease and to promote settlement. In general, however, drainage projects were limited by technology and a lack of coordination between landowners. To ensure proper functioning of constructed drainage systems, large outlets outside of each project's land boundaries were necessary. In Kentucky, planning and construction of those outlets was eventually accomplished through the establishment of county drainage districts by the Drainage and Reclamation Act of 1912 (Beauchamp 1987:15-16; US Census 1932). By the 1930s, over 585,000 acres statewide had been included in regional enterprises drained by more than 1200 miles of ditches, and most wetlands had been converted from natural to agricultural use.

2.3 CHANNEL RESPONSE AND EVOLUTION

The evolution of channel networks in the Bluegrass is dominated by the effects of hundreds of years of human modification of the region's hillsides, valleys, and streams (Table 2.3). Common stream and floodplain responses to those modifications include altered channel geometry, increased sediment transport capacity and load, decreased frequency of floodplain inundation, reduced variability of habitat, reconfiguration of the groundwater-stream interaction, and decrease in riparian vegetation.

The most significant effects of human activities were the alluviation of the valley bottoms and channel incision. Sediment deposition on valley bottoms in Kentucky, as elsewhere (Costa 1975, Jacobson and Coleman 1986, Knox 1987; Magilligan 1985, and Trimble 1981), was caused by 19th-century clearing, burning, and farming of hillsides, which led to soil erosion and the accumulation of those fine sediments on downstream floodplains. This accumulation of post-settlement alluvium (Happ et al. 1940) was enhanced by overbank flow and backwater from the thousands of dams built to power mills and other industries. In valleys throughout the Eden Shale Belt, Outer Bluegrass, and Knobs, alluvial deposits elevated some valley bottoms by more than 12-15 ft above pre-settlement levels.

The combination of thick alluvial deposits and subsequent channel incision increased channel bank heights and entrenchment, exposed underlying bedrock, and inhibited the interaction between the stream bed, the groundwater system, and vegetation. Channel incision into and through the post-settlement alluvium was caused by channel straightening and removal of channel blockages and dredging for navigation (Schumm 1999). Where alluvial deposits were thick, they exacerbated the depth of channel incision. Valleys that may previously have stored water and organic material are now filled with cohesive, relatively impermeable sediments (compared to

Table 2.3 Effects of Historic Land Use on Bluegrass Watersheds, Valleys, and Streams

Historic Land Use	Potential Effect on Watershed	Potential Effect on Valley Bottom	Potential Effect on Channel
Beaver dams	Increase groundwater in valley and retention of flood flows	Alluviation of valley bottom; probably heavy organic composition of sediment	Stepped profile Local reduction in channel slope Sedimentation in channels
Native American land clearing, forest fires, and horticulture	Increased runoff and sediment supply	Alluviation of valley bottom with fine grain sediment	Sedimentation in channels and increases in bank height because of floodplain alluviation
Reduction in Native American populations and associated agricultural practices Growth of cane breaks	Decreased runoff and sediment supply	Erosion of sediment deposited during Native American agriculture period Development of a low terrace	Reduction in bank heights as stream erodes terrace
Buffalo trails	Local increase in runoff and sediment supply where trails crossed streams	Minor alluviation of valley bottoms downstream of trail crossings	Local channel widening at crossings or along instream trails
Extirpation of beavers	Reduction in groundwater elevation	Erosion of pond sediment	Channel incision Increase in bank heights, and suspended sediment supply and transport
Extirpation of buffalo	Local decrease in runoff and sediment discharge	Little effect	Local channel recovery at some crossings not used by settlers
Settler forest clearing for cultivation and pasture Free roaming livestock Slash-and-burn cultivation	Increase in runoff and sediment supply	Alluviation of valley bottom	Increase in channel bank height
Settler construction of milldams, fish dams, and fish traps	Flow retention	Alluviation of valley bottoms	Storage of gravel in stream channels
Wood cutting for salt, iron, and brick furnaces	Increase runoff and sediment supply	Alluviation of valley bottom	Increase in channel bank height
Clearing and snagging of woody debris from rivers	Reduced retention and increased conveyance of flood flows that decreased flooding Reduction in wetlands	Decrease in frequency of floodplain inundation Decrease in alluviation	Increase in channel bank height, channel incision rate, and bank erosion rate Initiation and propagation of gullies
Agricultural drainage	Reduced retention and increased conveyance of flood flows that decreased flooding Reduction in wetlands	Decrease in frequency of floodplain inundation Decrease in alluviation	Increase in channel bank height, channel incision rate, and bank erosion rate Initiation and propagation of gullies

floodplain gravels and sands) that convey flow more efficiently downstream. Sediments deposited behind dams further increased bank heights and reduced the frequency and duration of floodplain inundation.

Many of the larger Bluegrass streams have experienced several cycles of floodplain alluviation and channel modifications, which caused them to incise multiple times. Consequently, several terraces have been formed in their valley bottoms, each representing the floodplain of the stream at some point during its past. Where channels have incised at least partially to bedrock or other bed control that holds channel grade for a period of several years, smaller channels are forming through the deposition of sand and silt within the incised channel. These incipient channels and their associated proto-floodplains are most clearly defined in reaches with a relatively high fine sediment load.

Basin-wide incision through post-settlement alluvium has increased sediment supply by increasing the drainage density of the watershed, releasing in-channel legacy sediments, and eroding high banks. Incision increases the drainage density of the landscape by relocating channel heads higher on the hillslopes. Sediment that prior to settlement was stored on hillsides above the channel head (and hence was unavailable to the stream network) has been re-deposited downstream, where it is accessible to the stream via bed and bank erosion. As headcuts propagate through defunct mill dams and farm ponds, the legacy sediments stored behind them are released to the stream channel. The high banks of the entrenched channels are also a common source of fine silts and clays. With few exceptions, stream banks are composed primarily of fine-grained sediments and a thin layer of coarse basal gravel, and the high banks are vulnerable to mass failures.

The increased supply of sediment, the entrenchment and disconnection of channels from their floodplains and groundwater aquifers, and the extensive exposure of bedrock in channel beds have all contributed to degradation of both riparian and aquatic ecosystems (Bravard et al. 1999). The supply of fine sediments from high, unvegetated banks and the reduction of overbank flooding and associated fine sediment deposition may contribute to the high suspended sediment concentrations that constitute a major water quality problem in the Bluegrass region (KDOW 2007). Bedrock exposed in the stream bed provides limited habitat diversity; the limestones and shales that break down to form silts and clays do not produce well-developed bedforms, resulting in a subdued riffle-pool sequence and reduced support for aquatic communities (Shields et al. 1994).

Much of the degradation of stream and floodplain biota can also be related to the altered interaction between groundwater recharge and stream flow (Bravard et al. 1999) due to alluviation and channel manipulation. Stream reaches that were straightened were typically moved away from the center of the valley bottom and aligned adjacent to the valley wall. This relocation and the deposition of alluvium in the valley bottoms perched the channels above the water table and disconnected them from groundwater recharge. The water table, controlled by the stream water surface, is often close to the bedrock layer. As a result of the separation between channel and alluvial aquifer, streams become dry in the summer except in isolated pools. The lowering of the water table and increasing bank heights also contribute to loss of riparian vegetation (Reilly and Johnson 1982), which may result in a reduction in species diversity as less tolerant species suffer extensive mortality (Miller et al. 1995). Loss of riparian vegetation can also be attributed to farmers' clearing of trees from riparian corridors to prevent debris from entering the stream channels. Clearing of vegetation and debris from Bluegrass corridors and streams became common practice in the early 1800s (Verhoeff 1917) and is still observable today. The resulting reduction in supply of debris has not only further reduced available channel habitat but has also retarded channel evolution and recovery of sinuousity, as an important mechanism for increasing sinuosity is scour around debris jams (MacDonald and Keller 1987). In the Bluegrass, streams that have an alluvial valley bottom and a drainage area of less than 20 mi^2 are rarely found to have recovered a sinuous planform.

While channel evolutionary processes in the Bluegrass are reforming active floodplains and channels, the processes are relatively slow for three main reasons. First, erosion-resistant channel boundaries composed of bedrock and cohesive banks prevent rapid bank erosion or bed degradation. Second, the supply of coarse sediment that would form bars and divert flow toward banks (Richards 1976) is low; dredging and removal of gravels by landowners further reduces the already limited supply. Third, the supply of sand-sized sediment that would rapidly reform floodplains is generally low. In other physiographic regions, improved floodplain access of incised streams has been documented following the initiation of channel widening and meandering and development of new, lower depositional surfaces (Thorne 1999). These processes are likely to remain slow in the Bluegrass, however, as erosion-resistant bed and bank materials prevent the rapid migration of headcuts, channel incision, and bank retreat that characterize channel instability in other regions (Schumm and Lichty 1965; Simon 1992; Simon and Darby 1999; Simon et al. 2000).

Measurement and Analysis Methods 3

Bankfull channel characteristics were measured at sites near stream-flow gauging stations operated by the US Geological Survey (USGS) Kentucky Water Science Center and at ungauged sites. Channel geometric and longitudinal profile data, bed material properties, and in some locations, crest gauge data were used to calculate channel dimensions and parameters needed for estimating bankfull discharge, classifying the channel, and developing bankfull regional curves. Where discharge was estimated for a gauged location with at least 10 years of record of peak annual flow, the bankfull discharge return interval was also estimated.

3.1 SITE SELECTION

Initial Screening of USGS Gauging Stations

All USGS gauging stations within the Bluegrass were considered in the selection of a sample to represent the population of Bluegrass streams. In order for the sample to be representative of regional stream conditions, it would ideally consist of sites on rural, unregulated, wadeable streams with active gauges and a wide distribution of drainage areas and geographic locations. Prior data collection in other physiographic regions of Kentucky, however, had shown that the number of gauge sites suitable for assessment is typically limited and unlikely to comprise a sample that meets all of the ideal criteria; channel conditions at stream gauge stations tend to be characterized by reach-scale instability, a lack of consistent and unambiguous bankfull indicators in incised channels, and recently modified channel geometry (Parola et al. 2005a, 2005b). Therefore, while geographic locations and drainage areas were identified and recorded, their distributions were not factors in site selection.

Each station was screened according to three preliminary selection criteria prior to field reconnaissance:

1. Recording frequency and duration of available discharge data. Stream flow records were available for a large number of Bluegrass streams and rivers. Discontinued gauge sites were excluded unless the record of annual maximum series data was suitable for flood frequency analysis. At least 10 years of data had to be available, spanning a period where the only breaks in the record were those unrelated to flood magnitude (USIACWD 1982:15). Active gauge sites with fewer than 10 years of annual maximum series data were excluded unless they had real-time discharge data for estimating bankfull flow.
2. Land use. Because streams in watersheds with a significant proportion of densely urbanized land tend to be undergoing rapid morphological change, watersheds that were more than 10 percent urbanized and those known to be undergoing urbanization were excluded.
3. Site characteristics. Sites known to have characteristics that would make them unsuitable for data collection (e.g., those that were known to be regulated, affected by waterway structures, or undergoing rapid morphological change) were excluded.

Contour maps and aerial photographs were then reviewed to identify characteristics that could be relevant to field evaluation of the sites that had not been eliminated from consideration. The following tasks were completed in the review:

1. All stations were located on 1950s USGS 7.5-minute topographic quadrangle maps.
    a. Reaches likely to present consistent and reliable bankfull indicators were identified.
    b. Stream reaches in the vicinity of the gauges were examined for evidence of channel straightening, realignment, or other modifications such as excavation for old mill races.
    c. Any structures spanning or encroaching on the stream channel were identified.
    d. Valley constrictions or sharp bends that could create backwater during high flows were recorded.
2. Aerial photographs were examined to identify recent land use changes and possible impacts to the stream channel and the floodplain.
3. The 1950s course of the stream was identified on the topographic maps and compared with the present alignment documented by aerial photographs, and discrepancies were recorded.
4. Maps indicating karst-prone areas (KGS 2006) at scales of 1:500,000 and Kentucky Geological Survey (KGS) 7.5-minute geologic quadrangle maps (1:24,000) were checked for karst-prone strata that might affect the relative proportion of surface and sub-surface flow.
5. The bedrock material underlying each site and its watershed were identified from the KGS 7.5-minute geologic quadrangle maps.
6. Surface drainage areas for each station were recorded from the total drainage areas provided with USGS gauge descriptions. While contributing drainage areas (total drainage area less the area of sinkholes in the basin) were also provided for some sites, their derivation was subject to an undetermined degree of error because the methods used to derive them relied exclusively on topographic data and could not account for groundwater conduits that cross topographic divides (G. Martin, pers. comm.). Therefore, total drainage areas were used for each site's watershed. Field reconnaissance was limited to streams in watersheds draining fewer than 200 mi^2.

7. The physiographic sub-region(s)—the Inner Bluegrass, Eden Shale Belt, Outer Bluegrass, and/or Knobs—drained by the watershed of each station were identified using geospatial datasets (KGS 2002; Noger 2002). None of the streams draining fewer than 200 mi^2 had significant portions of their watersheds outside the Bluegrass.

Field Reconnaissance

An initial reconnaissance visit was made to photograph and evaluate each potential site. The field evaluation was based on four additional criteria:

1. Access. To obtain morphological data, a stable reach near the gauging station had to be accessible. Sites not on public land were only selected if private landowners granted access.
2. Channel pattern. Only single-thread channels were selected.
3. Karst susceptibility. Much of the Bluegrass region is underlain by carbonate rock, and stream flow at nearly every site considered was therefore potentially susceptible to karst effects. At present, karst influences cannot be reliably predicted. Topographic maps and field observations provide clear evidence of karst surface features where present (Currens 2002), but the drainage patterns of karst aquifers may differ significantly from surface drainage patterns, and the apparent surface drainage area, especially in small basins, may not reflect the extent of groundwater conveyance. Similarly, maps of some groundwater karst basins relative to surface drainage boundaries are available (KGS 2005), but their information is currently insufficient to predict the influence of karst on the quantity of runoff at a particular site. Because dye-trace tests for karst flow were beyond the scope of the project, field inspections focused on identification of karst features (e.g., seep holes) that indicated that the stream was losing or gaining significant amounts of flow. One site was identified in the field reconnaissance as being significantly influenced by karst and was eliminated.
4. Channel morphology. Sites that met all of the above criteria were given further consideration only if the channel showed no signs of ongoing rapid morphological change and the geomorphic characteristics of a reach near the gauge were suitable for surveying of bankfull indicators.

The suitability of the channel for surveying of bankfull indicators was determined based on evaluation of the floodplain and channel morphology upstream and downstream of the gauge. At a minimum, the reach had to have (1) cross-sectional geometry with unambiguous indicators of the bankfull level and evidence of at least one bank having been formed by deposition (2) channel geometry that was not controlled by a structure, and (3) a drainage area that differed by no more that 10 percent from the drainage area at the gauge station. The bankfull level was determined according to the definition of bankfull flow proposed by Dunne and Leopold (1978), who described it as the flow that completely fills the channel so that its surface is level with the active floodplain. The active floodplain is the flat depositional surface 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). Dunne and Leopold also reported an approximately 1.5-year average return interval for bankfull flow; in the identification of the active floodplain of Bluegrass assessment reaches, however, no minimum or maximum bankfull return period was assumed.

The primary indicators used to identify the active or actively-forming floodplain were fine-grained depositional features (Dunne and Leopold 1978). The characteristics of these features varied depending on channel morphology. Many incised channels had multiple depositional surfaces—low, flat terraces that had to be distinguished from the active floodplain. In those channels, the primary indicator was a low depositional bench, and the bankfull level was identified as the point at which the slope transitioned between steep and horizontal (Figure 3.1). In cases where smaller, indistinct channels were forming within an incised channel, a primarily flat, vegetated bench was the most consistently observed depositional feature (Figure 3.2). Other incised channels lacked flat terraces; instead, the region between the valley flat and the channel was only a gently sloped incline. The bankfull level coincided with the top of bank below the valley flat and was identified as the point at which the slope transitioned between steep and more gradual (Figure 3.3). In streams that were not incised, the bankfull level coincided with the top of bank and valley flat (Figure 3.4).

Identification of the bankfull level was refined by comparing elevations of multiple indicators and evaluating secondary, non-morphological indicators. The elevations of bankfull indicators along the channel were compared to confirm that they were consistent relative to the water surface. When consistent indicators suggested a number of possible bankfull levels, the reach was nevertheless considered to be suitable for surveying. Secondary indicators of the bankfull level included the size fraction of the depositional material and changes in vegetation above and below the level identified as bankfull.

The second minimum requirement for selection of an assessment reach—channel geometry that was not controlled by a waterway structure—led to the elimination of several sites and necessitated that many of the reaches selected for assessment be located downstream or upstream of the gauge. Gauges typically were located at road bridges or culverts, which affect local channel geometry by altering flow velocity distributions, flow patterns, and sediment dynamics. Therefore, most of the gauge sites had cross-sectional geometries that had been affected by structural or other anthropogenic influences such as dredging or debris blockage removal. Some of these sites had to be eliminated because only inconsistent indicators of bankfull flow could be identified near the gauging station. Reaches selected for assessment were generally located downstream of the gauge to avoid the backwater influence of the bridge or culvert on floodplain and channel characteristics. Reaches upstream of the gauge were only chosen for assessment under two conditions: (1) when the configuration of the crossing structure associated with the gauge was considered to not significantly influence fine-grained sediment deposition required for floodplain formation, or (2) when the location of the upstream reach was considered to be beyond the backwater influence of the crossing structure associated with the gauge.

Final Site Selection

A total of 13 gauged sites on 11 streams met all of the above criteria. Although the sites constituted a small sample, the geographic locations and drainage areas represented by the sample were fairly well distributed. The 13 selected sites were located throughout all but the northern portion of the Bluegrass region, which had few gauged streams. Many of those were in watersheds that were urbanized or under development. The remainder lacked reaches in the vicinity of the gauge that would have been suitable for geomorphic assessment. The 13 sites represented a wide range of drainage areas even though the majority of active gauges had been located on large streams, as were those with sufficient annual peak discharge data for flood-frequency analysis. Five selected sites had drainage areas of less than 10 mi^2, five drained between 20 and 100 mi^2, and three drained more than 100 mi^2.

Figure 3.1 Cave Creek near Fort Spring, KY. The bankfull level is represented by a narrow, horizontal depositional feature below and distinct from the higher valley flat.

Figure 3.2 Stable, well-developed low depositional bench at Hough Run, Bullitt County.

Figure 3.3 Cave Creek near Fort Spring, KY. The active floodplain (bankfull) level is seen on the right bank, below and gradually sloping up to the valley flat.

Figure 3.4 Beech Fork near Springfield, KY. The bankfull level coincides with the valley flat.

After the 13 gauged sites had been identified, an additional 7 ungauged sites were added to increase the sample's size and representation of very small channels. Because streams draining fewer than 10 mi^2 are the focus of the majority of natural channel design efforts (i.e., those that would make use of regional curves), their representation in the sample was considered a priority. Six small ungauged sites on five additional streams were therefore added. One larger ungauged site was also added to increase the sample's representation of streams with drainage areas greater than 100 mi^2. Each of the ungauged sites was associated either with one of the 11 selected gauged streams or with another project for which data were being collected. Other criteria for choosing ungauged assessment reaches were the same as those applied to gauged sites, omitting those criteria related to the gauges. Drainage areas for all 20 sites (Table 3.1 and Figure 3.5) on 16 streams ranged from 0.25 mi^2 to 154 mi^2.

