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Historical Channel Evolution and Human Modifications of Blue River Near Kansas City Missouri

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HISTORICAL CHANNEL EVOLUTION AND HUMAN MODIFICATIONS OF BLUE RIVER NEAR KANSAS CITY MISSOURI

A Master's Thesis

Presented to

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In Partial Fulfillment

Of the Requirements for the Degree

Master of Science, Geography and Geology

By

Katie Grong

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ABSTRACT

Channel form can respond to changes in flood regime and sediment load caused by land use and climate disturbances. In the eastern United States, widespread soil and vegetation disturbances in the 1800s during agricultural expansion increased runoff rates, flood magnitude and frequency, and sediment loads often causing major changes in channel activity and floodplain sedimentation in local streams. Investigating the historical evolution of a stream channel system including its floodplains can help to advance geomorphological theory and benefit environmental managers. This study documents human impacts on historical changes in channel and floodplain widths since the early to middle 1800s in the Blue River in Kansas City, Missouri compared to a conceptual historical channel evolution model (HCEM) developed from the findings of other studies in the Midwest, U.S.A. The Blue River watershed drains the transitional area between the Ozark Plateaus in Missouri and Central Lowlands in Kansas. It has been affected by a long agricultural history as well as more recent and significant urban-industrial growth. Historical channel changes were assessed by: (i) General Land Office (GLO) surveys from 1826, 1827 and 1836 that describe pre-settlement channel conditions; (ii) Bank-line changes over time using aerial photography since the 1950s; and (iii) Locations, dates, and types of bank stabilization structures and channel modifications. Channel data combined with census data, flood records, soil maps, land use trends, and GLO surveyor notes indicate significant changes in channel width and planform of Blue River. Low-order channels responded to historical hydrological changes through incision and headward network extension. Middle watershed channels generally transitioned from a wide, shallow, multi-threaded planform to a narrower, deeper, single-channel stream. In addition, bank heights and floodplain extent increased by accelerated floodplain deposition of legacy sediment along most of the present-day channel. Lower main channel segments narrowed and possibly aggraded in response to higher sedimentation rates and artificial in-filling of urban land on the valley floor that possibly led to the need for the construction of engineered channel modifications to reduce flood risk since the 1970s.

KEYWORDS: fluvial geomorphology, channel width adjustments, General Land Office surveys, Kansas City, legacy sediment

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INTRODUCTION

River channel form can respond to changes in flood regime and sediment load caused by climate variability and land use disturbances at timescales from 10-100 years (Lazzaro 1990; Harbor 1994; Lecce 2013). If impacts are severe enough, hydrological connections between the channel and its floodplain can be altered greatly leading to geomorphic transformation of the river planform including channel depth and width, migration rate, and landform distribution (Knox 1977; Magilligan 1985; Owens, Walling, and Leeks 1999). Understanding the environmental history of a watershed and the historical evolution of a stream channel system, including its floodplains, can help to advance geomorphological theory and benefit environmental managers, especially in watersheds with a history of land conversion. (Knox 1977; Nunnally 1978; Brookes 1985; Simon and Thomas 2002; Landwehr and Rhoads 2003; Fryirs and Brierley 2012; Lecce 2013). An environmental history of a watershed generally compares the characteristics of the landscape prior to Euro-American settlement to subsequent human developments including how communities have managed watershed resources and what practices have led to the existing channel and riparian conditions on the valley floor (Finger and Morehouse 2007).

The field of fluvial geomorphology contributes to understanding environmental history by evaluating how human modifications, directly or indirectly, control channel form and its functions in the past to inform the future (Church 2002). Conceptually, a river channel is a three-dimensional form with its length, width, and depth shaped by flow and sediment load (Fryirs and Brierley 2012). The specific relationship between channel form and human activities can vary within the drainage network based on topography and landscape history (Church 2002;

Magilligan 1985). Geomorphic adjustments of a channel are therefore linked to interconnected processes governed by interactions among channel width, depth, slope, velocity, and bed and bank features where channel form tends toward an equilibrium condition (Rosgen 1996). As changes occur to one geomorphic variable, there are often subsequent adjustments by other variables needed to transition the channel towards a new equilibrium condition (Brookes 1992; Nunnally 1978).

In response to soil and vegetation disturbances, the relationship between increased flow and geomorphic response can vary downstream from the headwaters to the main channel. The headwaters and tributaries typically respond with incision and head-cutting to deepen the channel due to increased erosivity by deeper flow depths and faster velocities (Schumm 1984; Simon and Hupp 1986). Channel adjustments progressively shift downstream to increase stream power leading to higher rates of channel erosion and lateral migration in larger tributaries and the main channel (Lecce 2013). However, as slope decreases downstream, increased sediment supply can overcome transport capacity in the lower main channel thus increasing rates of floodplain deposition and possibly causing bed aggradation (Knox 1977, 1987). Disturbance is also part of the natural process of rivers as there is constant compensation for fluctuations in flow energy and sediment inputs. However, if imposed changes exceed threshold limits, the channel may respond dramatically to transform from its previous form to a new state with different geomorphic properties (Brookes 1992; Nanson and Croke 1992; Hupp 2000; Church 2002; Fryirs and Brierley 2012).

The present study focuses on the evaluation of historical planform changes in relation to land use disturbances in the Blue River watershed near Kansas City, Missouri. The region was dominated by prairie prior to Euro-American settlement and began experiencing the effects of agriculture-related activities in the early 1800s (Driever and Vaughn 1988). By 1880, agriculture was the dominant land use which gradually declined in area during the 20^{th} century as urbanization rapidly increased (Driever and Vaughn 1988). The geomorphic effects of historical land use conversion and contemporary urban-industrial growth are important to study as it contributes to knowledge of channel disturbance and evolution in the Midwest. The focus of this study will be on planform analysis of the Blue River which uses channel width including bed, bar, and island features to evaluate channel change over time (Wolman and Leopold 1957; Sherwood and Huitger 2005). Channel pattern adjustments are sensitive to environmental conditions and can be assessed though historical survey and map records and aerial photography for analysis within a geospatial framework using geographic information systems (Bourdo 1956; Bragg and Hulbert 1976; Friedman and Reich 2005; Dilts et al. 2012). As channel width is sensitive to variations in flood regime and sediment yield, it serves as a geomorphic indicator of channel evolution and disturbance response overtime (Wolman 1967; Knox 1977).

Width as a Key Geomorphic Variable

In relatively undisturbed streams, channel width increases with the bank-full or dominant flood discharge and upstream drainage area to contain the bank-full flood with a recurrence interval of about 1.5 years (Rosgen 1996). The continuity equation underscores the relationship of width to flow as follows (Equation 1):

$$Q_{water}\ (m^3/s) = \text{width (m) x depth (m) x velocity (m/s)} \quad \text{(equation 1)}$$

However, while this equation represents a hydraulic relationship, it can be applied to width adjustment by also assuming geomorphic adjustments of the hydraulic geometry of bed or banks by sediment deposition and erosion (Figure 1). Nevertheless, channel width is sensitive to variations in either flow depth or velocity (Rosgen, 1996). The importance of width as being geomorphic variable that can adjust to floods and sediment load s further supported by Lane's equilibrium relationship which conceptually balances flow force (discharge and slope) against channel resistance (sediment load and size) to predict channel aggradation (deposition), bed stability, or incision (erosion) (Lane 1955) (Equation 2):

$$Q_{sed}\ x\ D \sim Q_{water}\ x\ S \text{ (equation 2)}$$

Where:
Q_{sed} = Sediment load (mass/s)
Q_{water} = discharge (m^3/s)
S = Channel gradient or slope (m/m)
D = Sediment diameter (m)

Thus, the potential for channel adjustment, or change in width, is based on the balance between available stream power and its potential to do geomorphic work (i.e., Q_{water} x S) through variation in sediment load or erosion and deposition of sediment in the channel and on floodplains (Simon and Hupp 1986). Stream power is defined as the power per unit length being exerted on the cross-sectional area of a channel (Lecce 2013).

Historical Factors Affecting Channel Change

It is well documented that historical land use impacts from agricultural land-clearing, urbanization, channelization, and recent climate change can cause channel form adjustments (Table 1). Increased manipulation of river systems and clearing of forested land resulted from the need for a steady water supply and land for cultivation to support agricultural communities after European settlement (Fryirs and Brierley 2012). Natural vegetation cover is effective for dispersing precipitation and protecting soil from erosion. Agricultural land clearing for cultivation removed this protection and increased runoff, soil erosion, floods, bedload and suspended sediment transport, and floodplain sedimentation (Wolman 1967; Knox 1977; Knox 1987; Lecce 2013). So-called legacy sediments up to several meters thick were deposited as post-settlement alluvium on floodplains where the sediment delivery exceeded the transport capacity, which typically occurred along the main channel in river valleys (James 2013; Pavlowsky et al. 2017). Legacy sediments were the result of accelerated sediment production and subsequent floodplain sedimentation in response to anthropogenic disturbances such as logging, agriculture, and urbanization (James 2013). After some period, erosive floods can remobilize stored legacy sediment to add to modern sediment loads (James 2018).

The impacts of historical post-settlement agricultural activities often also intersect with more contemporary urbanization activities. Urban developments in forested or agricultural areas resulted in channel enlargement and instability of sediment erosion and deposition patterns in affected stream systems (Wolman 1967; James, Lecce, and Pavlowsky 2022). Expansion of impervious surfaces, such as roofs and roads created greater efficiency of storm water drainage which increased flow velocity and runoff volume and frequency. Urbanization can also lead to the reduction of sediment loads over time due to reduced sediment supply due to erosion management, channel hardscaping, and armoring by impervious surfaces while still increasing peak discharges through runoff, thus resulting in channel enlargement through higher erosion capacity (Fryirs and Brierley 2012). Variations in sediment delivery, upstream channel erosion, and downstream deposition can alter sediment transport capacity leading to channel adjustments (Buffington 2012) (Table. 1). In Washington state, flow regulation, bank stabilization, and log-jam removal in an urbanizing watershed resulted in channel narrowing by 50% from 1936 to 1989 and the transformation from a multi-threaded to single-threaded channel. Subsequent increases in stream power widened the mean channel width by 2011 with reaches confined by bank stabilization remaining narrow and unchanged (Gendaszek, Magirl, and Czuba 2012).

Channelization is a specific kind of human disturbance that reduces the connection between channels and floodplains. Channelization is the most prevalent way river systems are modified by humans. In general, this engineering practice exists to physically modify a river to create a straighter, more uniform channel that is easier to control to reduce flood risk and land instability (Fryirs and Brierley 2012). Channelization typically degrades riparian zones and floodplain areas and increases channel slope and flow velocity leading to higher rates of channel erosion and sediment transport to further perpetuate the disturbance cycle (Hupp 1992; Simon and Rinaldi 2006; Heine and Pinter 2012; Jerin et al. 2023). Some of the prominent reasons for channelizing a river, often through levee construction and gravel mining, include reducing floods, controlling erosion, and relocation in urbanized areas (Simon and Rinaldi 2006). However, rather than channelization being an isolated change, by altering the long-term availability of sediment to the river, morphological adjustments remain in a mode of recovery not being able to respond fully to a stable or naturalized condition (Landwehr and Rhoads 2003). This further contributes to the positive feedback cycle between erosion and deposition and human intervention (Jerin et al. 2023).

Just as land use changes influence fluvial processes, climate change also has implications for understanding channel changes (James, Lecce, and Pavlowsky 2022). Climate exerts a significant control on flood magnitude and frequency. Therefore, there are concerns about how increases in precipitation due to global warming will likely increase rainfall intensity and flood risk (Frost 2000; Heimann, Holmes, and Harris 2018). Increased flooding due to climate change floods has been documented in the neighboring Ozark Highlands and these effects may potentially extend to the Central Irregular Plains ecoregion (Pryor et al. 2014; White et al. 2015; Pavlowsky, Owen, and Bradley 2016; Heimann, Holmes, and Harris 2018). Both increased rainfall intensity due to climate change and decreased infiltration related to land use can amplify flooding in watersheds and therefore also further increase the risk of channel instability including changes in width and sediment transport (James, Lecce, and Pavlowsky 2022).

Historical Channel Evolution Model

Channels can become destabilized by both natural and anthropogenic disturbances which influence channel form over time (Knox 1977, 2006; 1986; Lecce 2013). In agricultural settings reduced vegetation cover and increased soil compaction can increase runoff, soil erosion, and bank erosion, most notably in headwater streams where channel width can increase runoff from a storm event by up to three times (Gifford, Faust, and Coltharp 1997; Poesen, Vandaele, and Wesemael 1996; Lecce 2013). The nature and degree of fluvial response to watershed-scale disturbances like agricultural land use change can vary downstream. The sequence of these changes can be organized spatially and temporally by a conceptual model based on findings from multiple studies in the Midwest, and primarily introduced by Knox (1977, 1987) (Figure 1). To begin, the initial pre-disturbance channel in low order headwater and tributary streams, often with relatively steep channel slopes, responds to increased upland runoff rates by channel incision and head-cut migration. However, channel deepening can also lead to an increase in width of the channel through bank under-cutting, slumping, and bank angle relaxation (Schumm 1984; Simon and Hupp 1986) (Figure 1A).

Further downstream, deeper flows sometimes over higher bed slopes increase peak stream power in larger tributaries or middle segments of the main river causing some incision, but bedrock or coarse bed lag tends to limit the depth of bed erosion. Thus, channel adjustments are related more to lateral erosion across the valley floor, forming a more active meander belt within which forms a wider channel with laterally-accreted bars available for vertical accretion by overbank floodplain deposition as channel meandering progresses (Knox 1977, 1987; Simon and Rinaldi 2006; Lecce 2013) (Figure 1B). In contrast, lower main channel segments with decreasing slope and lower stream powers, sustained sediment delivery, and increased flood frequency leads to accelerated rates of floodplain sedimentation and, in some cases, channel narrowing and bed aggradation (Knox 1977, 1987; Lecce and Pavlowsky 2001). In agricultural watersheds, increased sediment delivery from upland soil erosion and channel enlargement accelerated legacy sedimentation on floodplains along downstream tributaries and main channels resulting in higher bank heights and burial of riparian wetlands (Knox 1977; Jacobson and Coleman 1986; Walters and Merritts 2008) (Figure 1C.). The above-described geomorphic model will be referred to in this study as the Historical Channel Evolution Model (HCEM) and will provide the hypothetical framework upon which to interpret and evaluate past, present, and future channel processes in the Blue River watershed (Figure 1).

Historical Channel Width Assessment

Aerial photograph analysis is often utilized to document historical geomorphic changes in channel width and sedimentation on larger rivers (Martin and Ham, 2005; Buckingham and Whitney 2007; Cadol, Rathburn, and Cooper 2011). Galster, Pazzaglia, and Germmanoski (2008) used aerial photography from 1946 and 1999 to determine that width changes can be discernable for channels that are at least 6 to 15 m wide. Juracek (2000) used multiple-date aerial photography datasets to assess changes in bank-full channel width pre- and post-dam construction on the Neosho River in Kansas and generally found little channel change. Channel adjustments in the Minnesota River basin were assessed by Lauer et al. (2017) during a 77-year period showing significant increases in channel width in the main channel and major tributaries due to large increases in discharge over the last century. However, aerial photography is generally limited to time periods after the 1930s in the USA.

General Land Office (GLO) surveys contain information on pre-settlement land use and channel conditions during the early 1800s (Lecce 2013). Many studies concerned with land use changes and environmental management rely on understanding the pre-settlement characteristics of the watershed. Thus, for most watersheds in the U.S.A., GLO surveys probably represent the only source of pre-settlement baseline data for which to evaluate current conditions (Nelson 1997). Land surveys were initially conducted in Missouri beginning in 1815 to aid in the sale of the public domain to settlers after the Louisiana Purchase in 1803 (Schroeder 1982). Early GLO surveys in the Blue River watershed were completed in Missouri in 1826 and 1827 and in Kansas in 1836. The field maps and notes generally contain information on major land cover changes, stream widths along section lines, and comments about local vegetation, soil quality, and flood risk.

Research utilizing GLO surveys has primarily focused on assessing historical changes in vegetation and forest structures in relation to settlement (Bourdo 1956; Friedman and Reich 2005; Williams and Baker 2011). However, some previous studies have used archival data recorded in GLO surveys to reconstruct pre-settlement channel conditions and assess changes in geometry and hydrology related to land use conversion (Knox 1977). These studies generally found channel widening and higher discharges in post-settlement channels than in GLO survey channels (Lecce 2013). Knox (1977) used GLO survey and aerial photography analysis to assess the human impacts on stream channel of the Platte River, Wisconsin. During the historical period, he found that headwater and tributary channels became wider and shallower, leading to narrower and deeper lower main channel cross sections. Similarly, Lecce (2013) found that cross-sectional area increased in stream channels an average of three times in the Blue River watershed, Wisconsin. However, Gendaszek, Magirl, and Czuba (2012) found that relatively wide, multithreaded channels recorded in GLO surveys for the Cedar River in Washington became narrower, single threaded channels during the post settlement and early twentieth century period due to logging and urban development.

Purpose, Hypothesis, and Objectives

The purpose of this study is to analyze historical and contemporary channel width records to evaluate the influence of historical land use and climate change on flood regime, sediment load, and channel form in Blue River watershed (700 km^2) which drains western Missouri, including Kansas City, and eastern Kansas. Channel widths were obtained from GLO surveys and historical aerial photography. A few studies have examined channel width and planform change by evaluating the effects of historical land use conversion and contemporary urban-industrial growth in Central Irregular Plains ecoregion. One study of the Medicine Lodge river system in south-central Kansas used GLO records from 1871 to show that, while land use had not changed, a series of wet years in the 1940s allowed vegetation to density to increase on bars and banks which stabilized the channel and trapped sediment causing the channel system to narrow (Martin and Johnson 1987). The purpose of this study is to compare historical and recent channel morphology of Blue River to a general HCEM model of channel response developed from several studies in the Upper Midwest (Knox 1977, 2006; Magilligan 1985; Lecce 2013)

(Figure 1). Four specific research questions are addressed: (1) What are the spatial and temporal trends in channel widths along the Blue River and its tributaries since the early 1800s?; (2) Do observed patterns in widths indicate human impacts that have significantly affected channel form?; (3) Do downstream trends in historical channel widths conform to the hypothetical HCEM for the upper Midwest; and (4) Is there any evidence for channel adjustments to hydrologic changes related to recent climate change. This study will be the first to develop and verify a conceptual channel evolution model for a western Midwest watershed (i.e., the HCEM). As climate change progresses, it is essential to first understand how land use change has affected present-day channel conditions to inform management efforts to mitigate adverse effects.