3.2 DATA COLLECTION

At all sites, sufficient channel and overbank topographic data and bed sediment data were collected to calculate bankfull parameters and to identify the channel type according to the Rosgen (1996) classification system.

Channel Geometry

During the initial reconnaissance conducted during the site selection process, survey locations in each gauged and ungauged reach selected for assessment were marked with flags. Flags were used to mark upstream and downstream limits of each reach, USGS gauge benchmarks, cross section locations, tree lines along the banks, and bankfull indicators. In a second visit to each site, data was collected for development of regional curves. Gauge descriptions obtained from the USGS Kentucky Water Science Center were reviewed for indications of historical channel processes that had been observed by station monitors. Extensive photographic documentation was recorded for all sites. The specific geomorphic features that were recorded included bankfull markers, bed configuration, bank condition, flow patterns, valley configuration, dominant vegetation, and any structures that might affect flow within the channel or over the valley bottom. Field surveys recorded marked features and cross-sectional and longitudinal profile data.

Survey data were collected according to the procedures described in Harrelson et al. (1994). Survey control points were installed at each cross section location. Where practical, these consisted of at least two permanent concrete monuments. Where permanent monuments were not practical, or where landowner permission was not granted, wooden stakes were substituted. Cross sections, marked features, and longitudinal profiles were surveyed using a Topcon GTS-226 total station; measurements were accurate to within 1 cm in both the horizontal and vertical directions. Collected survey data were stored on a hand-held data logger during field activities and then transferred to a spreadsheet software program for analysis.

Cross sections were surveyed at locations that both coincided with a clear bankfull indicator and were representative of the reach morphology: at the crest of a riffle whenever possible or, at sites where no well-developed riffle was located in a reach with clear bankfull indicators, at a plane-bed section of the longitudinal profile. In reaches where multiple cross sections were taken, the cross section taken at the most clearly defined riffle crest was used to compute bankfull parameters. Selection of the most appropriate riffle crest for computing bankfull parameters was based on an extensive examination of the reach and its bankfull indicators. Only after the bankfull level was determined was the most appropriate riffle crest selected for surveying. Cross sections were surveyed to the width of the floodprone area or, when the floodprone width was

Table 3.1 Assessment Site Location Summary

	Stream Site	USGS Gauge	No.Yrs. Q_{peak} Data	Drainage Area (mi^2)	County	Latitude	Longitude	Physiographic Sub-region(s): at Stream Site	Physiographic Sub-region(s): Upstream Drainage*
1	Beech Fork *nr Springfield*	3300000	28	85.9	Washington	N 37° 42.25'	W 85° 8.75'	ESB	ESB (Outer BG)
2	Beech Fork *at Litsey*	—	—	100.7	Washington	N 37° 46.25'	W 85° 11.38'	Outer BG	ESB (Outer BG)
3	Bullskin Creek *nr Simpsonville*	3295702	9	54.8	Shelby	N 38° 13.12'	W 85° 18.12'	Outer BG	Outer BG
4	Cave Creek *nr Fort Spring*	3288500	27	1.93	Fayette	N 38° 1.25'	W 84° 35.63'	Inner BG	Inner BG
5	Eagle Creek *at Sadieville*	3291000	43	42.9	Scott	N 38° 23.37'	W 84° 32.60'	ESB	ESB
6	Floyds Fork *at Fisherville*	3298000	62	138	Jefferson	N 38° 11.30'	W 85° 27.62'	Outer BG	Outer BG
7	Harrison Fork *nr Samuels*	—	—	3.19	Nelson	N 37° 51.85'	W 85° 35.23'	Knobs	Knobs
8	Harrison Fork *nr Samuels*	—	—	3.55	Nelson	N 37° 51.86'	W 85° 35.45'	Knobs	Knobs
9	Hinkston Creek *nr Carlisle*	3252300	15	154	Nicholas	N 38° 14.55'	W 84° 3.15'	ESB	ESB (Outer BG)
10	Hough Run *at Mt. Washington*	—	—	1.11	Bullitt	N 38° 2.18'	W 85° 31.40'	Outer BG	Outer BG
11	Indian Creek *nr Owingsville*	3250150	12	2.43	Bath	N 38° 9.40'	W 83° 39.08'	Knobs	Knobs
12	Long Lick *at Clermont*	3298550	15	7.91	Bullitt	N 37° 55.67'	W 85° 39.22'	Knobs	Knobs
13	North Elkhorn Creek *at Man O War Blvd*	3287580	8	2.2	Fayette	N 38° 1.70'	W 84° 24.12'	Inner BG	Inner BG
14	North Elkhorn Creek *at Winchester Rd*	3287590	9	4.05	Fayette	N 38° 2.90'	W 84° 24.67'	Inner BG	Inner BG
15	North Elkhorn Creek *nr Georgetown*	3288000	43	111	Scott	N 38° 12.33'	W 84° 30.82'	Inner BG	Inner BG
16	Salt River *nr Harrodsburg*	3295000	28	39.7	Mercer	N 37° 45.43'	W 84° 52.38'	ESB	ESB
17	South Elkhorn Creek *at Fort Spring*	3289000	51	21.2	Fayette	N 38° 2.58'	W 84° 37.58'	Inner BG	Inner BG
18	Unnamed Trib A of Dix River *nr Crab Orchard*	—	—	0.25	Lincoln	N 37° 28.14'	W 84° 28.74'	Knobs	Knobs
19	Unnamed Trib B of Dix River *nr Crab Orchard*	—	—	0.51	Lincoln	N 37° 27.54'	W 84° 28.56'	Knobs	Knobs
20	Whittaker Run *at Smithville*	—	—	4.45	Bullitt	N 38° 1.34'	W 85° 31.34'	Outer BG	Outer BG

* Major and minor contributing areas. Parentheses indicate minor areas. BG = Bluegrass; ESB = Eden Shale Belt. The surface geology of each site is described in Appendix C.

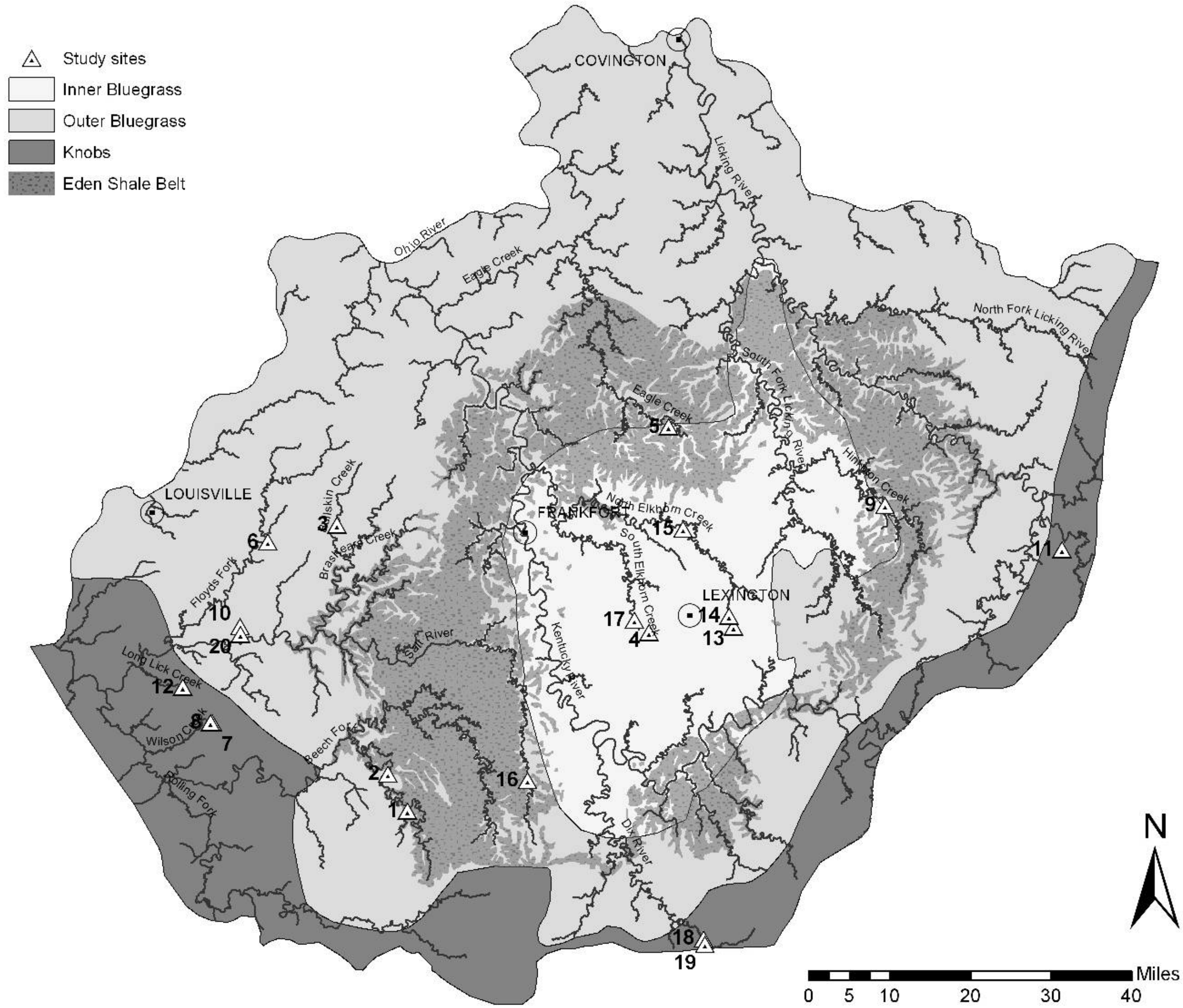

Figure 3.5 Locations of assessment sites (KGS 2002; KYDGI 2005a, 2005b). Streams shown are Strahler order 4 and above.

clearly greater than four times the bankfull width, to a point at least one bankfull width from the top of each bank. Longitudinal profiles measured the elevations of the thalweg, water surface, bankfull indicators, and top of bank at several locations along the assessment reach. All survey data at gauged sites were referenced to the gauge datum wherever gauge benchmarks could be identified.

The amount and extent of the survey data collection at each site depended largely on whether and how bankfull discharge was going to be determined. At sites where bankfull discharge was not to be determined, a single cross section was typically surveyed. At the five sites where bankfull discharge could be estimated from a rating curve, one or two cross sections and a longitudinal profile were surveyed. The longitudinal survey extended through the length of the assessment reach and past the gauge location. At all other sites, bankfull discharge had to be estimated by numerical modeling. Therefore, more extensive channel geometry data (i.e., a greater number of cross sections taken over a greater reach length) were required. A minimum of seven cross sections and a longitudinal profile were surveyed at those sites, whether gauged or ungauged. At the gauged sites, the longitudinal survey extended past the gauge location.

Bed Sediment Characteristics

The surface particle-size distribution was evaluated at each site on the riffle surveyed to compute bankfull parameters. The Wolman (1954) pebble counting procedure was used at each site where bankfull discharge would be estimated by numerical modeling. At most other sites, the size class corresponding to the median sediment size was visually estimated for the riffle.

Bankfull Discharge

Bankfull discharge at 15 sites was estimated using field surveys, current stage-discharge relations (rating curves), and/or a numerical model (HEC-RAS). Rating curves for each of the eight active gauge stations and Salt River near Harrodsburg were derived from gauging information (Form 9-207) obtained from the USGS Kentucky Water Science Center. At 12 sites where access was public or landowners granted permission for multiple site visits, crest gauges were installed along the assessment reach and, at those sites with a discontinued gauge, at the gauge location. Crest gauges offered a cost-efficient, practical means of measuring peak flow stages for multiple events that could be used to calibrate the HEC-RAS model or, when they recorded a bankfull flow, to estimate discharge from the rating curve. The crest gauges used in this project were constructed of PVC pipe and were a modified version of the USGS Crest-Stage Gauge Type A (Buchanan and Somers 1968).

At 10 sites, bankfull discharge was estimated using HEC-RAS (see Section 3.3). At the other five sites, the gauge rating curve was used to determine bankfull discharge based on the bankfull level identified at the cross section used for computing bankfull parameters. In each case, the bankfull level coincided with the top of bank at or near the level of the valley flat. The use of the rating curve varied, however, according to conditions at each gauge site:

- At North Elkhorn Creek at Georgetown, Hinkston Creek, and South Elkhorn Creek, the cross section for bankfull geometry was within three bankfull widths of an active gauge and had channel geometry similar to that at the gauge. Thus, the stage-discharge relation was considered to be the same at the gauge and the cross section. The bankfull stage at the gauge was determined by measuring the elevation difference between the water surface and the bankfull level at the cross section and adding it to the water surface elevation surveyed at the gauge at the same time; the rating curve was then used to derive the bankfull discharge associated with that stage.

At two of those three sites, the estimated discharge was cross-checked with additional data. The estimated discharge for Hinkston Creek was cross-checked using crest gauge data. The crest gauges recorded a flow stage that corresponded to the level identified as bankfull, and real-time data from the USGS gauge was used to determine the associated discharge. The bankfull discharge estimated using crest gauge data was 13.7% less than the discharge predicted by measuring from the water surface to the bankfull level. At South Elkhorn Creek, all of the events recorded by the crest gauges were well above bankfull, but the estimated discharge was cross-checked in the field during a high-flow event. The flow in the assessment reach was observed as it approached the level identified as bankfull. The time at which flow reached the bankfull stage was recorded, the stage recorded by the gauge at the same time was obtained from the real-time gauge data, and the discharge associated with that stage was derived from the rating curve. The bankfull discharge estimated using the real-time gauge data was 11.8% greater than the discharge predicted by measuring from the water surface to the bankfull level.

- At Floyds Fork, the cross section for bankfull geometry was more than 10 bankfull widths from the gauge and had different channel geometry. Moreover, the bankfull cross-sectional area in the reach exceeded 1000 ft^2, which precluded the collection of sufficient survey data for flow modeling. The bankfull discharge was therefore estimated in the field during a high-flow event. The flow in the assessment reach was observed as it approached the level identified as bankfull. The time at which flow peaked at the bankfull stage was recorded, the stage recorded by the gauge at the same time was obtained from the real-time gauge data, and the discharge associated with that stage was derived from the rating curve. Crest gauge data were used to confirm that the observed flow was at the level identified as bankfull in the assessment reach.
- At Salt River, the channel geometry at the gauge was much wider than at the cross section for bankfull geometry. Though the gauge was discontinued, the rating curve was considered to be reliable because potential for morphological adjustment of the channel at the gauge location was limited: the exposed bedrock in the channel bed provided a stable base-level control, and the upstream sediment supply was limited by an intact dam located upstream of the gauge. The bankfull discharge was estimated using crest gauge data for multiple flow events. Crest gauges installed in the assessment reach and at the bridge recorded flows both above and below the bankfull level. A bankfull flow event was also recorded in the reach. Because that event was not recorded at the gauge station, however, the bankfull stage at the gauge was interpolated from the other recorded flows. The discharge associated with that stage was derived from the rating curve.

3.3 DATA ANALYSIS

Bed Sediment Sizes

A cumulative frequency distribution was plotted from the particle sizes recorded in the pebble counts. From the distribution curve, the particle sizes that equaled or exceeded 50 percent

(D_{50}) and 84 percent (D_{84}) of the sampled material were determined for use in classifying each reach (Rosgen 1996) and modeling bankfull discharge. For classification purposes, the D_{50} of the most clearly defined riffle crest was considered to be representative of the dominant particle size throughout the reach.

Cross Sections and Profiles

Survey data were reduced using AutoCad. Cross section and longitudinal profile data were then extracted from AutoCad and plotted using Microsoft Excel. At sites where field surveys were referenced to gauge benchmarks, all elevations were plotted relative to the benchmark heights given by USGS gauge descriptions.

Each surveyed cross section at each site was plotted at a 1:1 horizontal-to-vertical scale so that breaks in slope could be clearly identified. Based on each cross section plot, multiple parameters were analyzed as follows:

- Bankfull indicators on both banks were identified and evaluated on each cross section plot to confirm that they corresponded to the active floodplain. Where bankfull indicators suggested a number of possible bankfull levels, the level indicated by the lowest depositional features that were consistent relative to the water surface elevation was selected as bankfull.
- The cross section taken at the most clearly defined riffle crest at each site was used to compute bankfull parameters needed for
  - Developing regional curves: bankfull cross-sectional area (A_{BKF}); bankfull width (W_{BKF}); and mean bankfull depth ($D_{BKF} = A_{BKF} / W_{BKF}$).
  - Classifying each assessment reach according to the Rosgen (1996) Level II classification system: maximum bankfull depth; floodprone width (W_{FP}); entrenchment ratio ($ER = W_{FP} / W_{BKF}$); and width-to-depth ratio (W_{BKF} / D_{BKF}).
- Cross section plots were compared to photographs of the same locations. Banks and depositional features in each cross section plot were examined in the photographs to evaluate their stability. The types of vegetation on the banks and floodplain were identified from the photographs for use in assigning roughness values for sites where flow would be modeled.
- For sites where flow would be modeled, geometric data for each cross section were tabulated for input into HEC-RAS.

The longitudinal profile of each surveyed channel thalweg, water surface, bankfull indicators, and top-of-bank elevation were plotted with an exaggerated vertical scale so that breaks in slope could be clearly identified. The locations of cross sections and the elevations of peak flows recorded by crest gauges, if used, were also plotted on each longitudinal profile. Based on each profile plot, multiple parameters were analyzed as follows:

- A regression line was plotted through elevations of all bankfull indicators that were consistent relative to the water surface elevation. Where bankfull indicators suggested a number of possible bankfull levels, the level indicated by the lowest depositional features that were consistent relative to the water surface elevation was selected as bankfull. The regression line represented the average bankfull level through the reach. In some cases, the bankfull level indicated by the regression line was used to re-evaluate cross section plots: where a residual for a bankfull level point at a cross section was large, or where no bankfull indicator elevation was plotted, the corresponding cross section plot was examined to determine whether a bankfull indicator could be identified close to the level indicated by the regression line.

- For sites where flow would be modeled, values required for input to HEC-RAS to either define or derive a boundary condition were calculated based on various parameters:
  - When a bankfull indicator was identified at the most downstream cross section, a known bankfull water surface elevation was obtained from the elevation of the indicator.
  - When a flow stage near the bankfull level at the most downstream cross section was recorded by a crest gauge, a known bankfull water surface elevation was obtained from the elevation of the crest gauge reading.
  - Regression lines were plotted through the elevations of peak flows recorded by crest gauges. A water surface slope was obtained from the line that plotted closest to the bankfull regression line.
  - A water surface slope was obtained from the regression line through the bankfull indicator points.
  - A water surface slope was obtained from the riffle-crest-to-crest slope. At sites where the surveyed water surface slope between riffle crests varied within the assessment reach, the riffle-crest-to-crest slope was calculated from the two most downstream riffles; otherwise the slope was derived from the best-fit line regressed through the riffle crest points of all cross sections.