Table 1. Channel response to periods of settlement.

Period of Settlement	Disturbance	Channel Response	Source
Pre-settlement	Natural disturbance, native vegetation	Tends towards low energy, balanced condition, high infiltration, low runoff	Fryirs and Brierley 2012; Buffington 2012; James 2013.
Agricultural Settlement	Land clearing, logging, pasture farming, wetland drainage, dam construction, channels deepened	Increased runoff, soil erosion, floods, and floodplain sedimentation (legacy sediment), and head-cutting	Wolman 1967; Knox 1977; Knox 1987; James 2013.
Urban/ Industrial Settlement	Expansion of impervious surfaces, mining activities, mechanized agriculture	Increased flow velocity, runoff, heavy metal pollutant storage in floodplains, erosion, and downstream deposition	Fryirs and Brierley 2012; Buffington 2012; Bai et al. 2010.
Climate Change	Increased flood magnitude and frequency	Increased erosion, flooding, channel instability	Pryor et al. 2014; Pavlowsky, Owen, and Bradley 2016; Heimann, Holmmes, and Harris 2018).

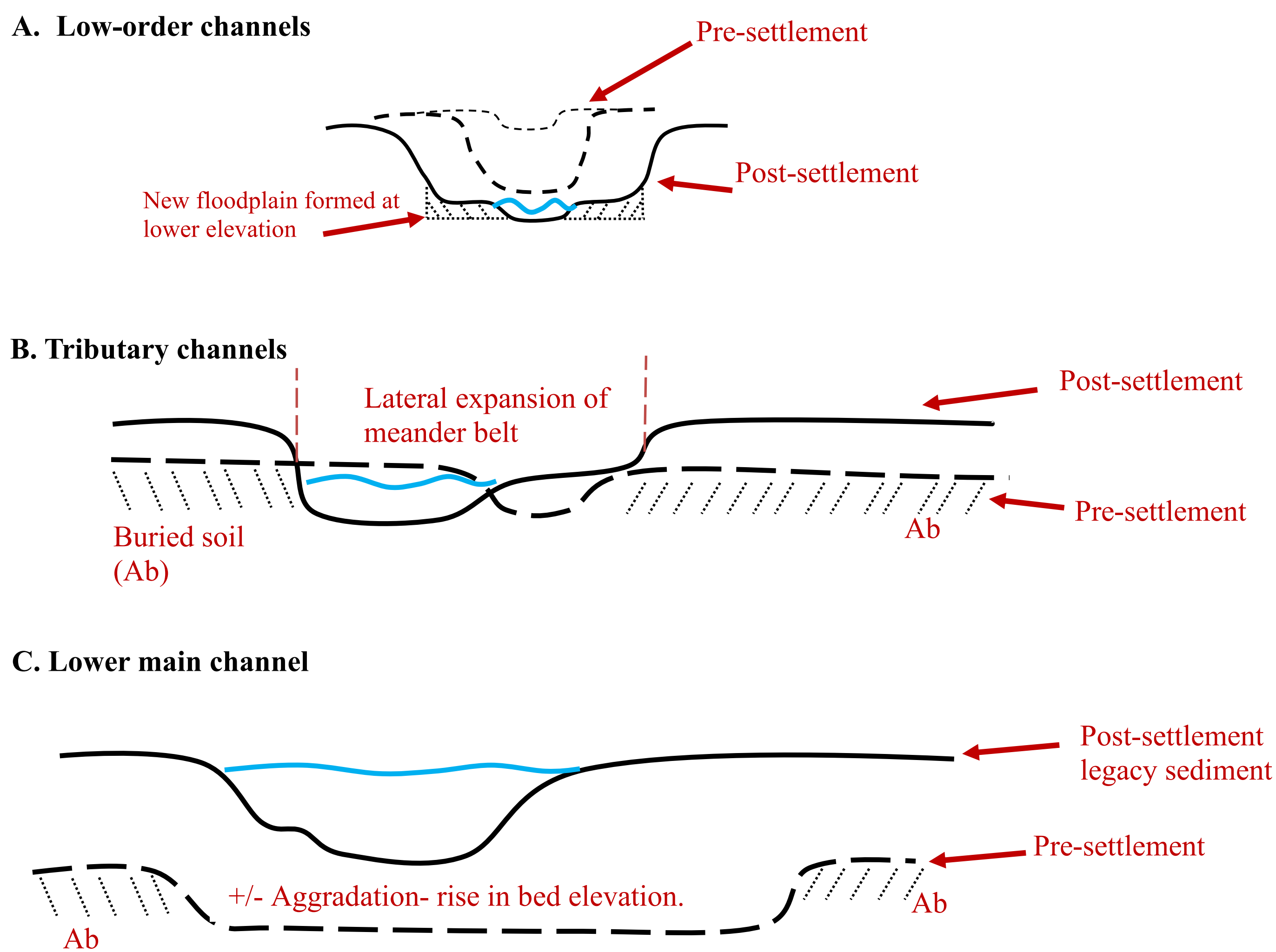

Figure 1. Hypothetical model of Historical Channel Evolution in the Upper Midwest (Knox 1977; Schumm 1984; Simon and Hupp 1986). Blue line shows the bank-full stage of present-day channel. Buried soils indicate older floodplain buried by legacy sediment.

STUDY AREA

Regional Location

The Blue River (HUC-10# 1030010101) flows for 66 km while dropping 62 m in elevation from its headwaters in the Central Lowlands of Kansas, through the Central Osage Plains in Missouri, and into the Missouri River at Kansas City (Metcalf 1966; US Geological Survey 2012) (Figs. 2 & 3). The Blue River watershed (701 km^2) has been classified into four sub-watershed segments based on network location (or stream ordering) to compare with HCEM segments: headwaters (133 km^2), upper main channel (150 km^2), lower channel (72 km^2), and Brush Creek (153 km^2), and Indian Creek (194 km^2) tributaries (Table 2) (Figure 2). The current land use of the entire watershed (700 km^2) consists mainly of urban and developed land (69%) and agricultural and pastureland (19%) and forest (12%) based on the 2019 National Land Cover Dataset (NLCD) (Table 2) (Figure 3). Most of the agricultural land use is concentrated upstream, in the headwaters of the Blue River which is comprised of 54% pasture and cropland (Table 2). The upper main channel drains a mixture of urban (44%), agricultural (24%), and forest (24%) land use types. The drainage areas of the other segments are heavily urbanized including lower main channel (85%), Brush Creek (86%), and Indian Creek (90%). All sub-watershed segments drain over 30% impervious surface, with the lower main channel having the highest with 47%.

Geology and Soils

The geology of Blue River Watershed is characterized primarily by Pennsylvanian age shales with some limestone, sandstone, and coal. Surface features are comprised of deep loess hills, deep loess and drift, and Cherokee prairies (US Department of Agriculture, 1984). Upland soils in the watershed are generally formed in Pleistocene glacial loess deposits which cover significant areas of the uplands to depths >1.5 meters thick. Loess is thickest close to the Missouri River and decreases to the south with distance from the Missouri River (US Department of Agriculture, 1984).

Four young and poorly developed soil series with “A over C” profiles cover most of the floodplain along Blue River (USDA 2023) (Table 3) (Figure 4). The Kennebec silt loam is formed in deep, moderately drained, silty alluvium (U.S. Department of Agriculture Natural Resources Conservation Service 2023). Blue River floodplains were originally mapped as the Wabash Clay in 1917 but were later mapped as the Kennebec soil series (Albertson 1917; US Department of Agriculture 1984). Urban soils are identified as land areas with high population densities in a largely built environment significantly changed by human-transported materials which are located along the main channel below the Indian Creek confluence (Figure 4). Urban soils generally indicate the location of artificial fill used to increase bank heights to contain floods or raise land elevations above flood stage. The Sarpy fine sand consists of very deep and excessively drained sandy alluvium generally located along the lower main channel near urban land (Table 3, Figure 4) (NRCS 2023). Lastly, the Haynie silt loam soil consists of very deep and moderately well drained calcareous alluvium (NRCS 2023).

Climate and Hydrology

The climate of the Blue River watershed is humid continental with cold winters and hot and humid summers (USDA 2023). Average annual temperature ranged from 7 degrees Celsius to 18 degrees Celsius during 2010 to 2020 (USGS 2023). Rainfall and river discharge are monitored by the United States Geological Survey (USGS) at gaging station no. 6893500 at Blue

River at Kansas MO at R-km 5 draining 487 km^2. There may have been a slight increase (9%) in annual precipitation in the Kansas City area over the past century. Around 1917, annual precipitation averaged 92 cm and ranged from 63 cm to 127 cm around that time (Albertson 1917). From 1972 to 1995, average annual precipitation was 97 cm ranging from 46 cm to 131 cm at the USGS gage. In the most recent period from 2010 to 2020, annual precipitation averaged 101 cm ranging from 65 cm to 144 cm at the USGS gage. It is typical for streamflow to peak in the spring and decline through the summer. The mean annual discharge of Blue River was 5 m^3/s over a period of record since 1939. The largest peak flow recorded was 1,243 m^3/s in 2017. Climate change effects may have also contributed to increased flooding since the 1970s with increased rainfall frequency and intensity in the Ozark Highlands to the southeast suggesting a similar pattern is possible for the Blue River watershed (Pavlowsky, Owen, and Bradley 2016; Heimann, Holmes, and Harris 2018).

Land Use

Pre-settlement Era. Prior to Euro-American settlement, 27 percent of land in the state of Missouri was prairie (Schroeder 1982). Jackson County was covered by 48 percent prairie, mostly distributed in the northeast portion of the county (Schroeder 1982). Upland timber was primarily restricted to steep tributary ravines and lower valley terraces (Schroeder 1982). However, along major streams, the timber belt may have been narrow or absent (Metcalf 1966). While prairies dominated the uplands adjacent to river valleys, they typically were also present along some riparian areas near streams. Similarly in Johnson County, Kansas the pre-settlement landscape was a tallgrass prairie with a mixture of oak hickory forest. A review by Metcalf (1966) found that extreme droughts were common occurrences in pre-settlement times, and as early as 1800 stream discharge, depth, and turbidity were highly variable throughout the upper and lower main channel of the Blue River (Mathews 1988) (Figure 5). However, in the lower main channel the stream was described as clear with a rapid current. Many of the tributaries in the region also had clear water and sandy or silty beds, while others were completely dry (Metcalf 1966).

Agricultural Settlement Period. Missouri became a state in 1821. Official patents issued for land purchases in Blue River watershed were first recorded in 1828 along with the first road petitions in 1826 in Kansas City which signify initial population growth, industrial development, and spread of agricultural trade (Hickman 1920). Kansas gained statehood later on in 1861. Jackson County, Missouri was formed in 1826 and Johnson County, Kansas in 1855. However, the region experienced land use effects of Euro-American settlement since the early 1800s which began with agriculture related activities, such as land clearing and removal of riparian forest along tributaries and low valley terraces for agricultural settlement (Driever and Vaughn 1988). Agriculture expanded greatly after the Civil War with the percentage of total county land in farms peaking at 96 percent in Jackson County and 91 percent in Johnson County in 1900 and steadily declined with urban development in Kansas City during the 20^{th} century (Figure 6) The percentage of land in agriculture dropped below 40 percent for Jackson County in 1992 and Johnson County in 2007. Row crop yields peaked for both counties in 1959, dropping sharply in 1964 and 1978 (Figure 6). Livestock numbers peaked in Jackson County for swine around 1910 and in Johnson County for cattle in 1964 (Figure 6).

Urban Growth. The decline of agriculture in the two counties corresponds to rapid urbanization along the lower Blue River beginning in the 1880s. The intersection of the Kansas River and Missouri River acted as a natural highway in 1833 and promoted the growth of the

Kansas City area, with the river valleys soon utilized for the first railways in the area leading to a boom in population and development for other industries reliant on natural resources (Albertson 1917). Subsequent land shortage pushed industrial factory and rail line locations to low grade, confined floodplains of the Blue River (Driever and Vaughn 1988). Populations in both Missouri and Kansas increased steadily from 1900 by almost 50 percent between 1900 and 2020 (U.S Census Bureau 2023) (Figure 7).

The confluence of the Kansas River and Missouri River acted as a natural highway in 1833 and promoted the growth of the Kansas City area, with the river valleys soon utilized for the first railways, leading to a boom in population and development for other industries reliant on natural resources (Albertson 1917). Rock quarrying grew with the population. Shale mining for building bricks, sewer pipes, and other building materials, as well as sand and gravel dredging, existed concurrently with agriculture (Albertson 1917). Subsequent industrial development and urbanization along the lower Blue River shifted the primary land use from agricultural to industrial starting in the 1880s (Driever and Vaughn 1988). To account for the need for extensive residential land, industrial land use expanded onto to the floodplains of the Blue River which had lower grades, inexpensive land, large building sites, and no established record of floods at the time (Driever and Vaughn 1988). To accommodate the need for labor, eight housing subdivisions were built adjacent to the floodplain of the Blue River in 1900. As more factories and mills were erected the area between the established city and the subdivisions along the floodplain became filled in with other developments and reflect the layout of the contemporary city (Driever and Vaughn 1988). With the conversion of agricultural to urban land use, the expansion of impervious surfaces potentially led to increased flow velocity, erosion, and downstream deposition.

Both urban development and climate change may have influenced Blue River hydrology over the past 40 years. In the Ozark Highlands region immediately to the east, climate change has been shown to cause increased flood magnitude and frequency since 1990, which can result in channel instability (Pavlowsky, Owen, and Bradley 2016; Heimann, Holmes, and Harris 2018). Increasing numbers of rainfall events and floods may continue in the future thus potentially increasing runoff and channel erosion rates (Pryor et al. 2014; Heimann, Holmes, and Harris 2018). Highly managed river systems frequently face flooding and erosion issues, which is true of the urbanized Blue River watershed in Kansas City, Missouri. For example, the Blue River Channelization Project was authorized in 1970 to combat erosion and flooding issues through direct channel modifications (Driever and Vaughn 1988). However, Blue River drains the Central Osage Plains region for which there have been few historical channel studies. The history of land use conversion in the area lends itself to examining historical geomorphic trends in channel adjustments related to land use changes. Early land clearing, logging, and pasture farming practices would be expected to increase runoff, soil erosion, flooding, and legacy sediment deposition on downstream floodplains (James, Lecce, and Pavlowsky 2022).

Channel Modification Project. As early as 1900, plans were being made for the construction of levees, channel straightening, and a dam to create a recreational lake in the Lower main channel (Driever and Vaughn 1988). At that time, these proposed channel modifications were rejected in favor of residential and industrial construction on the floodplains. The inclusion of flood control measures in the plans indicated flood concerns, with seven floods exceeding the estimated flood stage in 1906 (Driever and Vaughn 1988). The Flood Control Act of 1936 spurred nationwide flood control and levee construction. However, following a severe and destructive flood in 1923 on Blue River, with an estimated peak flow of 850 m^3/s, modification efforts including channel straightening and flood storage reservoirs were completed which city officials believed sufficient to eliminate floods without having to move factories away from the river in what had become one of the main industrial districts in Kansas City (Driever and Vaughn 1988).

An even larger flood in 1961 prompted the development of the Blue River Channel Modification project which authorized the design and construction of flood control structures from 1970 to 2010 mainly along the lower segment of the of Blue River below Indian Creek and near the confluence of the Missouri River in heavily industrialized areas (Table. 4). Construction began in 1983 and was completed in 2010 resulting in 1.4 million cubic yards of sediment excavated, channel relocations including approximately 4 meander cutoffs, and installation of 14 miles of channel structures (USGS 2007). The lower 20 km of Brush Creek which drained into the lower main channel segment was modified with extensive excavation and concrete bank structures during the 1990s (USGS 2007). The upstream extension of flood control structures was limited by concerns over preserving the historic Civil War area at Byram's Ford and nearby Big Blue Battlefield Park. Revisions were made to the plan in 2006 to install smaller-scale channel modifications that still provided flood protection but did not relocate the channel. These modifications included concrete grade control structures and low head rock toe protection structures (USGS 2007).

Table 2. Present-day (2019) land use for Blue River watershed segments.

Watershed	Total km^2	Forest %	Pasture %	Cropland %	Urban %	Impervious surface %
Total Watershed	700.9	12.1	12.2	7.3	67.7	38
Headwaters	133.1	13.3	34.2	23.2	27.9	31
Upper Channel	149.2	24	19.8	3.8	43.5	33
Lower Channel	71.5	10.1	3.3	0.6	85.4	47
Brush Creek	153.3	11.1	1.9	0.5	86.1	39
Indian Creek	193.8	4.2	4.2	1.2	90.2	43

Table 3. Primary alluvial soil series with poorly-developed A/C profiles along Blue River and its tributaries (U.S. Department of Agriculture, Natural Resources Conservation Service 2023).

Series Name	Soil Order	Valley Floor Area %	Hydrologic Soil Group	Landform	Flooding Frequency
Kennebec silt loam	Mollisol	60.7%	C	Floodplain steps	Occasional to Frequent
Haynie silt loam	Entisol	0.3%	B	Floodplain steps	None to Frequent
Sarpy fine sand	Entisol	6.4%	A	Floodplains	Rare to Frequent
Urban	Mollisol	16.2%	D	Hillslopes	Occasional to Frequent

Table 4. Direct Channel Modifications of the Blue River by year (Cooper 1996).