HEC-RAS Estimation of Bankfull Discharge

Bankfull discharge and friction slope in 10 reaches were modeled using the one-dimensional water surface profile program HEC-RAS 3.1 (Brunner 2001). Inputs to define the channel characteristics in the model are cross-sectional geometry data (minimum of 2 cross sections) and an estimate of the channel roughness, using the Manning *n* roughness coefficient. The cross sections were input directly from the tabular data prepared in Excel. Roughness values were estimated using the Limerinos (1970) relation and Chow's (1959) tables of roughness coefficients. Where the resistance of the channel at bankfull flow conditions could be attributed primarily to the channel bed, the Limerinos relation was applied to calculate *n*, using the D_{84} particle size from the pebble count and the magnitude of the average bankfull depth derived from the surveyed bankfull cross-sectional area and width. Where resistance of the channel could also be attributed to dense bank vegetation, as was the case for many of the larger stream systems where mature trees were found well down the banks, the *n* values for the entire bank and the overbank areas (Brunner 2001) were selected from those presented by Chow (1959:Table 5.6) for floodplains.

An iterative approach was adopted to estimate the bankfull discharge using HEC-RAS, whereby discharge was varied incrementally until the modeled flow best matched the regression line plotted through the elevations of the bankfull indicators. Roughness value inputs were also adjusted to obtain a flow that matched observed water surface elevations. Another input, the downstream boundary condition, was adjusted to obtain the best fit with the cross-sectional data and crest gauge data (when available for events near the identified bankfull level). The boundary condition at the most downstream cross section was defined by either a known bankfull water surface elevation or a water surface elevation computed by HEC-RAS using an input water surface slope and the normal depth assumption (Henderson 1966).

The selection of which parameter to use to define the boundary condition depended on what types of crest gauge data had been collected, if any, and whether the assessment reach was associated with an active USGS gauge. Types of information used to calibrate the HEC-RAS models are identified in Table 3.2. At three active gauge sites, crest gauges could be used to associate water surface elevations in the assessment reach with discharge at the gauge. When a flow stage near the bankfull level was recorded by both the USGS gauge and a crest gauge at or near the most downstream cross section, the elevation of the crest gauge reading was used to define the downstream boundary condition and thereby improve the estimate of the roughness coefficient (Manning *n* value). The use of crest gauge data increased the level of confidence in the roughness value and, consequently, the modeled water surface profile.

At three discontinued gauge sites and two ungauged sites, where active USGS gauge data were not available, the boundary condition was defined using a water surface slope obtained from the crest gauge regression line that plotted closest to the bankfull regression line. This provided a more accurate approximation of the hydraulic grade line (an approximation of the bankfull friction slope) than if morphologic features alone had been used.

At the two sites where crest gauges were not used, the boundary condition was based on surveyed elevations of bankfull features or riffle crests. When the bankfull level could be identified at the most downstream cross section, a water surface set to that elevation was used as the boundary condition. Otherwise, the boundary condition was derived using a water surface slope based on either bankfull indicators or the riffle-crest-to-crest slope in the assessment reach.

Frequency of Bankfull Discharge

Annual maximum series data for the 10 project site gauges that had at least 10 years of record were obtained from the USGS Kentucky Water Science Center or from their online datasets. Using the log-Pearson Type III distribution (McCuen 1998) as described in *Guidelines for Determining Flood Flow Frequency* (USIACWD 1982), frequency analysis was conducted for each of those 10 stations. From the frequency distribution, flows corresponding to the 1.5-year event were estimated for the 10 stations and the return periods of the bankfull discharges were estimated for the stations.

Table 3.2 Types of Site Data Collected

	Stream Site	USGS Gauge	Total DA (mi^2)	Gauge Active	Real-time Data	Q_{bkf} from HEC-RAS	No. Cross Sections	Survey Tied to Gauge Benchmark	Crest Gauges	High Water Marks	Longitudinal Profile	Bankfull Indicator
1	Beech Fork *nr Springfield*	3300000	85.9	No	No	Yes	7	No	Yes	No	Yes	Top of bank / valley flat
2	Beech Fork *at Litsey*	—	100.7	—	—	—	1	—	No	No	No	Top of bank / valley flat
3	Bullskin Creek *nr Simpsonville*	3295702	54.8	Yes	Yes	Yes	7	Yes	Yes	Yes	Yes	TOB* below valley flat
4	Cave Creek *nr Fort Spring*	3288500	2.53	No	No	Yes	8	Yes	No	No	Yes	TOB* below valley flat
5	Eagle Creek *at Sadieville*	3291000	42.9	No	No	Yes	11	Yes	Yes	No	Yes	TOB* below valley flat
6	Floyds Fork *at Fisherville*	3298000	138	Yes	Yes	No†	2	Yes	Yes	Yes	Yes	Top of bank / valley flat
7	Harrison Fork *nr Samuels*	—	3.19	—	—	—	1	—	No	No	No	Low depositional bench
8	Harrison Fork *nr Samuels*	—	3.55	—	—	—	1	—	No	No	No	Low depositional bench
9	Hinkston Creek *nr Carlisle*	3252300	154	Yes	Yes	No†	2	Yes	Yes	No	Yes	TOB* below valley flat
10	Hough Run *at Mt. Washington*	—	1.11	—	—	Yes	20+	—	Yes	No	Yes	Low depositional bench
11	Indian Creek *nr Owingsville*	3250150	2.43	No	No	Yes	11	No	Yes	No	Yes	Low depositional bench
12	Long Lick *at Clermont*	3298550	7.91	Yes	Yes	Yes	16	Yes	Yes	No	Yes	Low depositional bench
13	North Elkhorn Creek *at Man O War Blvd*	3287580	2.2	Yes	Yes	Yes	19	Yes	Yes	Yes	Yes	Low depositional bench
14	North Elkhorn Creek *at Winchester Rd*	3287590	4.05	Yes	Yes	Yes	19	Yes	No	Yes	Yes	Low depositional bench
15	North Elkhorn Creek *nr Georgetown*	3288000	119	Yes	No	No†	1	Yes	No	No	Yes	TOB* below valley flat
16	Salt River *nr Harrodsburg*	3295000	41.4	No	No	No†	2	No	Yes	No	Yes	TOB* below valley flat
17	South Elkhorn Creek *at Fort Spring*	3289000	24.0	Yes	Yes	No†	2	Yes	Yes	Yes	Yes	TOB* below valley flat
18	Unnamed Trib A of Dix River *nr Crab Orchard*	—	0.25	—	—	—	3	—	No	No	Yes	Low depositional bench
19	Unnamed Trib B of Dix River *nr Crab Orchard*	—	0.51	—	—	—	2	—	No	No	Yes	Low depositional bench
20	Whittaker Run *at Smithville*	—	4.45	—	—	Yes	20+	—	Yes	No	Yes	Low depositional bench

* TOB = top of bank.

† Bankfull discharge was determined using the stage-discharge relation for the gauge.

Geomorphic and Bankfull Characteristics of Bluegrass Channels 4

Bankfull channel parameters calculated for each assessment reach (Table 4.1) were used to develop regional curves for Bluegrass streams and to classify each reach. The curves describe the relationships between drainage area and bankfull channel geometry, and bankfull discharge. Bankfull discharge was also compared to the 1.5-year discharge for 10 sites. Classification of each reach according to Rosgen (1996) Type II classification parameters identified six Bc-, five C-, and nine E-type channels; the stream type was consistent for the entire length of each reach. Bed material in most reaches was a veneer or patches of gravel on bedrock.

4.1 BANKFULL REGIONAL CURVES

Bankfull regional curves for streams draining from 0.25 to 154 mi^2 were derived by using ordinary least-squares regression. Bankfull channel geometry and discharge data were plotted as a function of drainage area on a log-log scale (Figures 4.1 and 4.2). A best-fit line was regressed for each plot in the form of a simple power function:

$$Y_{bkf} = a\,DA^{b} \qquad (1)$$

where a and b are empirically-derived constants, DA is drainage area (mi^2), and Y_{bkf} represents a bankfull channel parameter: cross-sectional area, A_{bkf} (ft^2); width, W_{bkf} (ft); mean depth, D_{bkf} (ft); or discharge, Q_{bkf} (cfs). The resulting regression equations are provided in Table 4.2, along with calculated coefficients of determination and standard errors.

Coefficient of determination (R^2) values show that drainage area accounts for well over 90 percent of variation in the relationships between drainage area and channel bankfull parameters. Variation unaccounted for by drainage area may be attributed to other influences such as variability in sediment load caliber and quantity, hydrology, and the effects of local controls (Knighton 1987).

Table 4.1 Bankfull Geometry, Rosgen (1996) Type II Classification, and Discharge Data for Streams of the Bluegrass Region

	Stream Site	USGS Gauge	Total DA (mi^2)	A_{bkf} (ft^2)	W_{bkf} (ft)	D_{bkf} (ft)	ER*	W/D Ratio	Slope (%)†	D_{50} (mm)‡	Rosgen Stream Type	$Q_{1.5}$ (cfs)	Q_{bkf} (cfs)	RI (yrs)	No.Yrs. Q_{peak} Data§	No.Yrs. $Q_{bkf} < Q_{peak}$
1	Beech Fork *nr Springfield*	3300000	85.9	849	87.7	9.68	3.5	9.1	0.05	13	E4/1	4548	3000	1.06	28	27
2	Beech Fork *at Litsey*	—	100.7	600	100	6.0	>2.2	16.7	—	G	C4/1	—	—	—	—	—
3	Bullskin Creek *nr Simpsonville*	3295702	54.8	389	73.5	5.29	>2.2	13.9	0.10	50	E4/1	—	1500	—	9	9
4	Cave Creek *nr Fort Spring*	3288500	2.53	14.3	13.1	1.10	5.7	11.9	0.45	23	E4/1	83	50	1.14	27	21
5	Eagle Creek *at Sadieville*	3291000	42.9	394	69.9	5.65	2.7	12.4	0.21	32	E4/1	3676	1700	<1.01	43	43
6	Floyds Fork *at Fisherville*	3298000	138	1173	130	9.06	>2.2	14.3	—	G	E4/1	7828	4340**	<1.01	62	62
7	Harrison Fork *nr Samuels*	—	3.19	16.4	17.0	0.96	2.1	17.7	—	38	C4/1	—	—	—	—	—
8	Harrison Fork *nr Samuels*	—	3.55	17.0	24.5	0.69	1.7	35.5	—	G	B4/1c	—	—	—	—	—
9	Hinkston Creek *nr Carlisle*	3252300	154	1119	87.8	12.76	>2.2	6.9	—	BDR	E1	3888	2150**	<1.01	15	15
10	Hough Run *at Mt. Washington*	—	1.11	12.9	14.8	0.87	2.0	17.0	0.91	74	B3/1c	—	42	—	—	—
11	Indian Creek *nr Owingsville*	3250150	2.43	23.5	16.7	1.40	2.3	11.9	0.44	78	C3/1	469	55	<1.01	12	12
12	Long Lick *at Clermont*	3298550	7.91	88.1	37.1	2.38	1.8	15.6	0.47	69	B3/1c	1072	366	1.03	15	14
13	North Elkhorn Creek *at Man O War Blvd*	3287580	2.2	24.8	17.5	1.41	>2.2	12.4	0.35	57	E4/1	—	65	—	8	7
14	North Elkhorn Creek *at Winchester Rd*	3287590	4.05	29.5	18.9	1.56	4.8	12.1	0.33	32	C4/1	—	82	—	9	9
15	North Elkhorn Creek *nr Georgetown*	3288000	119	1029	123	8.36	>2.2	14.7	—	G	E4/1	3815	2700**	1.16	43	38
16	Salt River *nr Harrodsburg*	3295000	41.4	224	58.5	3.83	2.0	15.3	—	11	C4/1	2653	975**	1.01	28	27
17	South Elkhorn Creek *at Fort Spring*	3289000	24.0	118	53.7	2.19	1.7	24.5	—	8	B4/1c	826	500**	1.09	51	47
18	Unnamed Trib A of Dix River *nr Crab Orchard*	—	0.25	2.1	5.9	0.35	1.7	16.9	1.0††	G	B4c	—	—	—	—	—
19	Unnamed Trib B of Dix River *nr Crab Orchard*	—	0.51	3.4	5.5	0.62	3.5	8.9	1.2††	G	E4/6	—	—	—	—	—
20	Whittaker Run *at Smithville*	—	4.45	23.6	22.8	1.03	1.9	22.1	0.57	32	B4/1c	—	71	—	—	—

* ER is entrenchment ratio (dimensionless).

† Bankfull friction slope from HEC-RAS, unless otherwise indicated. Where no slope is provided, visually estimated slopes were used to classify the reach; for each of those sites, the slope of the reach was assumed to be less than the slope of the riffle used to compute bankfull parameters.

‡ BDR indicates that the streambed is predominantly exposed bedrock; G indicates that the median sediment size for the riffle was visually estimated to be in the gravel range.

§ The number of years (through water-year 2006 or, in the case of discontinued gauges, the last year of recorded data) for which (1) peak data was available online from the USGS and (2) the only breaks in the record were those unrelated to flood magnitude.

** Reaches where bankfull discharge was determined using the stage-discharge relation for the gauge. Flows for Hinkston Creek and South Elkhorn are those obtained from bankfull flow events. Bankfull discharge at other reaches was estimated using HEC-RAS.

†† Riffle crest-to-crest slope.

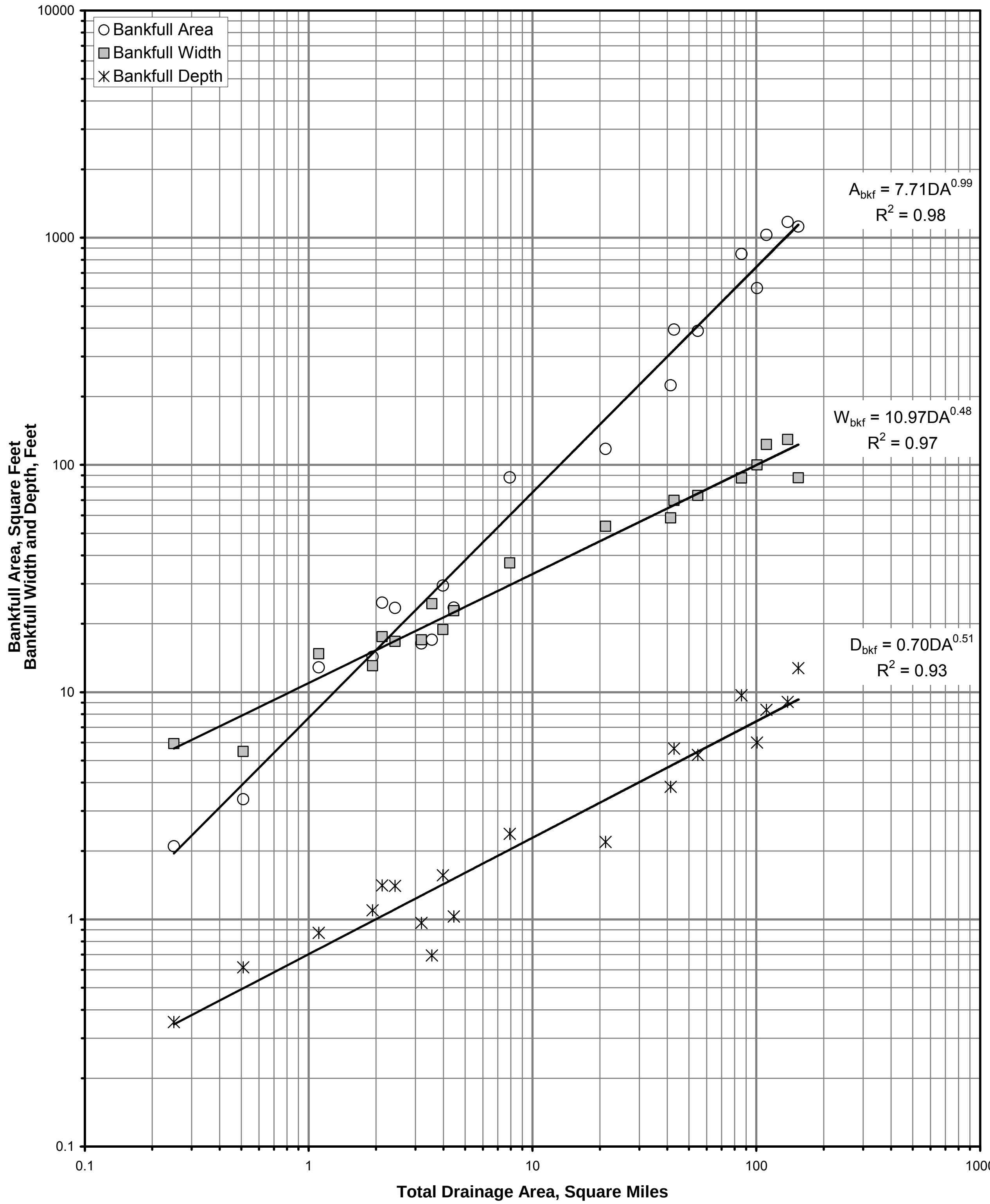

Figure 4.1 Bankfull cross-sectional characteristics as a function of drainage area for streams of the Bluegrass region.

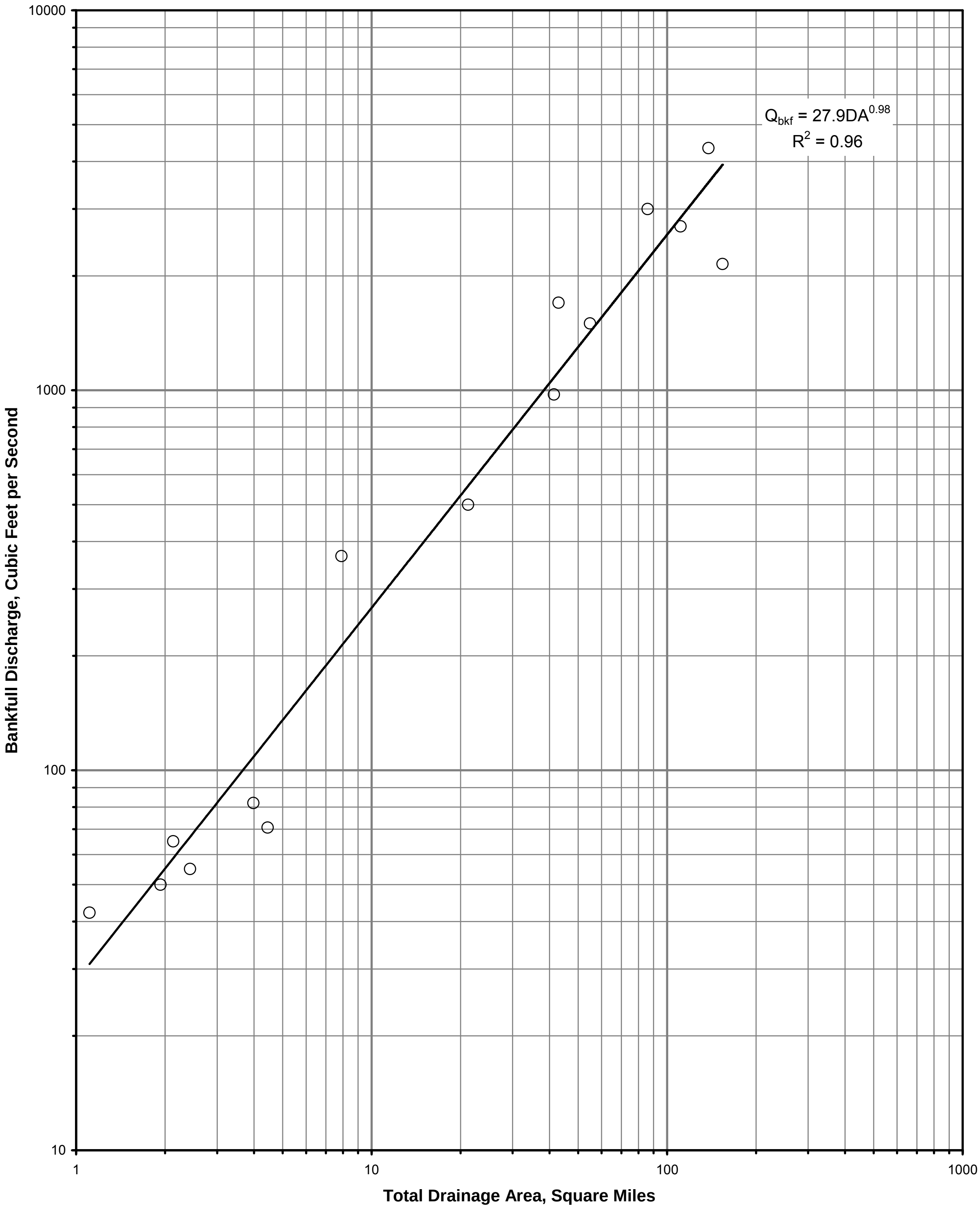

Figure 4.2 Bankfull discharge as a function of drainage area for streams in the Bluegrass region.