Blue River Channel Modification	R-KM	Year	Description
Channelization	0-17.5	1983-1990s	Channel straightening, channel clearing, and enlargement, and deepening to increase capacity from 7,000 cfs to 35,000 cfs.
Bank Stabilization: Low head rock toe protection	11.5-14.5	1990s-2010 2006	Large amounts of riprap used to stabilize the channel banks, utility crossings, pipe outfalls, slope drainage gutters, tributary confluences, and bridge modifications or relocations.
Concrete Structures	11.5-19.5	1990s-2010 1997-2002	After 22 kilometers of excavation along the channel, many of the banks were lined with concrete.
Excavation	11.5-14.5	1997-2001	This reach required approximately 1.4 million cubic yards of excavation.
Brush Creek	0-20	1990s	Channel straightening, concrete banks, riprap

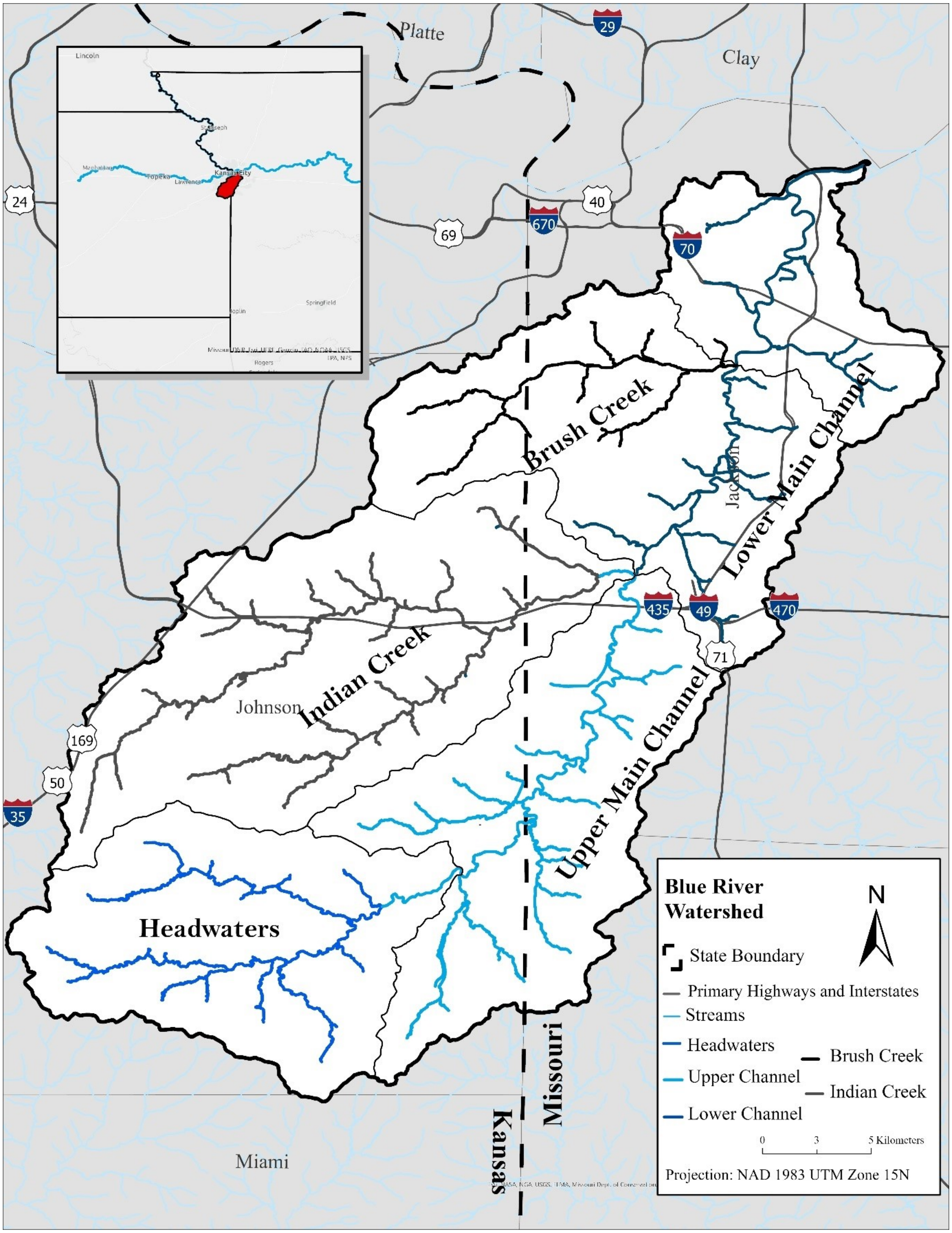

Figure 2. Blue River watershed study area.

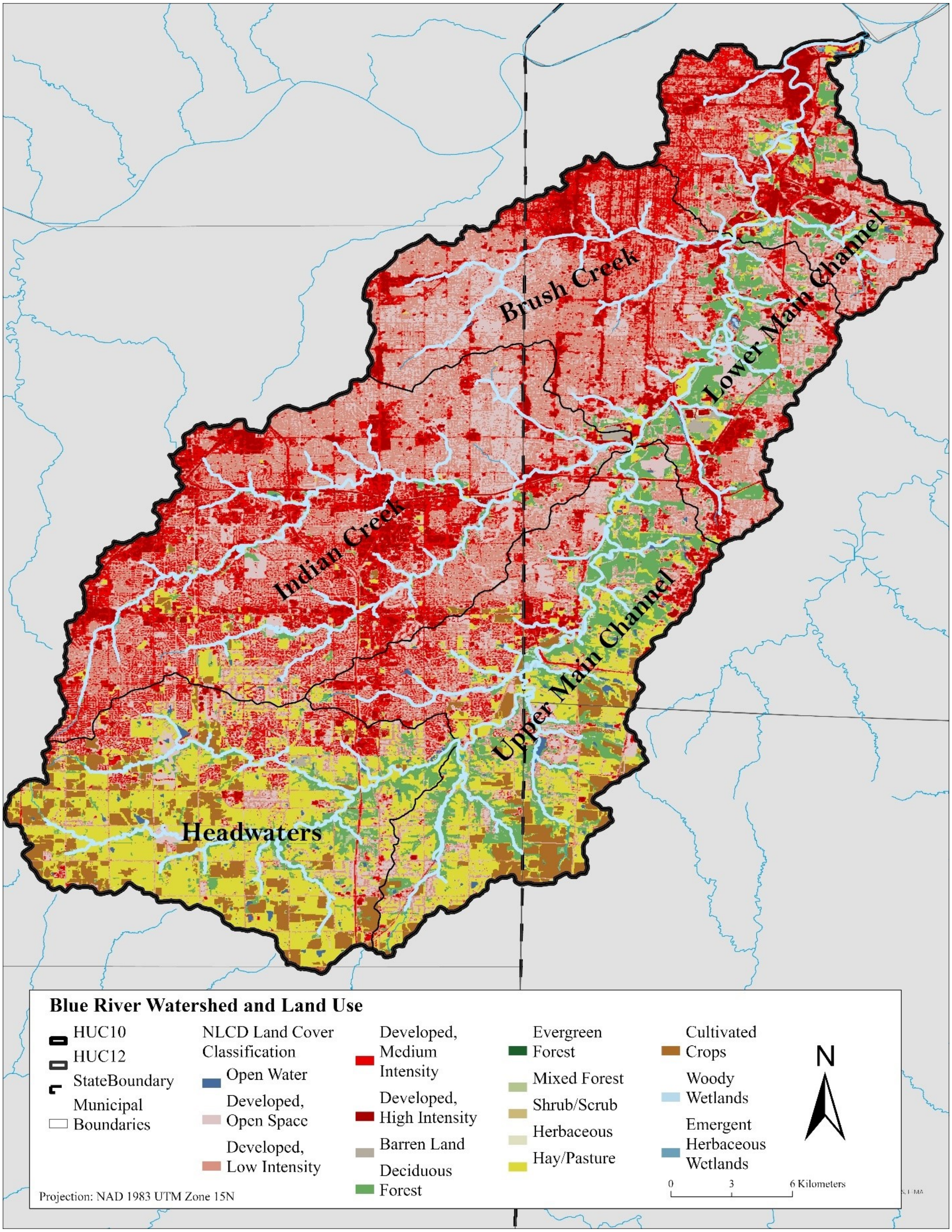

Figure 3. NLCD 2019 land cover classification in the Blue River watershed.

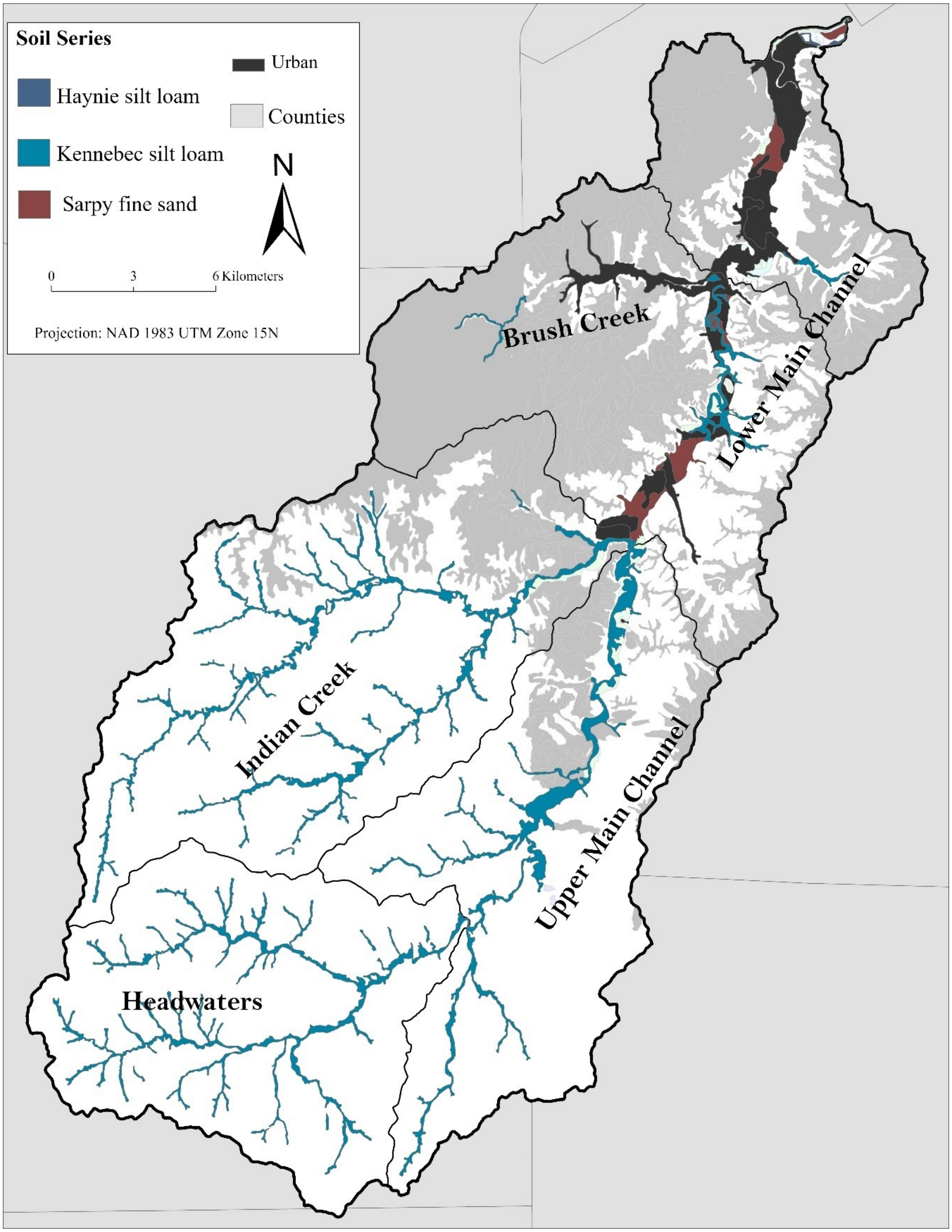

Figure 4. Fluvial soil series and urban soils in the Blue River watershed (USDA 2023).

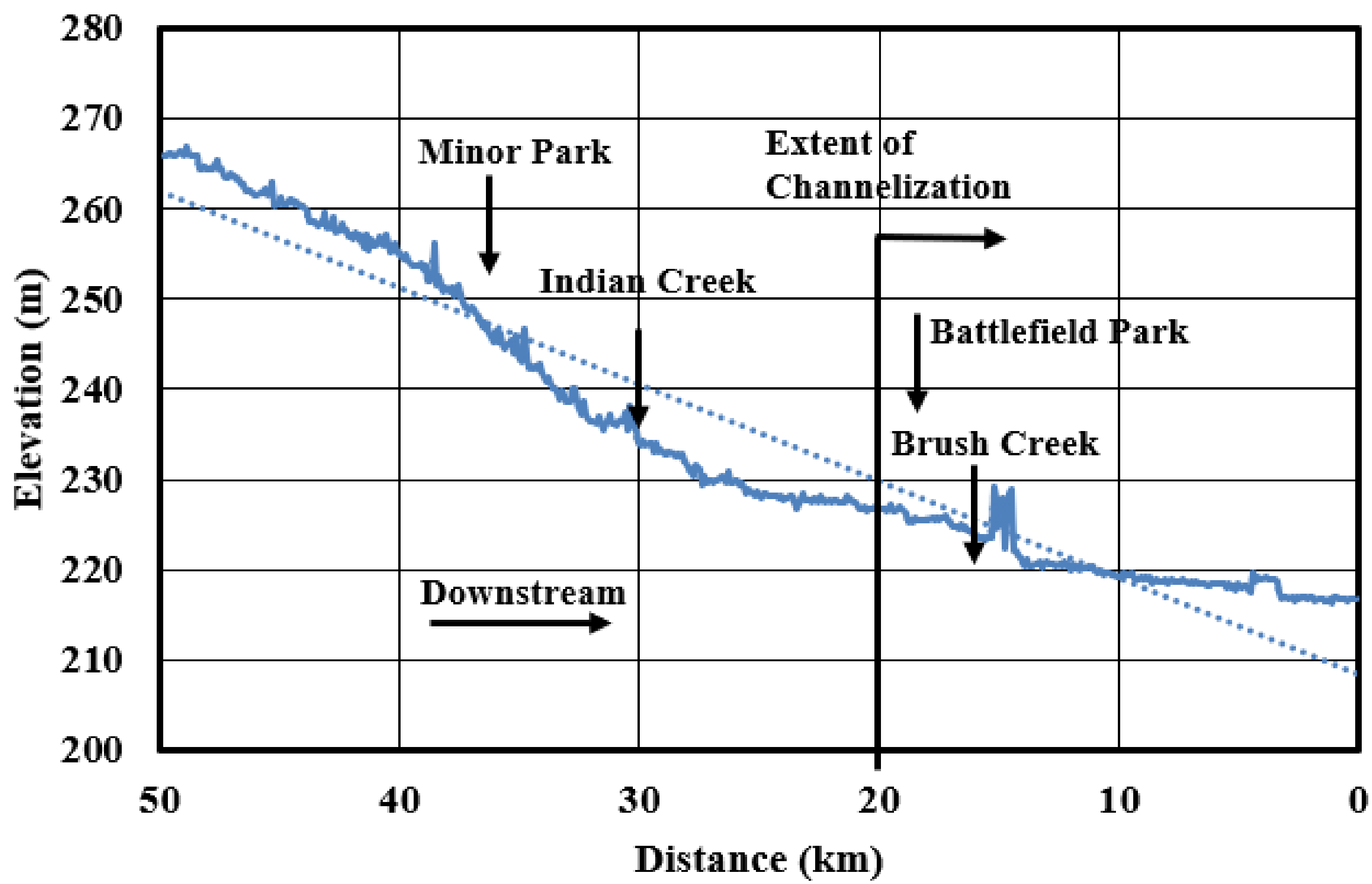

Figure 5. Long profile of the main stem of the Blue River watershed. Confluence with the Missouri River is at R-km 0. River slope (m/m) of trend line is 0.0011.

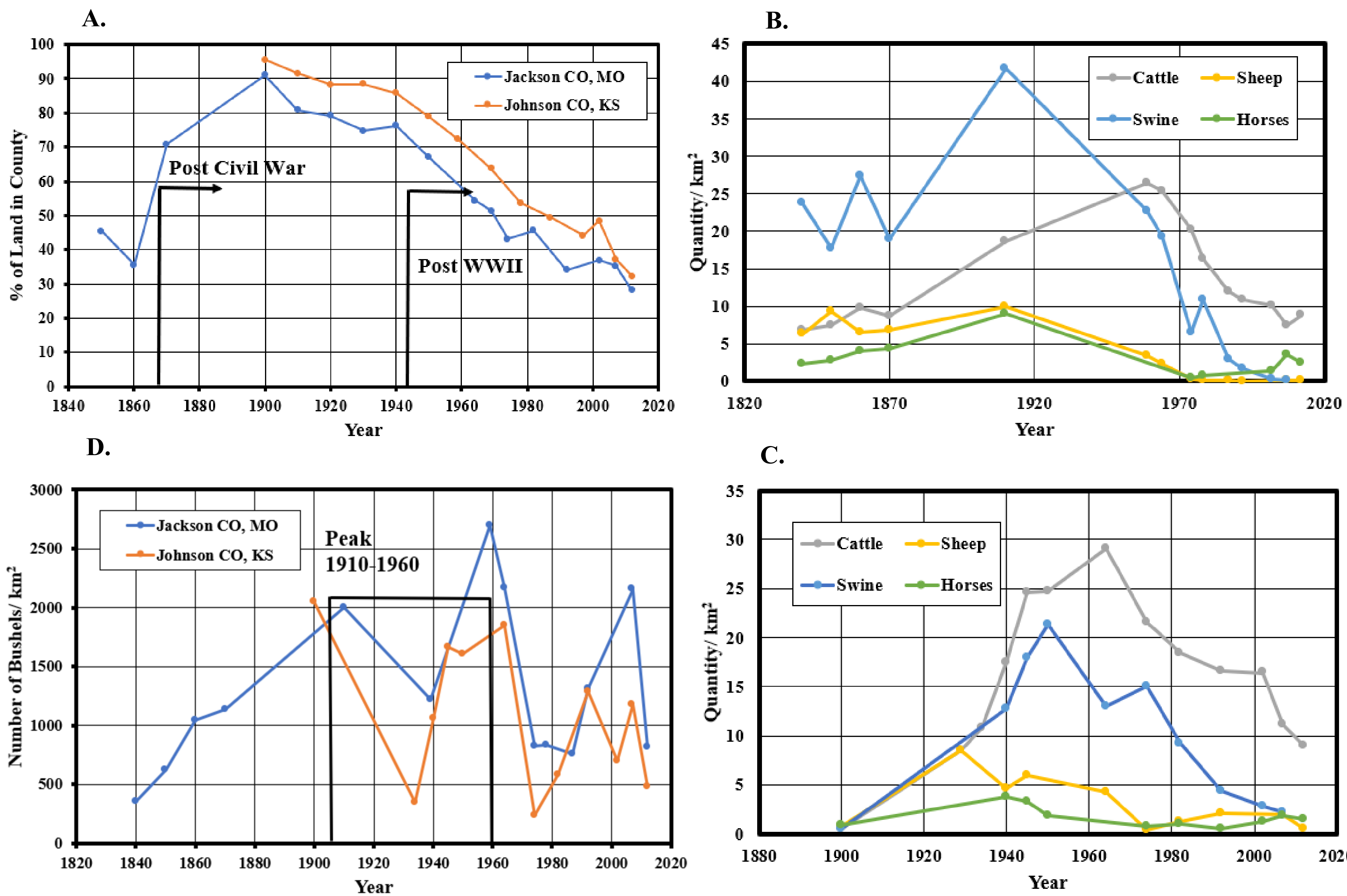

Figure 6. Historical land use trends from US Census records. A. Land in Farms, B. Jackson, MO Total Livestock, C. Johnson, KS Total Livestock, D. Row Crops.