Table 4.2 Bankfull Regression Equations for Streams of the Bluegrass Region of Kentucky

Regression Equation	n	Coefficient of Determination, R^2	Standard Error*, S_e (%)	Standard Deviation†, $\hat{\sigma}$ (%)
A_{bkf} = 7.71 $DA^{0.99}$	20	0.98	29.7	132.8
W_{bkf} = 10.97 $DA^{0.48}$	20	0.97	17.3	77.4
D_{bkf} = 0.70 $DA^{0.51}$	20	0.93	29.0	129.7
Q_{bkf} = 27.9 $DA^{0.98}$	15	0.96	35.1	135.9

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

The regression equations for area and discharge indicate that while discharge increases in almost direct proportion to drainage area, velocity remains almost constant. A nearly linear relationship between bankfull discharge and drainage area is indicated by the exponent of the regression equation for Q_{bkf}, which is approximately unity. This value is greater than the range of 0.65-0.80 that was suggested to be typical by Leopold et al. (1964), indicating that bankfull discharge increases with drainage area at a greater rate than has been computed for other physiographic regions (Dunne and Leopold 1978).

Mean bankfull velocity (V_{bkf}) was calculated from Q_{bkf} and A_{bkf} and plotted against drainage area for each assessment site where bankfull geometry and discharge were determined (Figure 4.3). In streams having a D_{50} in the gravel range, the values of V_{bkf} ranged from 2.6 to 4.4 ft/s, with a median equal to the mean value of 3.5 ft/s. Mean bankfull velocity and drainage area did not demonstrate a significant correlation; the coefficient of determination (R^2 = 0.0124) indicates that drainage area does not account for any of the variation in the values of V_{bkf}.

4.2 BANKFULL DISCHARGE RECURRENCE INTERVAL

Bankfull return periods computed for streams draining from 2.43 to 154 mi^2 range from just over 1.0 to 1.16 years (Table 4.1). The mean bankfull return period is 1.05 years; the median is 1.02 years. These return intervals are within the range of 1 to 2 years considered to be typical for bankfull flow, and they are consistent with the 1- to 1.2-year range identified by Hey (1975) for gravel-bed rivers in England. They are, however, more frequent than the approximately 1.5-year average reported for streams in other regions of the US (Dunne and Leopold 1978; Leopold et al. 1964; McCandless and Everett 2002; Mulvihill et al. 2005; Rosgen 1996; Williams 1978) and therefore do not support the concept of a universal return period that various researchers have either suggested (Dunne and Leopold 1978) or critiqued (Knighton 1998; Williams 1978).

The bankfull discharge is not only more frequent but also substantially less than the 1.5-year discharge for each assessment reach. In each of the 10 reaches for which both the 1.5-year flow and bankfull flow were estimated, bankfull discharge is between 11.7 and 70.8 percent of the 1.5-year discharge (Figure 4.4). On average, Q_{bkf} is approximately half (49 percent) of $Q_{1.5}$, and half of the sites for which the values were compared had a Q_{bkf} less than or equal to 53 percent of $Q_{1.5}$. Thus, the 1.5-year discharge cannot be considered to be a reasonable representation or estimate of the bankfull discharge for Bluegrass streams, and estimates derived from the regression equation for Q_{bkf} would likely be more accurate than those derived from flood frequency data.

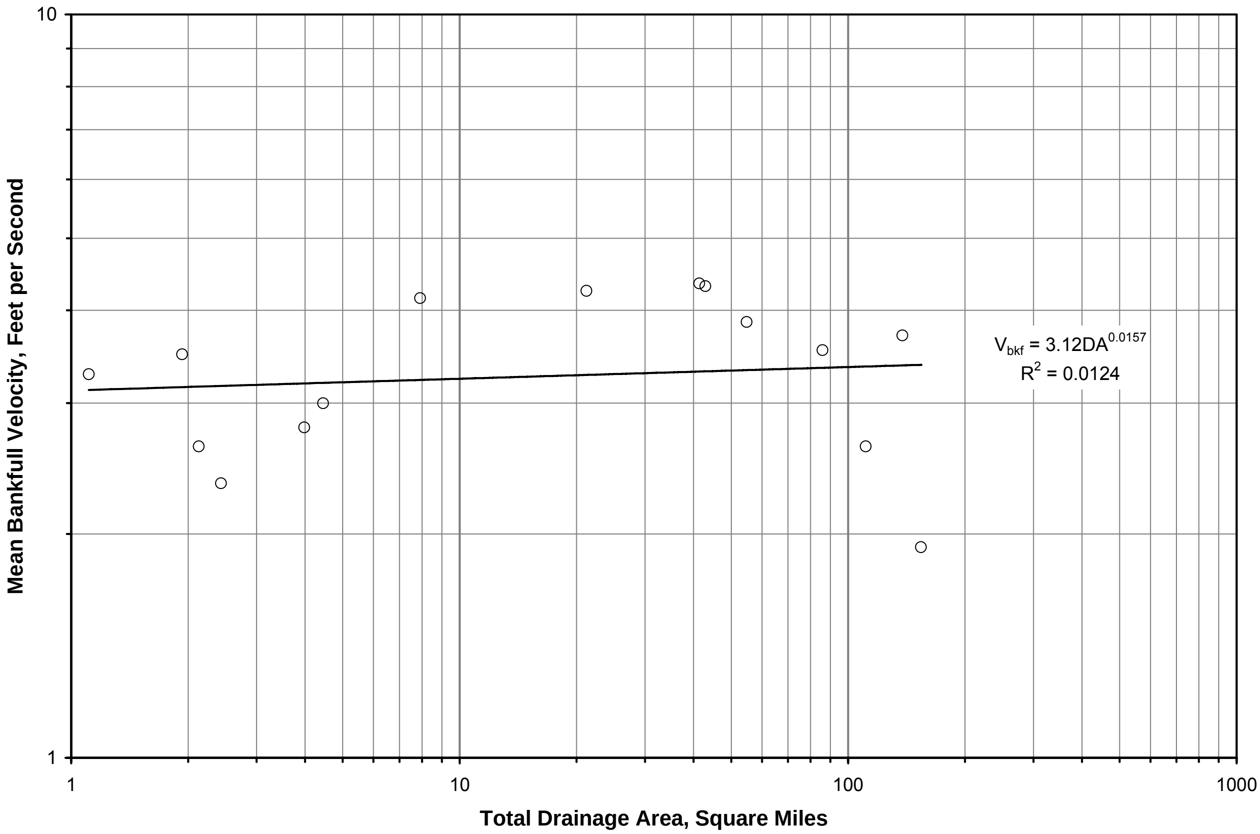

Figure 4.3 Mean bankfull velocity versus drainage area.

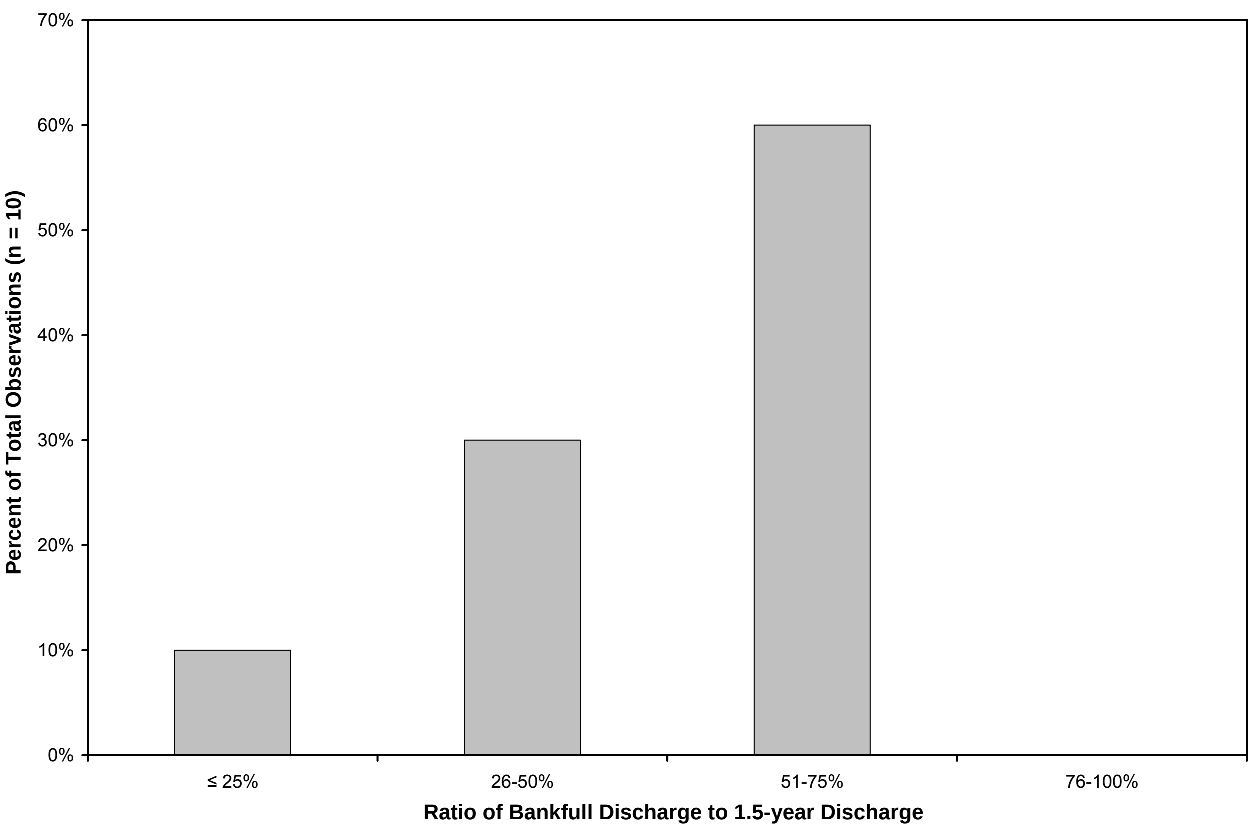

Figure 4.4 Bankfull discharge as a proportion of the flow associated with the 1.5-year return interval for the same site.

4.3 GEOMORPHIC CHARACTERISTICS OF BLUEGRASS CHANNELS

Sediment Production, Storage, and Yields

The majority of bed material in Bluegrass channels is comprised of locally broken bedrock and fine-gravel- and sand-sized sediments. The presence of bedrock within the channel boundary and underlying the basin has an important influence on the sediment supply and the geomorphology of Bluegrass streams. Bedrock in channel beds is typically entrained shortly after exposure and is transported only a short distance before it weathers into its constituent components. The bedrock underlying channels in the Bluegrass most frequently consists of thinly bedded and densely jointed limestones and shales. This type of bedrock is susceptible to moderate to rapid rates of erosion by fluvial stresses. In carbonate rocks, the chemical dissolution of rocks along bedding planes and joints produces loose detritus that is more easily eroded by the stream than intact bedrock. Other chemical weathering processes are effective agents of bedrock breakdown, leaving chemically resistant residual components of the rock; for shale this is predominantly clay, although larger residual grains may also be produced. These residual components are generally gravel-sized or smaller and can be transported during frequent flow events. Conversely, in a few locations in the Bluegrass where the underlying bedrock is massively jointed and has thick bedding planes, the residual material from chemical and mechanical weathering are cobbles and boulders that may be mobile only during infrequent large floods.

Finer sedimentary materials, specifically silt- and clay-sized particles, are carried by the flow as washload and contribute to floodplain development and in-channel bench formation. This fine silt and clay material is significant during overbank flows, where slower velocities allow the fine grains to settle, the cumulative effect of which leads to floodplain formation. In incised channels, the floodplain deposition may be represented by a low in-channel bench that may be an indicator of the bankfull channel geometry (Williams 1978). Because the primary source of fine bedload material is bank erosion, these sediments are, to some extent, supply limited and highly variable. In the Eden Shale Belt, for instance, where abundant fine-grained deposits can be observed within the channel, the underlying limestone units are generally thin, interbedded with shale, and weather rapidly. As a result, the bedrock breakdown rate (Weir et al. 1984) is much higher than in the Inner and Outer Bluegrass and the supply of fine bed material is high.

Events such as bank collapse, felled trees, and human disturbance may produce temporary increases in sediment supply. When these events do not occur, minimal bank erosion may be expected. Cohesive silts and clays may, however, undergo significant change in erodibility due to bank weakening processes, substantially increasing the rate of bank erosion (Lawler 1986). The two principal weakening processes observed in the Bluegrass were freeze-thaw and desiccation (Lawler et al. 1997). Freeze-thaw of bank materials throughout channel networks was noted in fieldwork conducted during winter months; this bank weakening process may be responsible for producing large volumes of fine-grained sediment. Extreme drying of the banks, observed during the summer drought of 2007, may also produce large volumes of sediment when considered over the entire length of channel network. These preparatory processes have been noted in other environments (Lawler 1986), but the climate of Kentucky is particularly conducive to these forms of bank weakening and sediment production.

Other significant sources of fine sediment are abandoned farm ponds and associated deposits at the base of hillsides. These sources have not been well documented, but they are common on small channels throughout the Bluegrass region. Ponds were built with a dam at the downstream end that trapped sediment from the upstream drainage area and stored it within the bottom of the pond and in the channel immediately upstream. Over time, many of these ponds filled to the height of the dam or spillway where they are present, creating a large wedge of clay-to-sand-sized sediment. At many sites visited during this project, the pond dam had been breached and a headcut was migrating through the deposited wedge, producing a locally elevated supply of fine sediment.

Reach-Scale Morphology

The most common reach-scale morphologies of Bluegrass channels can by classified as pool-riffle or plane bed. Anastomosed, cascade, step-pool, and subsurface channels can also be found in short reaches. Streams with pool-riffle channel morphology contain gravel riffles and bars that indicate a sediment supply equal to or greater than the capacity of channels to transport the bed-load (Montgomery and Buffington 1997). Streams with plane beds consisting of bedrock indicate a local capacity to transport more sediment than is supplied. Although channel gradients are generally mild in the Bluegrass region, small and steep cascade and step-pool streams can be found along the valley walls of the Ohio River and other major tributaries to the Ohio River. Step-pool systems are generally restricted to areas where boulders with a large [minor] c-axis are produced such as the Ohio River bluff line hills and the High Bridge formation around the Kentucky River near Lexington. Anastomosed reaches are found downstream of rapidly eroding bedrock reaches where the capacity to transport cobble and boulders is insufficient because of a local reduction in channel slope or other change in channel characteristics. Subsurface channels are present where joints or solution cavities form in soluble limestone or dolomite; however, interbedding of shale limits the extent of karst topography and the development of extensive subsurface channel networks in much of the Bluegrass region.

Channel Morphology

Channel morphologies in the Bluegrass vary according to local sensitivity of the streams and the landscape to anthropogenic or naturally-induced disturbances and the topographic control of sediment deposition in the channels and on valley bottoms. In general, however, four classes or groups of channel morphology are distinguishable within the region: low-incision small streams, highly-incised medium-sized streams, anabranched channels, and low-gradient large streams.

The first group, low-incision small streams (draining fewer than 10 mi^2), are found generally, but not exclusively, in the Inner Bluegrass. Of all Bluegrass channels, these appear to have been the least impacted by human land-use activity: they typically have lower bank heights, low incision, and greater access to their floodplains than streams in other sub-regions (Figure 4.5). The low degree of incision is due at least in part to the relatively thin (generally less than 3 ft) layer of alluvium over the bedrock valley floor. The karst-prone lithology and the gentle terrain and limited relief may have prevented massive soil delivery to the channels during periods of large-scale forest clearing and subsequent agricultural activities. These streams generally correspond to Rosgen F- or E-type channels depending on the amount of recent channel modification. Most bedrock breakdown of the karst-prone Lexington Limestone is through chemical weathering. As a result, the supply rate of coarse material to the stream is low, and in-channel bars, including riffles, are generally absent or are poorly-defined. In well-developed karst terrain, surface channels may be sparse or undetectable (Phillips and Walls 2004). In less intense karst landscapes, channels may be present but will convey less flow than non-karst stream reaches and may have a smaller cross section than other Bluegrass streams not affected by subsurface channels.

Figure 4.5 Cave Creek, March 2003. Small (approx 2 mi^2), limited-incision stream with moderate sinuosity.

The second group of channels, highly-incised medium-sized streams, are found throughout the Outer Bluegrass, Eden Shale Belt, and the Knobs. Larger streams in the Inner Bluegrass (draining greater than 20 mi^2) would also fall into this group. The distinguishing characteristics of these incised streams are high banks, composed mainly of fine-grained sediment; low channel sinuosity; subdued riffle-pool topography; low habitat diversity; and abandoned floodplain(s) or terrace(s) that are inundated during large floods (e.g., Eagle Creek, Figure 4.6). Most of these stream reaches correspond to Rosgen F4/1 and B4c/1 stream types. Riffles, where present, are composed of coarse (>36 mm intermediate diameter), platy material that is locally sourced from the degrading bedrock (Figure 4.7). The supply of fine sediment (<2 mm) in these streams varies from very low (e.g., Salt River at Harrodsburg) to moderate (e.g., Bullskin Creek at Simpsonville). The amount of sediment supplied to a reach was visually estimated based on the degree of deposition at the assessment reach, particularly at areas where deposition is indicative of channel load, such as the inside of bends (point bars). A large proportion of the bed material load of Bullskin Creek was comprised of non-silica sand- and fine-gravel-sized material. At least some of the sand-sized material may be iron-manganese concretions (Zhang and Karathanasis 1997).

The third group of channels found within the Bluegrass are anastomosed—having a multi-thread, anabranched channel planform, classified as Rosgen DA stream types. The anastomosed channel reaches in the Bluegrass are most commonly located in tributaries to the Kentucky River that experience high rates of bedrock breakdown due to locally high gradients and have abundant deposition of coarse, platy material due to backwater effects of lower-gradient downstream reaches. These anabranching channels form in short reaches after a single-thread channel has

Figure 4.6 Eagle Creek, March 2004, looking upstream. Eagle Creek is typical of Group 2 streams, with locally very high banks (up to 10 ft in this case on the right bank looking downstream) and an abandoned terrace that is inundated only during very large floods. The pools are shallow, riffles are relatively short, channel bars are absent, and the planform is relatively straight.

Figure 4.7 Sediment deposits in Drennon Creek, showing material directly sourced form the bedrock as viewed downstream (left) and upstream (right). The platy material is naturally prone to particle interlock, although subsequent weathering of individual clasts produces grains that are more exposed to the flow.

been blocked by debris or filled with coarse gravel. The blockage causes water upstream to overtop the banks and carve multiple smaller channels across the floodplain (Miller 1991). The blockage appears to migrate upstream and forms a general zone of aggradation in the valley bottom with cobble-sized particles accumulating on the floodplain surface at some locations. Other factors influencing development of these channels may be attributed to additional sources of sediment. A large amount of unconsolidated coarse sediment in the channel banks is supplied to the channels following bank erosion. Headcutting tributaries and eroding hillsides may also contribute to a locally high sediment supply (Figure 4.8). The influence of mill dams or other small dams and associated upstream gravel traps has not been investigated, but the downstream proximity of these types of storage zones to anastomosed reaches suggest that these types of dams may be one factor in their development. Another potential, though unlikely, factor is geologic control similar to that identified in south-central Indiana, where anastomosed reaches have been associated with non-resistant strata upstream of more resistant sandstone outcrops that create a local base-level for deposition (Miller 1991). This type of geologic control, however, was not found to be associated with the anastomosing reaches inspected in the Bluegrass.

The anastomosed stream reaches in the Bluegrass differ from the majority of channels within the Outer Bluegrass and Eden Shale Belt in several ways that improve habitat diversity and floodplain connectivity. They are the most active group of channels in the region; avulsions are common as channels fill up with coarse sediment and incise into the floodplain to form a new channel. Anastomosing reaches have a high level of interaction between the main channel and the floodplain, with more frequent and prolonged inundation. The abundant gravel and cobble deposition increases alluvial groundwater storage and locally raises the water table. These stream reaches are also the most diverse geomorphically, with eroding banks, headcuts, multifarious depositional areas with different grain-size distributions, and a network of abandoned channels and chutes spread across the valley bottom.

The fourth group are the largest channels and occur in the downstream, low-gradient portions of drainage networks near the Ohio River. Because these conditions are found only in channels with large drainage areas, the extent of these stream reaches is limited. These channels have limited bedrock exposure, mainly suspended silt and clay loads, high banks with multiple deposition and failure zones, and low width-to-depth ratios. Mass failures were observed commonly only along the larger streams (greater than 100 mi^2 of drainage area) and short reaches of streams with smaller drainage areas where bank heights were uncharacteristically high (e.g., Beech Fork at Springfield, Figure 4.9). Fine material has accumulated throughout each of the examined reaches, though evidence of deposition is typically obscured by vegetation. Numerous scars of shallow-seated rotational bank failures are present on both left and right banks, some of which appear to have slipped recently; others have vertical tree growth and are partially eroded. These failures are evident on both banks, and no evidence that the channel has been widening on a prolonged basis is apparent from the tree line, from aerial photographs, or topographic maps. Therefore, another mechanism must be operating to counteract the bank retreat that results from mass failures on both banks. These channel reaches appear to have a cycle of sediment accumulation on banks, followed by mass failure after high-flow events, followed by subsequent accumulation in the old failure scars. The sequence of alternating deposition and failure has created a range of surfaces at different elevations in these streams. These stream reaches would typically be classified as a Rosgen C or E stream type.

Figure 4.8 At Mill Creek, an incised tributary and eroding hillsides contribute large volumes of coarse sediment that is relatively immobile except during large flood events.

Figure 4.9 Beech Fork at Springfield (drainage area = 86 mi^2) showing the multiple levels on the right bank profile, each of which correspond to different discharges. Flow is away from camera.

Application of Bankfull Regional Relations 5

Regional curves describe characteristics that can generally be expected for streams of a given drainage area within a physiographic region. These descriptions are useful in the evaluation of stream stability, which includes the assessment of channel siltation, degradation, and bank erosion—factors that have substantial effects on aquatic habitat and sediment loads. They may be particularly useful in assessing channels undergoing rapid change, when bankfull indicators may be unapparent or ambiguous. Furthermore, these regional relations can be used as a basis for some restoration design methods (Rosgen 1998).

The regional curves for the Bluegrass were developed from sites with watersheds between 0.25 and 154 mi^2 where the channel was stable and had unambiguous bankfull indicators. The relationship between bankfull parameters and drainage area in the Bluegrass region is well described by the curves, which explain over 93 percent of the variation within the datasets for bankfull area, width, depth, and discharge. Standard errors are less than 30% for the bankfull geometry and less than 35% for bankfull discharge. On average, the bankfull discharge was found to be approximately half that of the 1.5-year discharge, and no consistent frequency represented the return period of the bankfull flow. Therefore, use of the 1.5-year event for bankfull flow would represent a gross overestimate in all reaches examined in this project; estimates based on morphological features and/or the regional curves would be more accurate.

The curves developed in this project will be most applicable to streams having characteristics consistent with those criteria used to select the assessment reaches. These include

- Physiographic region. Because the total number of assessment sites was insufficient to test for the influence of the effect of Bluegrass sub-regions on the curves, separate relations were not developed by sub-region. These curves apply to those streams with significant portions of their watersheds inside the Bluegrass.
- Land use. Streams in watersheds that are less than 10 percent urbanized are represented.

- Flow regulation. Streams that are not subject to flow regulation are represented.
- Drainage area. The curves apply only to streams draining between 0.25 and 154 mi^2.
- Karst susceptibility. Streams in watersheds with no evidence of subsurface conduits that cross topographic divides are represented. In karst landscapes, channels will convey less flow than non-karst stream reaches and may have a smaller cross section than those suggested by the regional curves.

Streams affected by downstream confluences of large streams or locally high or large-caliber sediment supplies are not represented in the dataset used to develop these curves. Therefore, bankfull characteristics of channels formed under these conditions may be substantially different.

Because regional curves provide regional estimates of bankfull parameters that broadly describe stream conditions, they do not predict channel parameters for specific conditions that would form channels at specific sites. The cross-sectional dimensions of a channel are the product of many complex geomorphic processes, including the transport of sediment and channel evolution after repeated 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. Local watershed and channel conditions may cause channel bankfull flows and bankfull dimensions to differ significantly from those estimated from the equations produced by this project. Therefore, these equations should not be the only data used to evaluate or estimate bankfull characteristics in assessment or design of Bluegrass channels. Rather, they should only be used in conjunction with field-based geomorphic assessment of the stream and its watershed. The results of field examination of bankfull conditions on the stream of interest should be compared to the Bluegrass regional curves. Channel dimensions that are more than one standard deviation greater or less than those dimensions estimated from the curves should be examined carefully to determine the cause of the variation. Likewise, designs that call for channel dimensions outside that range should provide sufficient data to justify the deviation from the curves.

Highly altered watershed conditions and direct manipulation of streams have changed watershed hydrology, sediment regimes, channel gradients, and base levels; ongoing maintenance continues to affect channel response and evolution. These altered reaches, from which the Bluegrass regional curves were developed, represent the geometry of evolving contemporary channels; if the channels were to completely recover from disturbance, their floodplains, planform patterns, and profiles would change, and their channel cross section characteristics would likely differ from those described by these regional curves. Therefore, if a restoration project intends to create bankfull characteristics similar to those that could be expected in a completely recovered channel, the design may require smaller dimensions than those that would be estimated from these curves.

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Appendices

Bluegrass Lithostratigraphy

C

Table C.1 Assessment Site Surface Geology

	Stream Site	USGS Gauge	Drainage Area (mi^2)	Local Stratigraphic Units* at Stream Site	Local Stratigraphic Units* of Upstream Drainage
1	Beech Fork *nr Springfield*	3300000	85.9	Okc	Okc
2	Beech Fork *at Litsey*	—	100.7	Oaf	Oaf–Okc
3	Bullskin Creek *nr Simpsonville*	3295702	54.8	Oaf	Oaf–Ob
4	Cave Creek *nr Fort Spring*	3288500	1.93	Ol	Ol
5	Eagle Creek *at Sadieville*	3291000	42.9	Ol	Ol–Oc
6	Floyds Fork *at Fisherville*	3298000	138	Oaf	Oaf–Od–Ob
7	Harrison Fork *nr Samuels*	—	3.19	Slw	Slw–Slb–MDnb
8	Harrison Fork *nr Samuels*	—	3.55	Slw	Slw–Slb–MDnb
9	Hinkston Creek *nr Carlisle*	3252300	154	Ol	Ol–Oc–Oaf
10	Hough Run *at Mt. Washington*	—	1.11	Oaf	Oaf–Od
11	Indian Creek *nr Owingsville*	3250150	2.43	Scb	Scb
12	Long Lick *at Clermont*	3298550	7.91	Ob	Ob–Slw–MDnb–MDbb
13	North Elkhorn Creek *at Man O War Blvd*	3287580	2.2	Ol	Ol
14	North Elkhorn Creek *at Winchester Rd*	3287590	4.05	Ol	Ol
15	North Elkhorn Creek *nr Georgetown*	3288000	111	Ol	Ol
16	Salt River *nr Harrodsburg*	3295000	39.7	Ol	Ol–Okc–Oaf–MDnb–MDbb–Msh
17	South Elkhorn Creek *at Fort Spring*	3289000	21.2	Ol	Ol
18	Unnamed Trib A of Dix River *nr Crab Orchard*	—	0.25	Scb (flows through Dix alluvium)	Scb–Mdnb–MDbb
19	Unnamed Trib B of Dix River *nr Crab Orchard*	—	0.51	Scb (flows through Dix alluvium)	Scb–Mdnb–MDbb
20	Whittaker Run *at Smithville*	—	4.45	Oaf	Oaf–Od–Slb

* Stratigraphic units are listed from downstream to upstream beginning at the site.

Table C.2 Surface Lithostratigraphy of the Bluegrass Physiographic Region

Symbol	Stratigraphic Units	Major Lithologies	Karstic Properties	Stratigraphic Age	Stratigraphic Age Notes	Physiographic Sub-Region*
W	Surface water	—	—	Quaternary	—	—
Qa	Alluvium	Alluvium	Non-karstic	Quaternary		Outer BG and Knobs
Qg	Glacial deposits	Outwash, till, lacustrine deposits, drift	Non-karstic	Quaternary		Outer BG (P); Knobs (S)
Pbl	Breathitt (Pikeville) Formation	Sandstone, siltstone, shale	Non-karstic	Pennsylvanian	Middle	Outer BG
Plc	Lee Formation	Sandstone	Non-karstic	Pennsylvanian	Basal	Outer BG
Mpn	Paragon Formation (Pennington and Newman Formations)	Shale, sandstone, limestone	Intense	Mississippian	Upper	Knobs
Mgl	Ste. Genevieve and St. Louis Limestones	Limestone, sandstone, shale, chert	Intense	Mississippian	Upper	Knobs
Mn	Newman (aka Slade) Formation	Carbonate unit	Intense	Mississippian	Upper	Knobs (P); Outer BG (MO)
Msh	Salem, Warsaw, and Harrodsburg Limestones	Limestone, siltstone, shale	Prone	Mississippian	Upper	Knobs
Mf	Borden and Fort Payne Formations	Dolomite, limestone, siltstone, shale, chert, basal glauconite	Non-karstic	Mississippian	Lower	Outer BG and Knobs
MDbb	Borden Formation; Sunbury, New Providence and Bedford Shales; Berea Sandstone	Shale, sandstone, siltstone	Non-karstic	Devonian-Mississippian	Upper D. to Lower M.	Knobs (P); Outer BG (MO)
MDnb	New Albany, Chattanooga, and Ohio Shales, Boyle Dolomite, Sellersburg Limestone	Shale, limestone, phosphatic nodules	Non-karstic	Devonian-Mississippian	Middle D. to Lower M.	Outer BG and Knobs
Dsj	Sellersburg and Jeffersonville Limestones	Limestone, dolomite, chert, glauconite	Intense	Devonian	Lower to Upper	Outer BG
Sb	Bisher Dolomite	Dolomite	Prone	Silurian	Middle	Outer BG
Slw	Louisville Limestone, Waldron Shale	Limestone, dolomite, shale	Intense	Silurian	Middle	Outer BG (P); Knobs (MO)
Scb	Crab Orchard Formation, Brassfield Dolomite	Clay shale, dolomite, chert	Prone	Silurian	Lower to Middle	Outer BG and Knobs
Slb	Laurel Dolomite, Osgood Formation, Brassfield Dolomite	Dolomite, limestone, clay shale, glauconite, chert	Prone	Silurian	Lower to Middle	Outer BG (P); Knobs (MO)
Od	Drakes Formation	Dolomite, limestone, mudstone, shale	Non-karstic	Ordovician	Upper	Outer BG (P); Knobs (S)
Ob	Bull Fork Formation	Limestone and Shale	Non-karstic	Ordovician	Upper	Outer BG (P); Knobs (MO)
Odb	Drakes and Bull Fork Formations	Limestone, dolomite, shale, mudstone	Non-karstic	Ordovician	Upper	Outer BG (P); Knobs (MO)
Odc	Drakes Formation, Grant Lake and Calloway Creek Limestones	Dolomite, limestone, mudstone, shale	Prone	Ordovician	Upper	Outer BG (P); Knobs (S)
Oaf	Ashlock Formation, Grant Lake and Calloway Creek Limestones, and Fairview Formation	Limestone, shale, mudstone, siltstone	Prone	Ordovician	Upper	Outer BG (P); Knobs (MO)
Ok	Kope Formation	Shale, limestone, siltstone	Non-karstic	Ordovician	Upper	Outer BG
Okc	Garrard Siltstone, Kope and Clays Ferry Formations	Limestone, shale, siltstone	Non-karstic	Ordovician	Middle to Upper	ESB
Oc	Garrard Siltstone and Clays Ferry Formation	Limestone, shale, siltstone	Non-karstic	Ordovician	Middle to Upper	ESB
Ol	Lexington Limestone	Limestone, calcisiltite, shale, chert	Intense	Ordovician	Upper of Middle	Inner BG (P); Outer BG (S)
Ohb	High Bridge Group	Limestone, dolomite	Intense	Ordovician	Lower of Middle	Inner BG (P); Outer BG (MO)

* Parenthetical notations indicate whether the unit is a primary (P) or secondary (S) consituent or is represented only by minor outcrops (MO) within the sub-region. BG = Bluegrass; ESB = Eden Shale Belt.
Sources: Carey and Stickney 2001; Field 2002; Florea et al. 2002; McDowell 2001; Noger 1988; Phillips and Walls 2004.

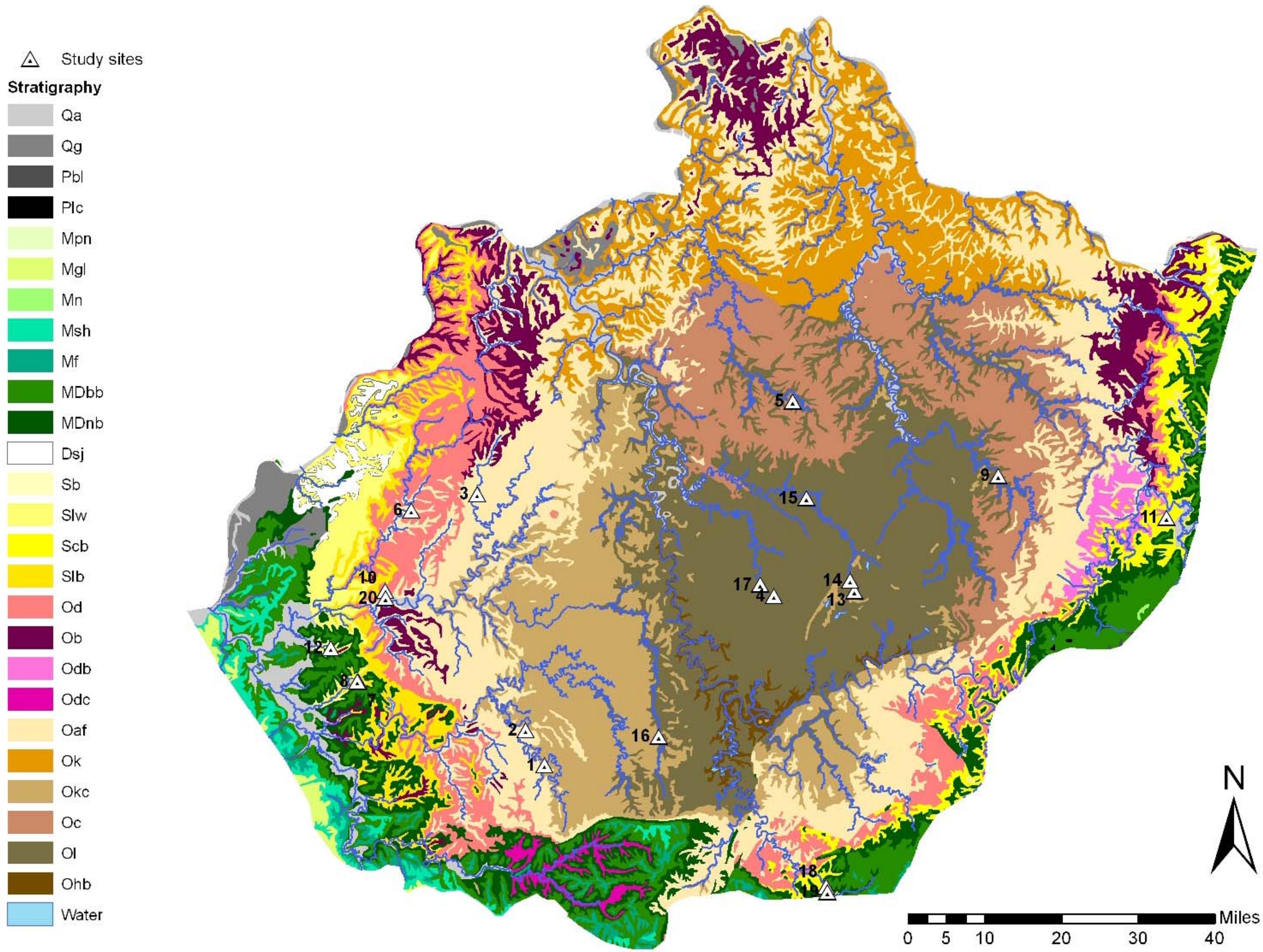

Figure C.1 Detailed geologic map of the Bluegrass region (KGS 2002; KYDGI 2005; Noger 2002).

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History of Bluegrass Land Use | D

EARLY OCCUPATION

Human occupation of the Bluegrass region dates back more than 10,000 years. The earliest inhabitants were gatherer-hunters whose subsistence activities made little impact on the environment. As early as 2000 BCE, however, Native Americans in the eastern US began to domesticate plants. In the Woodland periods (c.1000 BCE–1000 CE), people in the area began to build earthworks and cultivated some crops. While they relied heavily on gathering and hunting (Railey 1996), their horticultural activities nevertheless may have affected runoff and erosion rates. Pollen and sediment records from a southwestern Ohio earthwork settlement indicate that the area surrounding the site was deforested and experienced high levels of erosion 2000 years ago (McLauchlan 2003).