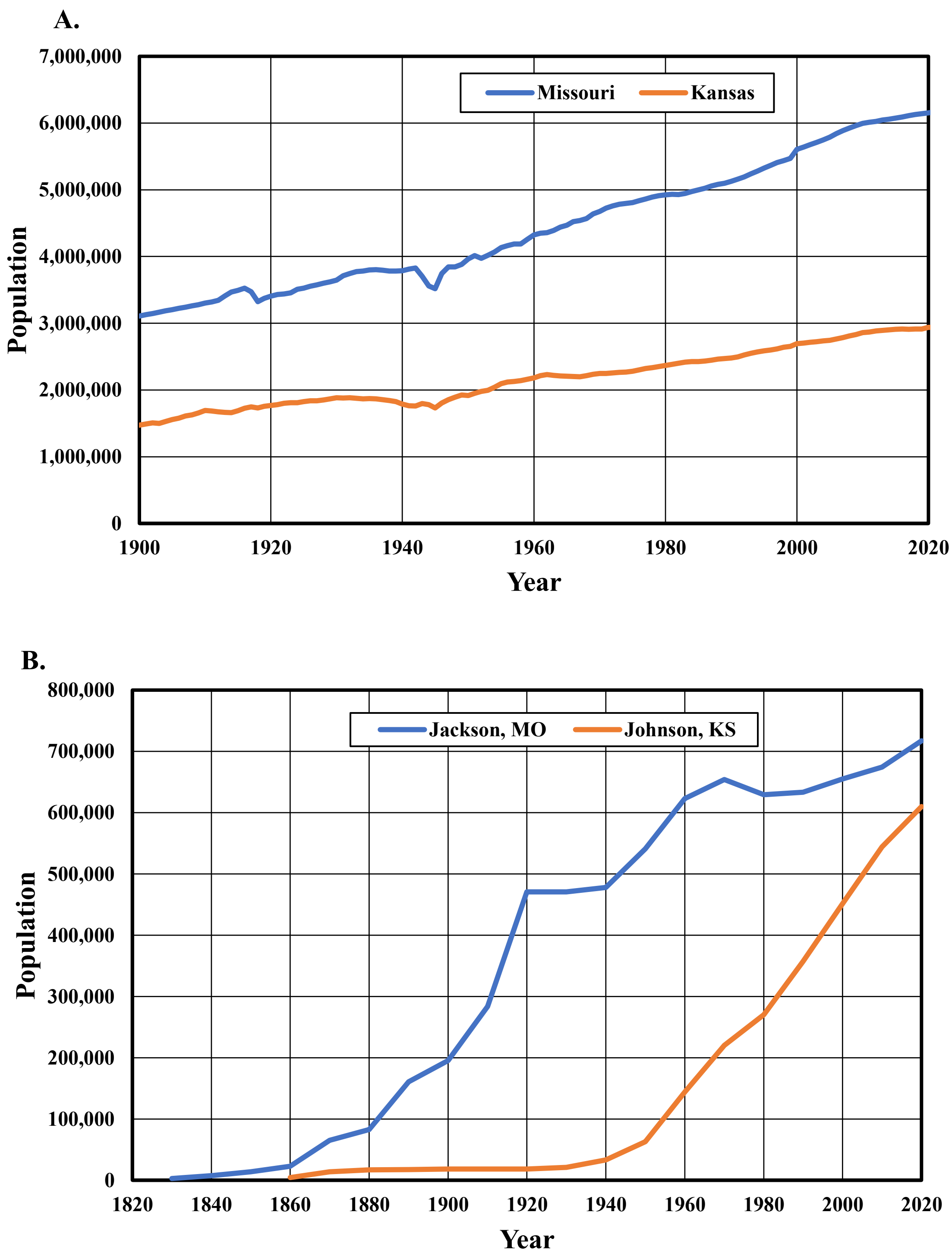

Figure 7. Population trends for Missouri and Kansas by State and County A. Population trends for Missouri and Kansas since 1900. B. Population trends by county (U.S Census Bureau 2023).

METHODS

This study assesses channel width changes related to historical land use conversion and other factors. A combination of geospatial information system (GIS), field, and laboratory techniques were utilized to: 1) assess the history of channel planform and width changes from 1826 GLO surveys to 1955, 1995, and 2015 aerial imagery; 2) analyze temporal and spatial width change trends according to stream order and network location; and 3) evaluate floodplain soil cores and sediment properties for evidence of legacy sediments. These methods served as indicators of geomorphic change in the watershed to assess the effects of historical and recent land use on channel floodplain form and connections.

Geospatial Data

Data for this study were obtained from multiple sources in various formats (Table 5). A one-meter spatial resolution LiDAR derived digital elevation model (DEM) covering the Kansas portion of the watershed (USGS 2015) was combined with LiDAR for Missouri (MSDIS 2015) to create a final one-meter LiDAR DEM dataset for the entire watershed area (Table 5). Land use data were acquired from NLCD 2019 land cover classification raster data sets (NLCD 2019) to assess land use classification, impervious surface coverage, and drainage networks (Table 5). Soils data from NRCS (2023) were used for mapping and analysis of age, distribution, and profile development (Table 5). Geospatial mapping of the Blue River channel system and watershed were used to assess contemporary channel form and conditions. Aerial imagery from 2015 and 1995 were selected for this purpose from the Missouri Spatial Data Information Service (MSDIS) database since the imagery was comprehensive for the entire watershed within

Missouri with a sufficient resolution to allow for digitization and relatively precise comparison of channel width measurements (MDIS 2023). In addition, aerial imagery from 1955 was downloaded from Earth Explorer and was geo-rectified to the 2015 aerial dataset (Earth Explorer 2023).

GLO Survey Records and Georectification

Channel widths were typically recorded by surveyors at survey crossing lines using Gunter Chains and Links, which were converted to meters for this study (National Museum of American History 2023; Professional Surveyor 2001). One chain length is equal to 20.1 meters and is made up of 100 links each 0.2 meters long (National Museum of American History 2023). General Land Office survey maps and notes from 1826, 1827, and 1836 were obtained from the Missouri Agriculture Land Survey Index for township and ranges comprising the Blue River watershed in Missouri (MALSI 2023) and from the Kansas Historical Society for the township and ranges in Kansas (KHS 2023).

The exact procedures used for historical GLO width measurements along Blue River and its tributaries were not recorded. However, procedures for GLO surveys were described in 1855 by the Surveyors-General of the United States, 29 years after the earliest width measurements at Blue River (Bourdo 1956). The 1855 guidelines mainly described standard procedures for larger, navigable streams which was how the Blue River was categorized at that time. The locations of the channel on the section line and channel width measurements across the stream were generally described in 1855 as follows: “Intersections by line of water objects. All rivers, creeks, and smaller streams of water which the line crosses; the distance on line at the points of intersection and their widths on line” (Bourdo 1956). This wording suggests that channel widths were measured between confining banks perpendicular to flow direction at the crossing point of the section line, but not along the section line (see also Martin and Johnson 1987; Casagrand 2021). Therefore, it was assumed for this study that GLO channel widths were representative of the active channel width perpendicular to flow direction equal to or below the elevation of the bank-full stage but above the low water surface (Knox 1977; Martin and Johnson 1987).

Stream Network Classification

In ArcMap 3.0, the hydrology toolset produced fill, flow direction, and flow accumulation rasters. To build the stream network, a flow accumulation threshold was defined to classify cells with flow accumulation greater than 2 km^2. This threshold was based off the DEM resolution, size of the watershed, and to eliminate topographic effects of roads and other urban features. The stream order tool classified the resulting stream network using Strahler link ordering (Strahler 1957). However, while based on Strahler numbering procedures, the coarse resolution of the base-DEM omits the identification of actual first and some second order stream links as defined by hydro-geomorphic criteria. Probably all first order streams and many second streams will have drainage areas less than the minimum used for order analysis in this study. Thus, stream ordering here is useful for hierarchical classification of channel locations but is not an accurate representation of the true hydrologic network or stream ordering as it undercounts first and second order links (Hughes, Kaufmann, and Weber 2011). All GLO survey sites were attributed by stream order (Table 6).

Distribution of GLO Sites Within Blue River Segments

This study organizes the Blue River watershed into headwater and tributaries, and upper and lower main channel segments by stream order for comparison to the HCEM, which relates specific geomorphic responses to downstream locations in the watershed as broadly evaluated by stream order classification here (Tables 6 & 7). The headwaters main channel segment generally includes the drainage area upstream of the Kansas state line. The upper main channel segment extends from the state line to the confluence of the Indian Creek tributary which also includes drainage from Kansas. The lower channel segment extends from Indian Creek to the mouth of the Blue River. The Brush Creek segment flows into the lower segment of Blue River (Figure 8). The 67 GLO sites assessed for this study were distributed as follows: (i) Headwaters, none (0%); Upper Blue River, 9 (14%); Lower Blue River, 28 (52%); Indian Creek, 15 (22%); and Brush Creek, 15 (22%) (Figure 8) (Table 8).