As the region's Native Americans became more sedentary, their effects on the land became more significant. Practices of land clearing, plant cultivation, and setting of forest fires are thought to have affected vegetative composition of previously forested areas throughout the Southeast (DeVivo 1991). For more than 700 years before Europeans began to settle Kentucky, Fort Ancient groups in the Bluegrass built villages and practiced swidden horticulture, using fire to clear forested land in floodplains, where they cultivated primarily maize, beans, and squash. Fire was also used extensively for hunting, for warfare, and for improving pasturage for game (Pyne 1982; Williams 1989). Many Fort Ancient villages were occupied by between 100 and 300 inhabitants year-round and were periodically relocated every 10 to 30 years, depending on the extent to which nearby soils, game, and timber were depleted (Sharp 1996). Soil records indicate that erosion rates again increased during this time of intensified disturbance (Delcourt 1987). Significant declines in the population of freshwater mussels in Kentucky and neighboring states have been found to have coincided with this period, suggesting that stream sedimentation may have increased due to land-use activities (Peacock et al. 2005).

EUROAMERICAN SETTLEMENT

Native peoples continued to thrive in the area until their populations were decimated by diseases introduced by European colonists in the East. The rapid, dramatic decline in population reduced the area under cultivation, and abandoned fields were colonized by opportunistic successional vegetation (Delcourt et al. 1993). Thus, when Euroamerican settlers moved into Kentucky in the 1770s, the richly vegetated land they claimed in the Bluegrass region was not the pristine wilderness they assumed it to be. In fact, Inner Bluegrass vegetation patterns at the time of Euroamerican settlement were so peculiar that Braun (1950) described the area as more anomalous than any other vegetative region in the eastern US. While the forests of the Outer Bluegrass were probably quite dense, as much as half of the Inner Bluegrass was savannah-woodland, cane, and meadows of grass and clover (Figure D.1) (Braun 1950; Campbell 1980).

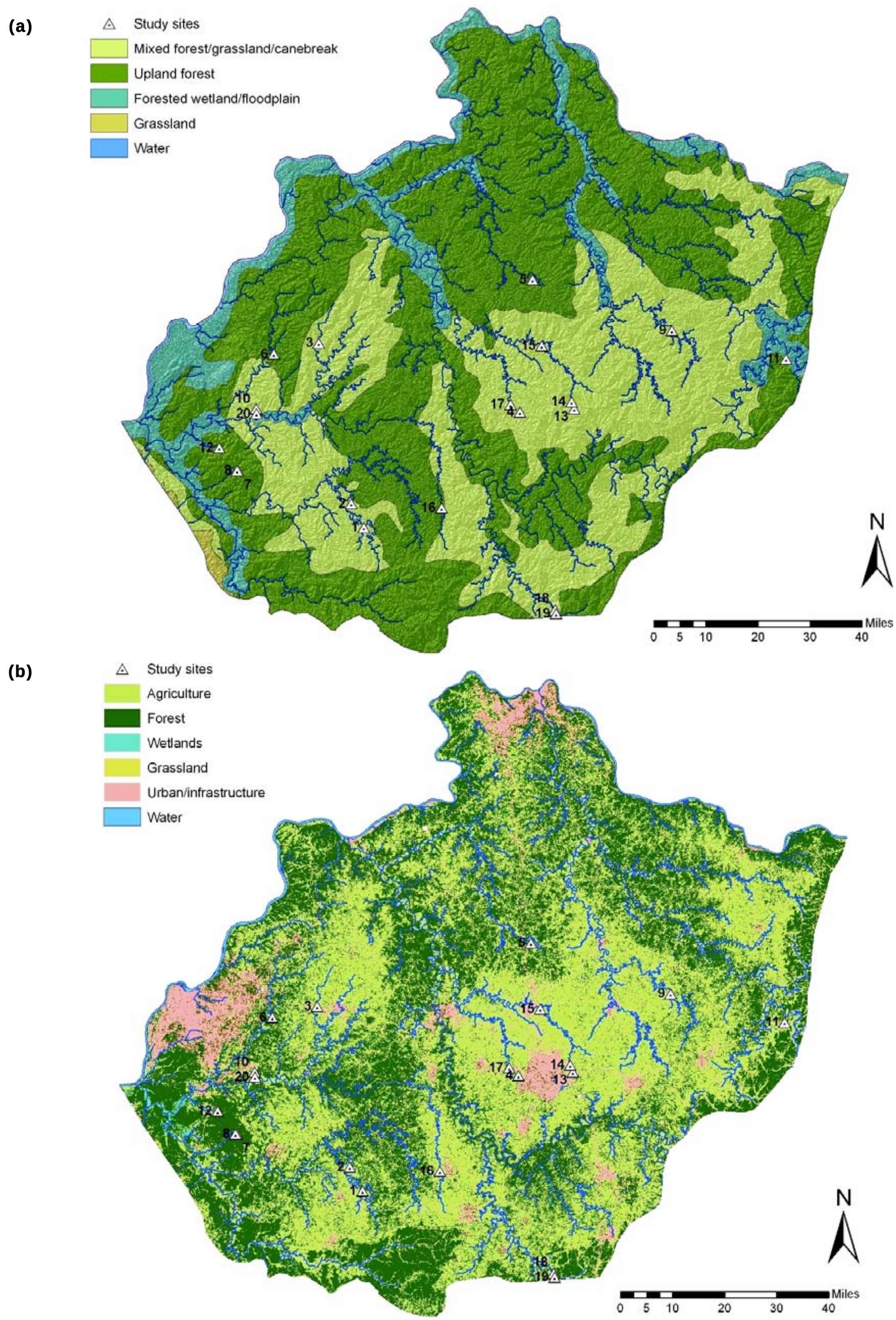

Figure D.1 Generalized land-cover map of the Bluegrass region (a) prior to Euroamerican settlement (KGS 2002; KYDGI 2003; KYDGI 2005b; Mitchell 2004) and (b) in 2001 (KGS 2002; KYDGI 2005b; USGS 2004).

Pioneer and surveyor journals described the Inner Bluegrass landscape as extremely fertile, with astounding numbers of game animals and "amazing" growth of grasses, legumes, and trees. The immense herds of bison, thought now to have arrived in the eastern woodlands as recently as the 1600s, were particularly spectacular to early explorers and settlers (Jakle 1969). By 1784, however, Filson (1784:27) noted that the once prolific buffalo—a hunter had told him of seeing a herd of a thousand at Blue Lick—could be found in "great number [only] in the exterior parts of the settlement" as "the first settlers had wantonly sported away their lives." Filson was nevertheless able to witness for himself "amazon herds of Buffaloes" and roads they made "from all quarters, as if leading to some populous city; the vast space of land around these [salt] springs desolated as if by a ravaging enemy, and hills reduced to plains" (1784:32). The great herds had traversed the same areas repeatedly, wearing broad paths along ridges and stream channels, over shallow fords, and through mountain gaps. Travelers' accounts noted great swaths cut through the wilderness, trampled and eroded several feet into the earth (Jakle 1969), and areas were cleared of vegetation for as much as 20 hectares around salt licks (Campbell 1980).

These travel arteries, which had also been used by Native Americans as trade and war paths, were most heavily concentrated in the Bluegrass region, and they eventually determined routes of pioneer immigration and settlement. The east-west-oriented Kentucky traces were favored by the earliest settlers, even though they were smaller than those running north-south. Prior to 1783, settlers predominantly entered Kentucky from the east, rather than from the north or south. The earliest pioneer stations and settlements, especially those between Maysville and Frankfort, developed along these east-west traces, which also served as transportation and supply roads and routes of escape from Native American war parties (Jakle 1969).

Pioneers erected stations and forts, beginning with Harrodsburg and Boonesborough in 1775 (Clark 1992), in defensible locations near permanent sources of fresh water that would be accessible during raids by Native Americans. Stockaded communities afforded them some measure of protection against attacks while they worked to establish land claims and grow subsistence crops, and an estimated 200 acres of Indian corn were planted in the region by 1775 (Rohrbough 1978:24). Persistent raids, however, sometimes prevented settlers from cultivating crops and forced them to subsist on a largely meat-based diet (Gray 1933:867).

Despite harsh and uncertain conditions, the Bluegrass population continued to grow. In 1776, Virginia incorporated Kentucky County as far west as the Tennessee River (Clark 1992). Following the end of the Revolutionary War, Native American attacks became more sporadic and settlement surged, reaching at least 20,000 by 1785. Little clearing of land for agriculture had taken place at that time, though, and the woods were still an important source of subsistence. Bear, buffalo, deer, and other game were easily obtained until they were depleted or exterminated in the 1780s, and their pelts were an important currency in the early barter economy of the area (Gray 1933:863-8). By the first Census in 1790, the population had increased to 73,677, including 12,430 slaves, and was still almost entirely restricted to the Bluegrass (US Census 1791; Davis 1927:6). The areas bordering the Ohio River northeast of Louisville and those regions outside the Bluegrass saw few settlements until after 1795, when Native Americans agreed to a truce (Gray 1933:863). By 1800, the population tripled to 220,955 and included settlers in all regions of the state, excluding the Chickasaw territory west of the Tennessee River and the Cherokee reservation south of the Cumberland and Tennessee Rivers; the Bluegrass population had reached 177,782 (Clark 1992:156; US Census 1801). By 1810 it had reached 268,631 and accounted for two-thirds of the population of the entire state.

AGRICULTURE AND INDUSTRY

The period from about 1790 to 1820 brought significant changes to the Bluegrass landscape, as settlers commenced clearing large acreages for cultivation and pasture and developed mining and manufacturing industries. Early Bluegrass agriculture was broadly based on corn, wheat, and rye for both subsistence and surplus trade; hemp and, to a lesser extent, tobacco were also grown as cash crops (Mitchell 1978). Though agricultural development was initially limited, farms were producing surpluses as early as 1787, when James Wilkinson floated a cargo of tobacco, ham, and other agricultural commodities down the Ohio and Mississippi rivers to New Orleans (Gray 1933:868-9). According to François Michaux (1805), Kentucky was supplying more than two-thirds of New Orleans' commercial goods at the beginning of the nineteenth century. This expanding trade in agricultural and manufactured goods stimulated the rapid growth of commercial centers, which developed at the junctions of the rivers and tributaries and crude overland paths that served as transportation routes.

The navigable Kentucky River connected Bluegrass farmers with an extensive external trade network through the New Orleans seaport (Clark 1992:175), and market demands largely influenced the selection of crops that would be produced by Bluegrass farms. East coast planters who relocated to other parts of the Bluegrass region with their slaves and tried to raise tobacco found that its value after the costs of transporting it to market was not enough to profit from the use of land and slaves. They resorted instead to raising a combination of livestock, grains, and hemp (Hopkins 1951:27).

Pioneers had driven horses, cattle, hogs, and sheep over the Wilderness Road and on rafts down the Ohio River into the Bluegrass, where they were turned loose in the forests and cane lands. Despite harsh climate conditions, livestock thrived in the Bluegrass, and Kentucky earned an early reputation as a source of quality hogs, cattle, sheep, horses, and mules (Clark 1977). Following the Panic of 1819, wealthier landowners sought to increase their livestock production. Farm sizes increased through land consolidation during the first half of the nineteenth century as stockmen bought land from smaller farmers in the 1820s and 1830s (Gray 1933:876). By the 1830s, the livestock trade had become so lucrative that it had completely displaced other agricultural products in some Bluegrass counties.

Year-round grazing by free-roaming livestock contributed to a rapid decline in cane and other forest vegetation. Continuous browsing defoliated cane stalks, and swine rooted out and ate the rhizomes required for its reproduction. By 1810, Kentucky's only remaining canebrakes were in unsettled areas (Michaux FA 1805; Cuming 1810). In his 1828 and 1829 catalogs of Inner Bluegrass vegetation, Short (1828c:562; 1829:448) noted the loss of flowering plants such as the showy orchis and "immense orchards of large trees" due to "cultivation and the ravages of cattle". At the turn of the nineteenth century, red (slippery) elm far outnumbered white elm (Michaux FA 1805), but by 1828, cattle had almost entirely eradicated slippery elm from the area around Lexington, with the exception of some cliff sections along the Elkhorn and Kentucky rivers. Short also associated agriculture or livestock grazing with declines in several smaller tree species, including the hazel bush, spicewood, crab-apple, pawpaw, mulberry (whose bark was a "favourite" of horses and sheep), and Indian arrow-wood (Short 1828a:251; 1828b:419; 1828c:561,562,569; 1829:446). As natural pasturage was expended, farmers cleared more forest for the cultivation of browse and feed.

Most Bluegrass farmers also cultivated some amount of hemp prior to the Civil War. For many years, the Bluegrass grew more hemp than the rest of the country combined, and in 1830 hemp exports were exceeded only by exports of livestock (Hopkins 1951:14,27-34,131). Hemp production generally preserved the soil's fertility to a far greater extent than tobacco, corn, or other crops. Hemp seed was not sown in rows, but rather was scattered in a cross-plowed field, the stalks growing closely enough together to shade out any weeds that might compete with the crop. In the fall, the cut stalks were either steeped in streams or ponds to rot the gum between the bark and fiber, or they were spread across the fields for dew rotting, which returned soluble minerals and humus to the soil in which they had grown (Hopkins 1951:53-8). Dew-rotted hemp usually depleted the soil to such a limited extent that growers re-planted the same fields every year for more than a decade without adding fertilizers or cover crops, only clearing new fields when the yield became unprofitable. Nevertheless, continuous cropping had noticeably leached humus and nutrients from Bluegrass soils by the mid-1800s (Hopkins 1951:20-24).

Though most Bluegrass farms produced some combination of grains, hemp, and livestock (Mitchell 1978), disparities in the amounts of land and labor to which farmers had access resulted in sometimes radical differences in their land use and consequent effects on the landscape. Yeoman farmers, with little cash, relatively small acreages, and few or no slaves, relied on shifting ("slash-and-burn") cultivation, which maximized the short-term return they would get for their time and toil (Otto & Anderson 1982; Williams 1989:60-63). Slash-and-burn methods cleared fields ten times faster than clear-cutting and were the most expedient way to bring forested areas under cultivation. Some large trees were chopped down for use as building logs, fences, or fuel; most were girdled and left to deaden in the new fields. Small trees and underbrush were cut and grubbed out by hand and then burned, releasing crucial nutrients into the soil and killing insect pests (Williams 1989:60-63). By planting crops in these "deadenings," farmers were able to avoid the much more intensive labor and time required to fell the trees and uproot the stumps.

Despite the advantages slash-and-burn methods afforded farmers, the practice was profligate in its use of the land and its resources. Shifting cultivation required that a large proportion of land be left fallow, so less than one-third could be cultivated at any given time. Moreover, new patches had to be created annually; without the addition of fertilizers, the crops quickly leached nutrients, and the deadenings were only productive for a few years. The root networks and stumps in the deadenings required that farmers use hoes or, in larger fields, light, maneuverable plows. This precluded the use of deep plowing, which could have extended the life of the soil by bringing low soil layers and their nutrients up to the crop zone and creating large furrows that would have slowed erosion. Side roots rotted away within two years, and the stumps rotted in less than seven; when the fields were abandoned, the soils eroded badly before they were reclaimed by shrubs and trees (Otto & Anderson 1982:137,142; Trimble 1974; Williams 1989).

Slash-and-burn methods were not uncommon among the small planter class, too, before the Civil War (Swem 1916:71), but some small planters in the Inner Bluegrass were able to afford to farm intensively. They practiced crop rotation, regularly replacing crops with pasture grasses to draw nutrients back into the soil (Schwaab 1973:299). They not only removed unsightly stumps from their fields but also built spacious homes with gardens and woodland parks that required regular weeding and maintenance (Hopkins 1951:19). According to an 1834 visitor, "not a spot" on the Inner Bluegrass plantations he saw remained in wilderness (Schwaab 1973:267).

Forest clearing and other landscape changes also occurred with the rapid development of industries based on natural resources. In the late 1700s, Bluegrass entrepreneurs began drilling for salt, mining and processing iron ore, mining clay, quarrying limestone, and cutting timber for internal markets and for export (Clark 1992). The Bluegrass was not as rich in minerals as other parts of the state, but sizeable quantities of salt, iron, and clay were identified and exploited.

Most of the larger salt springs in the Bluegrass were brought into production by 1790, and six Bluegrass sites became significant salt producers: Lower Blue, Bullitt's, Mann's, Big Bone, Drennon's, and May's licks. Salt furnaces commonly consisted of slate trenches topped with up to 60 cast iron kettles containing about 20 gallons of brine apiece. Some salt wells offered brine so weak that, depending on the manufacturing methods, the extraction of a single bushel of salt required the evaporation of 1000 gallons of water over the furnace, while better wells and production methods required only 300 gallons or less per bushel. Wood to fire the furnaces was cut from surrounding forests. Once the forests near the furnaces had been cleared for fuel, the furnaces were moved closer to remaining tree stands and the brine was piped to the furnace, sometimes for miles, through bored gum or sassafras logs buried below the frost line (Jakle 1969). Within a few decades, however, salt production rapidly declined throughout the state as timber fuel was depleted and other mines in Pennsylvania and Virginia entered the market (Editor 1832). In 1840, Kentucky produced only 219,695 bushels (US Census 1814, 1841).

Salt making also supported the development of Kentucky's iron ore industry, which supplied the 40-inch cast iron pots used in the salt furnaces. In 1791, the site for the first iron works to be built west of the Appalachian mountains, Bath County's Bourbon Furnace (or Slate Furnace) on Slate Creek, was selected both for its proximity to a ready market of salt manufacturers and for its abundance of necessary resources (Jakle 1969). Operations of early furnaces had four basic necessities in addition to proximity to ready markets: accessible iron ore deposits, limestone for processing the ore, a stream for supplying water power to the bellows, and vast acres of forest for making charcoal (Coleman 1957:228-9). Enormous quantities of trees were cut down and burned in an extremely inefficient process of rendering the ore into metal. About three tons of ore were required to produce just one ton of pig iron, and the typical furnace produced between three and ten tons per day (Coleman 1957; Richards 1961:93).

Demand for iron continued to grow throughout the 1820s; while some furnaces went out of blast, others continued to be built, though most of these were in eastern Kentucky. By the late 1830s, most of the state's furnaces and forges were in Greenup County (Coleman 236), but three of Kentucky's six cast-iron-producing counties—Bath, Kenton, and Nelson—were in the Bluegrass (US Census 1841). Kentucky ranked a close third at the time in the country's iron-producing states and furnace construction continued. Deposits were mined in Bourbon County on Slate Creek between Owingsville and Olympia at Howard Hill Bank and Black Horse Bank, about two miles from the Bourbon Furnace, and on Caney, Clear, and Brush creeks. Blasting furnaces were located on Caney, Clear, Beaver, and Slate Creeks, and Maria Forge (Richards 1961:89) operated on the waters of Slate and Mill creeks. Caney Furnace on Caney Fork of Licking River in Bath County was constructed in 1838, the same year as Bourbon Furnace was retired. The 1840s and 1850s saw construction in the Bluegrass of the Nelson Furnace on Rolling Fork in Nelson County and Belmont Furnace on the Salt River in the Knobs of Bullitt County in 1844. This period also marked the peak of Kentucky's iron industry. By the beginning of the Civil War, it was in decline (Coleman 1957:239). Like the salt industry, the iron industry faced dwindling fuel resources (coal was not commonly used as fuel until the 1860s and was still expensive in the 1870s) and competition from more efficient operations in other states. Though the expanding railroad system temporarily boosted demand, production continued to decline through the end of the century, by which time almost all of the commonwealth's furnaces had "blown out" (Coleman 1957:241).

A third industry that made early use of timber fuel was brick making. Soft bricks were formed from clay, dried in the sun or under shelters, and then stacked and fired for a period of several days in kilns usually fueled by wood. With the exception of minerals from Kentucky's saline springs, clay has been extracted and used longer than any other mineral in the state. Large-scale clay mining has taken place primarily in the Mississippi Embayment and Eastern Kentucky Coal Field regions, but deposits throughout the state, including the Bluegrass, have been exploited for local use since the eighteenth century (Ries 1922; Jillson 1926). In 1786 or 1787, clay mined from land on Cedar Creek near Crab Orchard, Lincoln County, was used to build Kentucky's first brick house (Jillson 1926:5). At Sugar Tree Grove, about five miles east of Lexington, the remains of an old pit from which clay was mined for construction of an early house are still identifiable (Lancaster 1991:63).

The buildings constructed from these bricks often had stone foundations as well as stoops, steps, windowsills, and other components (Lancaster 1991:65). Carbonate rock, especially limestone and dolomite, and some sandstone was quarried from hills, the sides of valleys, and streambanks in the Inner and Outer Bluegrass. Little use was made of Eden Shale beds, which were thin and friable. Crystallized limestone ("Kentucky marble"), however, was used extensively for building structures and monuments, especially in Frankfort. Kentucky marble was also used for curbing, bridges, culverts, abutments, paving, railroad ballast, road work, and locks and dams. Limestones were used not only for building and road construction but also for making white and tinted limes, for producing beet sugar, for making glass and Portland cement, and for fertilizing fields. Limestones were also commonly used as a flux to capture impurities in the processing of iron ores (Richardson 1923).

By the early nineteenth century, stone was being quarried in Bourbon, Clark, Fayette, Harrison, and Mason counties. In 1840, the Bluegrass counties of Fayette, Fleming, Franklin, Garrard, Jessamine, and Kenton accounted for 6 of the 16 stone-producing counties and nearly half of the value of the stone produced in the state. Stoner Creek, Houston Creek, the Kentucky River, Boone Creek, and Elkhorn Creek all offered convenient locations for quarries because the rivers offered the easiest and least expensive method for transporting the cut stone. Fayette County was especially well-suited for quarrying because the stone was widely distributed; early distribution was facilitated by the Kentucky River and, later, by the railroad system hub at Lexington. An inventory of both active and inactive Kentucky quarries in 1923 identified a total of 610 sites, more than half of which were in Bluegrass counties. The number of quarries in the state did not peak until 1916, when 119 were active (Richardson 1923:328).

Clear-cutting for manufacturing, mineral processing, and agriculture, and overgrazing of forest vegetation by free-roaming livestock took a heavy toll on the Commonwealth's forests. Although the Bluegrass was almost entirely forested in the 1770s, so much of the Inner Bluegrass forest had been cleared by 1822 that the need to conserve timber resources was being discussed in public forums (Gray 1933:868). In 1825, a visitor to the region speculated that Kentuckians would soon "be obliged to rely on stone coal for fuel, and on raising timber for other purposes" (Swem 1916:70-71). By 1850, more than 80 percent of the region was in farms, and 59 percent (approximately 3.3 million acres) of that land was classified by census takers as "improved." Improved lands included land under cultivation; cleared or tilled land, whether fallow or in pasture; orchards; nurseries; vineyards; gardens; and land on which buildings had been constructed. In the next 10 years, improved land in farms totaled almost 4 million acres, or 68 percent of farm land (US Census 1853, 1864; n.b., these figures were collected by county and therefore are only a close approximation of the Bluegrass region).

The continued use of fire for clearing lands for agriculture caused the loss of thousands of additional acres. In 1880 alone, 10 documented wildfires burned more than 556,000 acres of woodlands in the state. Nearly half of those fires had started as part of land clearing efforts (Sargent 1884:491). Hogs, too, were still being cited in the 1880s as a potential factor in the loss of white oaks in Kentucky (Sargent 1884). The number of improved acres decreased in many Bluegrass counties in the 1880s, but land clearing continued throughout the remainder of the century. By 1900, the amount of improved land in farms peaked at more than 80 percent (about 5 million acres).

Extensive land degradation was noted by William Linney in his surveys of selected western, southern, and eastern Bluegrass counties from 1882-1887. Just two decades later, an inventory of Kentucky's remaining forestry resources revealed that only 39 percent of the state remained in forest. The survey, begun in 1907, blamed practices dating back more than 100 years for the needless destruction of former stands and the debilitated fertility of the remaining forests (Hall 1909). Less than 14 percent of the Bluegrass region was forested by the early 20th century; most of the region's counties had been almost completely denuded, with less than 6 percent of their land still in forest (Barton 1919).

Soils in much of the Bluegrass were likewise depleted by the early 1900s. Regional studies by the Kentucky Geological Survey in the 1920s found that many farmers were trying to cope with exhausted land. Farming efficiency had peaked near the turn of the century, and in regions of limited fertility, such as the Bluegrass Hills, even marginal lands had been brought into production in spite of their meager yields. The thin soils of the Bluegrass Hills, however, were more prone to severe erosion than much of the rest of the Bluegrass, and cultivated slopes washed badly. By the 1920s, many of those lands had already been abandoned and had been colonized by secondary growth of persimmon, sassafras, and other shrubs (Davis 1927:24,48). A decade later, nutrient-depletion and erosion of soils were significant problems in most of the state. By that time, the condition of soils in even the most fertile areas, such as the Inner Bluegrass, was so poor that drastic changes in land use and land management needed to be implemented (Clark 1992:460,470).

MODIFICATION OF DRAINAGE NETWORKS

The activities of Euroamericans affected not only the physical landscape but also the drainage networks of the Bluegrass almost immediately following the beginning of settlement in Kentucky. The removal of beavers, construction of milldams, channel modifications, and drainage enterprises all affected the hydrology and geomorphology of Bluegrass watersheds.

Removal of Beavers

One of the earliest changes Euroamericans introduced to Bluegrass channels, as elsewhere (e.g., Wohl 2005), was the removal of beavers from the area. The number of beavers estimated to have been living in North America between the arctic tundra and the deserts south of the Rio Grande River at the time of European contact is between 60 and 400 million (Seton 1929). Prior to fur traders' extirpation of most beaver from Kentucky in the 1750s and 1760s (Cline 1974), beavers had flourished for so long that their activities are thought by some to have re-formed valley morphologies on a scale that rivals the effects of glaciation (Ives 1942; Ruedemann & Schoonmaker 1938; Rutten 1967).

By constructing dams, canals, and other structures, beavers effect extensive hydrogeomorphological alterations of drainage networks, both in riparian areas and in stream channels. In riparian zones around dammed areas, impounded water elevates the water table and increases the area of saturated, anaerobic soils. Ponds and their associated wetlands mitigate floods by absorbing and retaining high flows (Hillman 1998) and dissipating their energy. In stream channels, the effects of beaver dams vary depending on stream size. In the floodplains and backwaters of large rivers (orders 9 and greater), beavers cut wood and construct dams and canals. Middle-order streams (orders 5-8) are less favorable than small streams for dam-building because the dams are more likely to be washed away by floods. They do, however, receive increased inputs of debris from upstream beaver activities. This debris accumulates and leads to sediment and detritus storage, often forming small islands in the channels (Naiman et al. 1988). Dam construction activities have been estimated to have the potential to affect 20-40 percent of the total length of second- through fifth-order streams (Naiman et al. 1986). Small streams (orders 1-4) are most susceptible to the effects of beaver dams, which influence discharge, erosion, and sedimentation processes. The low dams reduce the variability of the discharge regime by lengthening the period during which water is retained in the upper elevations of the watershed. Even though surface evaporation rates increase, surface and groundwater storage also increases, causing water discharged to lower elevations to be more evenly distributed throughout the year. The increased stability of the flow not only reduces flooding but can also change flow regimes from intermittent to perennial (Pollock et al. 2003; Wilen et al. 1975).

The cumulative effects of beaver habitat modification undoubtedly created drainage networks that were substantially different from those without beavers, but the geomorphic consequences of their rapid removal following European contact remain relatively unknown. In low-gradient streams, unoccupied dams that remain intact continue to trap sediment until the pond eventually fills, creating gently-sloped, alluvial plain beaver meadows (Ruedemann & Schoonmaker 1938). In higher-gradient streams, where high-energy flows are likely to cause dams to fail, pond deposits are flushed downstream. The sequence identified as typically following beaver elimination is (1) dam breach; (2) pond dewatering; (3) channel incision; and (4) rapid lowering of the water table (Neff 1957; Parker et al. 1985). The incision of streams into the impounded sediment and their subsequent erosional down-cutting have been attributed to the removal of beaver (Parker et al. 1985). Lower groundwater levels and a change in flow regime from perennial to ephemeral have likewise been associated with beaver removal (Pollock et al. 2003). Their removal from the Bluegrass could very well have contributed to conditions that led French traveler Victor Collot (1826:99) to describe North Licking Creek in 1796 as "never fordable in any season; the banks are steep, the bottom muddy, and the land on each side marshy."

Mills, Water-Power, and Industry

When surveyors and pioneers crossed the Appalachians in the eighteenth century, their journals and reports noted not only the vegetation and landscape qualities that marked fertile soils but also the many opportunities that Kentucky's "amazingly crooked" streams and "fine mill seats" afforded for powering the mills that were an integral part of rural communities of the period (Filson 1784; Hunter 1979). Virtually every farm required the services of a gristmill to grind the corn that was a staple of pioneers' diets. The alternative, grinding corn and other grains by hand at home, produced an extremely coarse meal, and the process was so inefficient that traveling 20 or even 40 miles to a gristmill—a trip that could require traveling for several days on muddy roads and fording multiple streams, sometimes on foot with more than 100 pounds of grain—was preferable to laboring over a mortar and pestle every day. The lack of mills was considered to be one of the greatest hardships faced by pioneers, and the first priorities of new settlers after erecting their log cabins were the establishment of gristmills, sawmills, and roads (Gaines 1905:3; Hunter 1979:8-14).

From the time of first settlement in the Bluegrass, Virginia laws prohibited the erection of structures that would obstruct the passage of fish or boats on navigable Kentucky streams. Navigability was determined by the county courts, which authorized dam construction. When the courts determined that a stream was not navigable, they could choose to permit dams with no restrictions regarding passage (Robertson 1914:144-153; Verhoeff 1917:18-19). In 1792, after statehood, the Kentucky Legislature adopted Virginia's law regarding stream obstructions in "An act more effectually to prevent obstructions in watercourses," which mandated that navigable streams "be kept free and open for the passage of fish and the transportation of the growth and produce of this country." Violators who blocked fish or boat passage with fish dams, slopes, stops, weirs, hedges, or any other obstacle could be fined two dollars for every 24 hours of obstruction. Because gristmills were considered a public utility, however, their proprietors were permitted to construct dams as long as they incorporated locks and slopes; the petitioning miller could also be required to compensate neighbors whose lands would be flooded by the millpond (Kentucky 1792:38; Robertson 1914; Verhoeff 1917:18-19).

A mill usually consisted of several improvements to a site. In addition to the waterwheel constructed beside, beneath, or inside the mill building, the typical complex included a dam, a pond, a headrace, a sluice, and a tailrace. Most of these involved modifications to the stream channel that supplied the mill. A dam constructed at or upstream of the mill building location increased the depth of the streamflow and created a millpond to collect water overnight while the mill was inactive. By raising the water level, the dam increased the vertical distance over which the flow would travel or fall; a medium head/fall measured between 5 and 25 ft. Both the head and the flow volume determined the potential energy available to the waterwheel. The dam also influenced the quantity of flow entering the headrace. The headrace or millrace was a channel constructed to carry water to a gated sluice, which directed the water to the waterwheel. Water leaving the wheel was conveyed back to the stream by a tailrace channel (Hunter 1979:54-63).

The height of a milldam, and thus the size of the head or fall, could be restricted by the county courts or special legislative acts. In 1824, for example, the legislature declared the Dix River navigable and required that dams built on the Dix provide locks to facilitate passage of flatboats up to 60 ft in length; dams for waterworks on the Dix were restricted to a maximum height of 8 ft (Kentucky 1824). The height of the dam was, however, only one factor in establishing the head. In low-gradient streams, the head could be increased through a number of different measures. One option was to build the dam further upstream and lengthen the millrace; some races were as much as a mile long. This technique was also used to avoid millpond flooding of expensive nearby farmland. Another option was to excavate the headrace across an abandoned meander or across the terrain between a tributary and a larger stream near their confluence, or to cut off an existing meander (Hunter 1979:59). The latter technique was employed at George Macklin's flour mill near Frankfort, where excavation of a millrace of between 200 and 300 yds in length at a "horse-shoe" bend in the stream produced a fall of 21 ft (Leffel 1881:52).

Most rural mills were small and were usually operated by millers whose primary occupation was farming. These small operations were typically run as "custom" mills, whose proprietors took a share of the raw material or product (e.g., corn, meal, flour, lumber, shingles, or leather) as payment for processing (Hunter 1979:4). The quantity of the share was sometimes established by custom, but in Kentucky the toll was fixed by statute in 1797. The law required grist millers to "well and sufficiently grind their grain" and to take as a toll no more than one-eighth of grain intended for meal or one-sixteenth of grain intended for hominy or malt (Kentucky 1797:198).

Construction of small dams for water-powered mills promptly followed the introduction of agriculture to the Bluegrass. The first milldam to be authorized by a Kentucky county court was built on the Dix River in 1783 (Verhoeff 1917:18). By 1795, when most of the population was still restricted to the Bluegrass, a British visitor reported that the state already had a thousand mills (Winterbotham, as cited in Hunter 1979:3). If Winterbotham's estimates were generally accurate, then, as Clark (1977:15) asserted, nearly every Bluegrass tributary of the Kentucky River was indeed dammed for milling by the turn of the century.

Water was used to power not only gristmills but also, in some cases, sawmills, tanneries, fulling mills, carding mills, iron furnaces and forges, distillery mills, and mills producing paper, gunpowder, and linseed (flax) oil (Hunter 1979). By 1810, Bluegrass counties had over 1600 distilleries and a wide assortment of other industries (Table D.1). Gaines (1905:3) estimated, based on county records, that more than 80 gristmills and sawmills were established in Scott County between 1776 and 1820—approximately 1 mill for every 177 county inhabitants (US Census 1821).

Along with gristmills, sawmills were considered to be essential to new communities and quickly followed—or on occasion even preceded—the establishment of water-powered gristmills. Sawmills provided the materials for board floors, frame houses and barns, furniture, and other goods necessary for permanent settlement. Pairing grist- and sawmills allowed the miller, who was often also a farmer, to make more efficient use of his water resources and his time, especially when the areas served by the mill were still so sparsely populated that the gristmill was underutilized (Hunter 1979). Louisville's first sawmill, for example, was added to the underutilized Hikes gristmill shortly after its construction in 1800 on South Fork Beargrass Creek (Ford and Ford 1882:17). The density of sawmill sites was necessarily greater than gristmills, owing to the greater difficulty of transporting logs and lumber compared to grains, and sawmills usually quickly outnumbered gristmills (Hunter 1979).

Another operation commonly combined with gristmilling was distilling. Proprietors of water-powered gristmills, who accumulated a surplus of grain from the tolls charged for grinding, often added distilleries to their operations. Gristmills and distilleries were a logical combination because grain had to be ground in order to be distilled, and the fermentation process required a supply of fresh water. As an added benefit, the "slop" byproduct of the distilling process could

Table D.1 1810 Bluegrass Manufactures (US Census 1814)

Industry	Bluegrass* Total	State Total
Cotton Factories	14	15
Hemp Bagging Mills	13	13
Carding Machines	21	21
Fulling Mills	29	33
Iron Furnaces, Forges & Naileries	12	18
Tanneries	201	267
Flaxseed-Oil Mills	9	9
Distilleries	1639	2000
Paper Mills	4	6
Gunpowder Mills	47	63
Saltworks	27	36

* Boone, Bourbon, Bracken, Bullitt, Campbell, Clark, Fayette, Fleming, Franklin, Gallatin, Garrard, Harrison, Henry, Jefferson, Jessamine, Lewis, Lincoln, Madison, Mason, Mercer, Montgomery, Nelson, Nicholas, Pendleton, Scott, Shelby, Washington, and Woodford counties.

be used as feed for the farmer-miller's livestock. In some cases, a miller whose gristmill proved unprofitable could abandon the custom milling process altogether and turn a profit by operating solely as a distillery (Granger 1984:79; McKee & Bond, 1936: 151).

By 1840, the Bluegrass had more than 1300 mills (Table D.2). By 1880, the number of mills had already declined by more than 60 percent, though their number remained high in many areas, with mills located approximately every half-mile on some sections of streams (Figure D.2). This decline in the number of mills was due largely to the growth of cities and the consolidation of the milling industry as large "merchant mills," which produced flour and meal for sale in the market, became more common (Hunter 1979). Eventually, water-powered mills would also be replaced by steam-powered mills.

For several decades, steam was often employed only as an auxiliary power source (Hunter 1979:519-20). With the growth of manufacturing in cities and improvements in steam engine design and construction after 1850, steam power gradually became more economical than water power (Hunter 1979:516-17). Custom milling and other small-scale manufacturing for local markets declined in the late nineteenth century in large part due to the inability of small manufacturers to compete with urban mass production and improvements in transportation networks that allowed the large producers to reach large markets. In 1870, water power sources narrowly outnumbered steam engines by a ratio of about 5 to 4. In 1880, the state's flour, grist, and saw mills were powered by a combination of 612 water wheels and 1084 boilers; an estimated 250 water wheels were probably in operation in the Bluegrass at that time (Table D.3). By 1900, when electricity was becoming increasingly common, steam engines had become four times as common as waterwheels (Atack et al. 1980:282), though some water-powered mills continued to operate well into the twentieth century (Hunter 1979).

Channelization

Long before the Kentucky frontier opened, colonists in the East were implementing channelization practices inherited from Europe. These commonly included the excavation of open ditches in farm fields and the clearing of obstacles from streams (Beauchamp 1987:15). The primary objectives of many early channelization projects were to facilitate navigation for the transportation of goods to markets and to improve drainage for agriculture. In the Bluegrass, modification of drainage networks began almost immediately following the establishment of permanent settlements.

Transit and Navigability

One of the first priorities of frontier settlers was the establishment of transit routes, which prompted both the opening of roads and the improvement of navigable stream channels. Prior to the 1830s, precinct surveyors appointed by county courts oversaw the clearing and maintenance of roads as part of a militia-style system of road labor. State law required that all "male, laboring persons of the age of sixteen years or more, except such as are masters of two or more male laboring slaves … be appointed by the court to work on some public road" (Littell and Smith 1809:634-635). These laborers were ill-equipped and untrained, however, and frontier Bluegrass roads were generally neither surveyed nor constructed. Though some of these primitive wagon roads were graded and ditched with rudimentary engineering techniques, most were little more than buffalo trails or rutted paths cut through the brush by wagons or pack-animals (Michaux A 1805:38; Toulmin 1948:69). Roads received trained labor crews, stone surfacing, and culverts for drainage only after 1835, when the Board of Internal Improvement adopted a general policy for the improvement of both roads and streams (Morehead 1838:99-104; Verhoeff 1917).

Table D.2 Number of Bluegrass Mills and Population by County, 1840 and 1880 (US Census 1841, 1883a, 1883b)

		1840					1880				
County	**Year Estab-lished**	**Population**	**Flour and/or Grist Mills**	**Persons Per Mill**	**Saw Mills**	**Total Mills**	**Population**	**Flour and/or Grist Mills**	**Persons Per Mill**	**Saw Mills**	**Total Mills**
Anderson	1827	5,452	9	606	7	**16**	9,361	4	2340	0	**4**
Bath	1811	9,763	11	888	7	**18**	11,982	5	2396	0	**5**
Boone	1799	10,034	23	436	10	**33**	11,996	4	2999	7	**11**
Bourbon	1786	14,478	9	1609	7	**16**	15,956	8	1995	2	**10**
Boyle	1842	—	—	—	—	**—**	11,930	7	1704	4	**11**
Bracken	1797	7,053	11	641	7	**18**	13,509	7	1930	2	**9**
Bullitt	1797	6,334	25	253	9	**34**	8,521	2	4261	18	**20**
Campbell	1795	5,214	0	0	0	**0**	37,440	4	9360	5	**9**
Carroll	1838	3,966	3	1322	5	**8**	8,953	0	0	3	**3**
Clark	1793	10,802	38	284	21	**59**	12,115	14	865	0	**14**
Fayette	1780	22,194	26	854	11	**37**	29,023	3	9674	1	**4**
Fleming	1798	13,268	33	402	13	**46**	15,221	11	1384	10	**21**
Franklin	1795	9,420	15	628	5	**20**	18,699	6	3117	13	**19**
Gallatin	1799	4,003	10	400	4	**14**	4,832	n/a	n/a	n/a	**n/a**
Garrard	1797	10,480	41	256	11	**52**	11,704	3	3901	4	**7**
Grant	1820	4,192	10	419	8	**18**	13,083	12	1090	16	**28**
Harrison	1794	12,472	64	195	34	**98**	16,504	9	1834	0	**9**
Henry	1799	10,015	12	835	10	**22**	14,492	8	1812	11	**19**
Jefferson	1780	36,346	28	1298	17	**45**	146,010	9	16223	17	**26**
Jessamine	1799	9,396	41	229	26	**67**	10,864	6	1811	2	**8**
Kenton	1840	7,816	16	489	4	**20**	43,983	8	5498	7	**15**
Lewis	1807	6,306	0	0	6	**6**	13,154	7	1879	14	**21**
Lincoln	1780	10,187	10	1019	3	**13**	15,080	9	1676	9	**18**
Madison	1786	16,355	23	711	3	**26**	22,052	10	2205	0	**10**
Marion	1834	11,032	17	649	11	**28**	14,693	5	2939	7	**12**
Mason	1789	15,719	37	425	17	**54**	20,469	6	3412	3	**9**
Mercer	1786	18,720	58	323	21	**79**	14,142	16	884	6	**22**
Montgomery	1797	9,332	14	667	11	**25**	10,566	0	0	1	**1**
Nelson	1785	13,637	47	290	25	**72**	16,609	11	1510	17	**28**
Nicholas	1800	8,745	19	460	10	**29**	11,869	5	2374	6	**11**
Oldham	1824	7,380	14	527	13	**27**	7,667	6	1278	7	**13**
Owen	1819	8,232	12	686	12	**24**	17,401	7	2486	11	**18**
Pendleton	1799	4,455	9	495	4	**13**	16,702	10	1670	10	**20**
Robertson	1867	—	—	—	—	**—**	5,814	n/a	n/a	n/a	**n/a**
Rowan	1856	—	—	—	—	**—**	4,420	0	0	0	**0***
Scott	1792	13,668	35	391	20	**55**	14,965	11	1360	0	**11**
Shelby	1792	17,768	48	370	21	**69**	16,813	8	2102	10	**18**
Spencer	1824	6,581	16	411	9	**25**	7,040	n/a	n/a	n/a	**n/a**
Trimble	1837	4,480	12	373	5	**17**	7,171	3	2390	0	**3**
Washington	1792	10,596	32	331	7	**39**	14,419	12	1202	0	**12**
Woodford	1789	11,740	49	240	19	**68**	11,800	10	1180	0	**10**
BG Total		**407,631**	**877**	**465**	**433**	**1310**	**729,024**	**257**	**2837**	**222**	**479**
KY Total		**779,828**	**1773**	**440**	**718**	**2491**	**1,648,690**	**651**	**2533**	**668**	**1,319**

* 1880 census returns stated no manufactures.

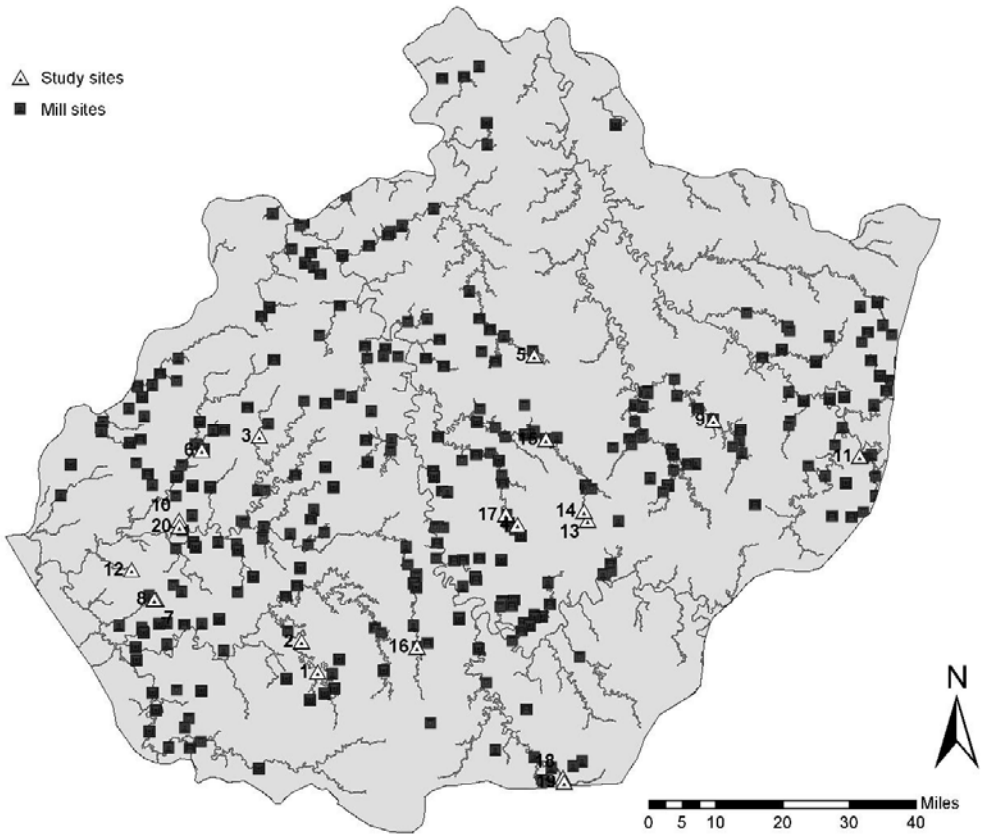

Figure D.2 A partial inventory of nineteenth-century mills shown on historic maps of 22 Bluegrass counties identified 358 mills at 305 different sites. On some streams, such as South Elkhorn Creek near Lexington, mills were located nearly every half-mile (Beers & Co. 1876, 1877a, 1877b; Beers & Lanagan 1879a, 1879b, 1879c; Bergmann 1858; Bevins 1981; Blanton 1934; Griffing 1882a, 1882b, 1882c, 1883a, 1883b, 1883c; Hewitt and Hewitt 1861; KGS 2002; KYDGI 2005; Lathrop and Summers 1884; McKee and Bond 1936).

Table D.3 Water- and Steam-Power Use, 1880 (Hollerith 1883)

Industry	No. Establishments	No. Water Wheels	No. Boilers
Flour and Grist Mills	651	508	424
Lumber, Sawed	668	104	660
Cotton Goods	4	1	8
Printing and Publishing	19	1	19
Woolen Goods	95	35	69
Other Industries	236	6	278
KY Total	**1673**	**655**	**1458**

Prior to Kentucky statehood, Virginia laws governed the modification of navigable channels and gave the county courts the authority to regulate the improvement of streams. Laws governing the improvement of navigable streams were substantially similar to those governing road improvements, empowering the courts to levy taxes and conscript labor crews for open-channel work (Verhoeff 1917:19). Following statehood, a version of the Virginia law governing the improvement of streams was not adopted until 1816, though the 1792 legislature considered a resolution to regulate a system for removing obstructions from the Kentucky River. Prior to adoption of the stream improvement law, the improvement of individual streams was directed by special legislative acts. The 1816 law authorized county courts to assign navigable streams to precincts and superintendents who oversaw crews of "laboring tithables" conscripted from those men who lived nearest the streams. The law was very similar to that governing road improvement, and men conscripted to work on the streams were exempt from road work for the year. Virginia's custom of passing special legislative acts to establish public ferries was also perpetuated in Kentucky (Verhoeff 1917:19).

Ferry landings, fish traps, fish dams, milldams, timber booms, and other obstacles were added to streams that in their natural state were already not very conducive to navigation. Flow varied enough to render even the largest streams impassable for several months each year. Rocky shoals, islands, debris snags, accumulations of gravel and sand, and overhanging trees blocked potentially navigable channels (Verhoeff 1917:12-13). Nevertheless, any stream which could carry a flatboat during a period of high flow could be considered navigable (Robertson 1914).

Early efforts to make the streams more navigable to the rafts and flatboats that transported logs and goods to markets included both open-channel work and construction of slack-water systems. Open-channel work focused on removing or reducing channel obstructions. Labor crews snagged the channels to remove debris, removed vegetation from the banks, and constructed wing-dams, dikes, and training walls to increase flow depth at the shoals. Flood flows carried and deposited debris that created alluvial fans, dams, and islands, some of which were 10 or 12 ft high; the streams required constant maintenance to clear the obstacles (Verhoeff 1917:12-13).

Throughout the 1800s, the legislature attempted to improve navigation on Kentucky's navigable rivers and tributaries, though often with limited success. Prior to 1818, the legislature's attempts to direct the removal of fish dams, logs, trees, brush, and rocks from the Kentucky River, the South Fork, and its Goose Creek tributary were largely ineffective. During that time, special legislative acts and county courts continued to permit construction of milldams and ferry landings. In 1801, the legislature chartered The Kentucky River Company and charged it with removing all obstructions that would hinder boat passage between the mouth of the Kentucky River and the mouth of the South Fork. Though the state appointed commissioners to oversee the project, no work was completed. Attempts to complete the work were made again in 1811, 1812, and 1813, to no avail.

Aside from limited legislative acts to approve improvements to certain sections of the river and its branches, no other attempts to improve the entire river were made until 1818. That year, the legislature appropriated $40,000 for the improvement of the Cumberland, Green, Licking, Salt, and Kentucky rivers and their tributaries. Commissioners and their hired laborers removed logs, debris, snags, fish traps, and fish dams. They also constructed brush wing dams to narrow and deepen the channels and increase flow velocity to attempt to scour out bars (Johnson 1974; Verhoeff 1917). Though obstructions were removed and brick and stone dikes and dams of rocks, brush, and logs were added to the channels, the efforts proved so unprofitable that the state sold the equipment used for the improvements in order to recoup some of its funds (Clark 1992:178).

In 1819, the legislature chartered the Elkhorn Navigation Company to improve the navigability of Elkhorn Creek and its forks, including the main stem from its mouth to its forks, the North Fork to Georgetown, and the South Fork to Lexington (Verhoeff 1917:24n). That same year, a canal was excavated to allow river craft to navigate around a milldam at the village of Sodom on South Elkhorn Creek (Bevins et al. 1998).

Beginning in 1825, snags were removed from the Ohio River (Johnson 1974:38-56), and construction of the Portland Canal began. In spite of the importance of the project, which was intended to facilitate the river commerce essential to the state's growing economy, nearly 20 years had elapsed since the legislature had chartered the Ohio Canal Company to improve navigability at the Falls of the Ohio by constructing the canal. In 1830, nearly 20 years after the first successful voyage of a steamboat on the Ohio and Mississippi rivers, the Uncas steamer was the first to pass through the completed canal (Clark 1992:176).

In 1828, the Board of Internal Improvement commissioned a survey of the Kentucky River to determine the potential for increasing channel depth. The survey identified the nature and location of each riffle. In 1835, sixty-five fish dams and milldams were removed from the Kentucky River between Frankfort and the South Fork. That same year, the Board extended the 1828 survey to include the upper river and recommended a number of improvements to the river and its branches. In 1835, the Corps of Engineers was authorized to improve navigation on the Ohio River by three methods of open-channel work: removal of snags and other similar obstructions; blasting of boulders from channels; and construction of riprap dikes to increase flow over bars (Johnson 1974:74). A survey was made of the Licking River, which carried products from the Bluegrass to markets in Cincinnati. Snags were removed and dikes and dams were added to the channel to deepen it. The Board's recommendations for construction of slack-water systems to improve navigation on the main channel of the Kentucky River were also adopted in 1835. Work commenced in 1836, but only 5 of the intended 17 locks were completed before the project was abandoned in 1842 (Verhoeff 1917; Clark 1992).

River transit continued to receive attention and support from the legislature even after railroad development began in the Bluegrass in the 1830s. Railroads were slow to gain the support of state officials, who tended to favor traditional transportation methods. Officials were so convinced that river commerce could be improved and expanded that they even entertained the notion of constructing a series of internal canals to connect the Kentucky River to the Atlantic coast. The proposed canal system, intended to allow Kentucky to compete with the Erie Canal, would have connected the South Fork of the Kentucky River to Goose Creek to the Cumberland River. A canal or tunnel under the Cumberland Gap would have led to the Powell River, where another canal would have connected it to the Clinch and Tennessee rivers to Chattanooga, the Hiawassee River, and finally to Savannah on the coast (Clark 1992:178).

Kentuckians made use of the Kentucky River slack-water system until the Civil War, when Union engineers attempted to maintain the system by constructing three-foot-high walls of timber on top of the dams of the five locks. By the end of the war, however, floods had undermined the dams, which collapsed in some places and were breached in others. Boats and rafts could safely navigate the system only during periods of high flow, when the water carried them over the dams. In 1880, the Corps of Engineers commenced repairs of Locks and Dams 1 through 5 and construction of additional locks and dams shortly thereafter. Lock 6 opened in 1891 and Lock 14 was not completed until 1917 (Ellis 2000). Beginning in the late 1880s, however, river commerce noticeably declined. By that time, extensive railroad networks had been constructed through the state (Table D.4) and transportation of goods by rail was more economical than by river. Thereafter, the improvement of rivers for navigation received much less attention than it had in the ante-bellum period (Raitz 1980:35). During the same period, lumbering increased, and timber became the principal commodity transported through the Kentucky River system (Verhoeff 1917:114).

Table D.4 Kentucky Canals and Locks, 1860 (US Census 1866)

Canals & River Improvements	Points Connected	Miles of Navigation: Canals	Miles of Navigation: Slack Water	Dimensions: Width (ft)	Dimensions: Depth (ft)	Locks: No. of Structures	Locks: Chambers: Length (ft)	Locks: Chambers: Width (ft)	Total Rise and Fall (ft)	Cost of Construction
Louisville and Portland	Louisville--Portland	2.50	---	50	10	4	---	---	22	---
Kentucky River Navigation	Mouth of Kentucky-- Junction of North Fork	---	260	---	---	17	175	38	216	$2,500,000
Licking River Navigation	Mouth of Licking-- West Liberty	---	231	---	---	21	130	25	310	$2,000,000

Agriculture and Urbanization

Water management efforts in frontier Kentucky focused mainly on manipulation of surface waters, especially wetlands and small streams. The primary objectives of many early drainage projects were to eliminate sources of disease, especially yellow fever and malaria, and to increase the acreage of arable land available for farming. Surface waters were regarded as a "common enemy" (Vanoni 2006), and wetlands were believed to be pestilent wastelands that released disease-causing gases (Williams 1989:59).

Kentucky is one of only ten states to have lost at least 70 percent of their original wetland acreage. Based on soil surveys from the 1970s, approximately 1,566,000 acres (6.1 percent) of Kentucky's 25,852,800 acres are estimated to have been wetlands at the time of first settlement (KSWCC 1982). By the mid-1980s, only 300,000 wetland acres remained—a statewide loss of 81 percent (Dahl 1990). Of the 125,000 acres of wetlands estimated to have been in the Bluegrass at the time of settlement, 92,000 acres (73.6 percent) had been drained as of 1978 (KSWCC 1982). Agricultural development was responsible for most of the loss, as wetlands were drained, filled, or otherwise converted to cropland.

Extensive cutting of bottomland timber began with the arrival of pioneers, and wide-scale drainage projects were carried out in some areas of the Bluegrass as early as the 1790s to prevent disease and to promote settlement. Frankfort was located on an abandoned oxbow channel of the Kentucky River, and a pond on the northwest side of the city was drained around 1795-1796 with constructed ditches, a process perpetuated by the town's inhabitants to prevent disease (Verhoeff 1917:78). By 1800, the town's population had increased to 628, making it the state's second largest. Lexington's population at the time numbered 1795.

Drainage projects in the Louisville area in the early 1800s also focused on warding off disease. Louisville's population lagged behind both Lexington and Frankfort; despite the city's commercially advantageous location on the Falls of the Ohio, it had only 359 inhabitants by 1800. The city was plagued with a reputation for being "the Graveyard of the Ohio" (Wade 1959:17) because of health problems associated with its nearby swamps, which were eventually drained in the 1810s (Yater 1979:24). The drainage project produced "an extensive plain of dark rich soil" (Schwaab 1973:344) around the city. Jefferson County contained many other swamps, however. In 1838, Henry Ruffner noted equally rich soils "cursed" by stagnant ponds with "rank and rotting vegetation" for twenty miles south of Louisville (Schwaab 1973:345).

In the early 19th century, drainage projects were limited by technology and a lack of coordination between landowners. Many early drainage projects were conducted by various unrelated entities such as states, counties, towns, individual land owners, and private companies. By the middle of the century, drainage of land for agriculture had become "an almost universal practice" in some areas of Kentucky (Owen 1857:26). The lack of coordination of efforts within a drainage basin, however, compromised the effectiveness of these piecemeal drainage projects. To ensure proper functioning of constructed drainage systems, large outlets outside of each project's land boundaries were necessary.

In Kentucky, planning and construction of those outlets was eventually accomplished through the establishment of county drainage districts by the Drainage and Reclamation Act of 1912 (Beauchamp 1987:15-16; US Census 1932). Drainage systems, or enterprises, constructed by the districts consisted of canals and drains that carried water from the saturated land to a series of main canals draining the area. These drainage enterprises relied almost exclusively on ditches, though subsurface, covered tile drains had been used by landowners in the nineteenth century and were commonly used in early twentieth-century drainage enterprises in other parts of the country (US Census 1932). Thus, channelization projects were revolutionized not only by the involvement of government agencies in coordinating efforts within watersheds but also by heavy earthmoving equipment, such as bulldozers, necessary for construction of extensive networks of ditches and canals.

Swamps and wetlands that were drained by the districts in order to make them suitable for cultivation were primarily in the Western Kentucky Coal Field and the Mississippi Embayment (KSWCC 1982). In the Bluegrass, however, Shelby and Jefferson Counties had large areas in drainage enterprises in the early 20th century. More than one-third of Jefferson County acreage was in drainage enterprises by 1920, including some areas that had been drained as early as 1858 (US Census 1932). By the 1930s, over 585,000 acres statewide had been included in regional enterprises drained by more than 1200 miles of ditches, and most wetlands had been converted from natural to agricultural use.

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