Channel Width Measurements

Channel widths were determined for GLO sites based on the presence of a measurement listed at a survey crossing line on the map which was verified in field notes by surveyors. The locations of the recorded GLO width sites were then assessed by stream order and river segments (Figure 9). USGS Earth Explorer aerial imagery from 1955 was geo-rectified to the MSDIS 2015 imagery using methodology from Hughes, McDowell, and Marcus (2006). For all three aerial datasets, right and left bank tops were digitized in ArcPro 3.0 at 1:1,000 scale for the entirety of the Blue River and the primary tributaries. Best visual judgement was used to determine the bank tops from the aerials as well as from a LiDAR derived hill shade used to aid in the process. The digitized banks were verified by another worker to precisely decipher the locations of the bank lines. Channel widths were collected from three photo-years and compared to the GLO widths using the same methods for the MSDIS imagery. The survey line grid was overlaid over all aerial datasets, along with the GLO sites, which determined the location of channel widths recorded from 1955, 1995, and 2015. Points were created at each survey crossing line where a channel width was recorded. At selected GLO sites, triplicate measurements of channel width were made at the crossing point and at one channel width both upstream and downstream of the point to assess the effects combined influence of location, channel variability, and photograph data errors on width measurements (Table 9). In first and second order streams the width errors ranged from 0.3-1.8 m in the headwater and tributaries while 3rd order ranged from 1.1—1.3 m in the upper main channel. 4th and 5th order errors ranged from 0.7-1.8 m in the lower main channel segment (Table 9).

Floodplain Soils Assessments

Soil series mapping and field samples were utilized in this study to validate specific sediment and geomorphic characteristics in support of geospatial assessments. Soil series information was available from published USDA county soil survey reports and datasets were downloaded from USDA Web Soil Survey Glossary (USDA 2023). Alluvial soil series were mapped throughout the Blue River watershed which consisted of four primary series which all have A/C profiles along the main channel and its tributaries. Poorly developed soil in this setting may indicate young and recently deposited floodplains composed of post-settlement deposits or legacy sediments overlying buried A-horizons marking the depth of the pre-settlement surface (Knox 1977; Schumm, Michael, and Chester 1984; James 2013; Pavlowsky et al. 2017).

Floodplain Core Analysis. Three deep floodplain sediment cores were collected along cross-valley transects at two sites: Minor Park at R-km 35 and Battlefield Park at R-km 17 (Figures 5 & 9). Additional surface samples and shallow cores were collected from other terrace, floodplain, and bench features at six sites along the upper and lower main channel of Blue River (Figure 9). Sampling sites were selected based on soil mapping analysis and USGS gage station locations to represent a range in channel locations. Topographic surveying and soil sampling along valley transects was performed in December of 2022 using an auto-level and 100 m tapeline. Forty-two Oakfield core sediment samples were collected from 12 coring sites, with the depths ranging from 5 to 270 cm. Samples were collected at each study site on varying floodplain landforms and were labeled and stored in 1-quart freezer bags to be transported to the laboratory at Missouri State University for analysis. The soil samples were dried in an oven at 60 degrees Celsius for 48 hours or until moisture was no longer present and then measured for total mass in grams. Later all 42 samples from 12 cores and two grab samples were disaggregated with a mortar and pestle to allow for them to be properly sieved to <2 mm to separate out fine soils to be used for X-Ray Fluorescence (XRF) and organic matter analysis (Appendix. A, B,C,D,E,F). Hand texturing and Munsell color analysis were completed for all samples following a standard procedure of a feel, squeeze, and ribbon test of moistened soil to determine texture and characteristics for classifying the sample along with Munsell color using hue, value, and chroma (Whiting et al. 2014) (Appendix A).

XRF Analysis. XRF analysis can aid in the stratigraphic analysis of floodplain profiles by correlating metal pollutant peaks in core profiles with the timing of industrial and urban land use development in a watershed (Matschullat et al. 1997; Lecce and Pavlowsky 2001; Owens, Walling, and Leeks 1999; Hennekam et al. 2019). In this study, a handheld Thermo Scientific

Niton XL3t series handheld X-ray fluorescence was used to measure concentration (parts per million) of calcium (Ca), iron (Fe), lead (Pb), and zinc (Zn) in sediment and soil samples (Hennekam et al. 2019). Similar methods were used compared to the Ozarks Environmental Water Resources Institute (OEWRI) and EPA standard methods including, standard, duplicate, and blank measurements that were analyzed after every 10 samples to assure quality assurance and consistency of the results (USEPA 1998; OEWRI 2007). Instrument errors ranged from 259-523 ppm for CA, 312-366 ppm for Fe, 6-9 ppm for Pb, and 14-19 ppm for Zn.

Loss on Ignition Analysis. Loss on ignition (LOI) analysis has been utilized to determine organic matter (OM) within sediments to determine buried soils, sedimentation, and possible sorption capacity (Abella and Zimmer 2007; Downing et al. 2008; Akpomie, Dawodu, and Adebowale 2015). After samples KG1-KG42 were sieved they were analyzed for peaks in organic matter content using OM-LOI OEWRI Standard operating procedures (OEWRI 2019) modified from the procedures published in the Soil Science Society of America Methods of Soil Analysis (Sparks 1996). Each sample was weighed out to approximately 5 g in a pre-weighed crucible. First, oven-fried samples were heated for two hours at 105 degrees Celsius to remove all residual moisture and then cooled in a desiccator before weighing the pre-burn dry mass of the sample. Second, the dry sample was burned at 600 degrees Celsius in a muffle furnace for eight hours to oxidize the organic matter drive off the mass of carbon dioxide. Samples were then cooled in the desiccator and measured for the post burn weight. The final percentage of organic matter was calculated taking the difference of the pre and post burn weights, divided by the pre-burn weight and multiplied by 100 to calculate dried mass lost during combustion.

Flood Records

Annual discharge and peak flood records were evaluated for the USGS gaging station Blue River at Kansas MO (#6893500) at R-km 5 with a period of record since 1939. The records were organized and ranked by highest peak discharge. This was used to calculate the recurrence interval (RI) through division of the rank by the number of records plus one. This is a technique adapted from Karim, Hasan, and Marvanek (2017) for flood frequency analysis used to estimate average interval time between floods of the same magnitude (USGS 1982). The 2 and 10 year recurrence intervals were determined from the median and 90th percentile peak discharges for the Blue River at Kansas MO gage over 30 year time intervals to compare flood magnitude and frequency during the period of record, as these have the most influence over channel width and bank height formation (Wolman and Leopold 1957; Sherwood and Huitger 2005; Wohl 2014).

Historical Land Use

Historical records of agriculture, population, and channel modifications provided the foundation for historical analysis of land use and channel change for this study. Agricultural census data was acquired from the USDA Census of Agriculture Historical Archive (2023). Population data for both state- and county-level data were acquired from the U.S Census Bureau records (2023). Aside from aerial photography datasets, other documents and various sources provided information on land use change and channel modifications in the watershed. This information primarily came from USGS (2007) plans and studies for Blue River and Brush Creek channel modification projects as well as documentation from Albertson (1917), Metcalf (1966), and Driever and Vaughn (1988) on watershed and land use history.

Table 5. Geospatial data used in Blue River watershed analysis.

Data Type	Year	Resolution (m)	Source
LiDAR DEM	2015	1	USGS, MSDIS
Land Use	2019	1	NLCD
Soils	2022	NA	NRCS
1955 Aerial Photography	1955	0.86	EarthExplorer
1995 Aerial Photography	1995	1	MSDIS
2015 Aerial Photography	2015	0.15	MSDIS

Table 6. Total channel length by stream order and sub-watershed.

Segment	1^{st} Order km	2^{nd} Order km	3^{rd} Order km	4^{th} Order km	5^{th} Order km
Headwaters	34	25	15	0	0
Upper Channel	47	20	1.4	25	0
Lower Channel	13	9	0	0	16
Indian Creek	48	31	22	8	0
Brush Creek	43	22	1.4	0	16
Total	185	107	40	33	32
% of Total	47	27	10	8	8

Table 7. Range of drainage areas by stream order.

Stream Order	Drainage Area Range (km^2)
1^{st}	2.0 – 15.3
2^{nd}	7.1 – 61
3^{rd}	32 – 133
4th	193 – 280
5^{th}	>280-694

Table 8. Number of GLO sites evaluated by Blue River watershed segment.

Segment	1^{st} Order Sites	2^{nd} Order Sites	3^{rd} Order Sites	4^{th} Order Sites	5^{th} Order Sites
Headwaters	0	0	0	0	0
Upper Channel	3	1	0	5	0
Lower Channel	4	6	0	0	18
Indian Creek	1	2	6	6	0
Brush Creek	6	8	1	0	0
Total Watershed	14	17	7	11	18
% of Total	21	25	11	16	27

Table 9. Triplicate channel width measurements for the main Blue River channel 2015.

A. Number of sites with triplicate measurements.

Segment	1st Order Triplicates	2nd Order Triplicates	3rd Order Triplicates	4th Order Triplicates	5th Order Triplicates
Headwaters	0	0	0	0	0
Upper Channel	3	0	0	5	0
Lower Channel	0	3	0	0	18
Indian Creek	0	2	2	2	0
Brush Creek	1	6	1	0	0

B. Chanel width measurement errors by stream order.

	1st Order	2nd Order	3rd Order	4th Order	5th Order
Average Width (avg., m)	13.8	16.3	28.4	22.6	27.9
St. Deviation (avg., m)	2.5	1.9	3.1	2.6	2.5
Co. of Var. 1-s (avg., %)	19.2	11.6	10.5	12.3	8.8

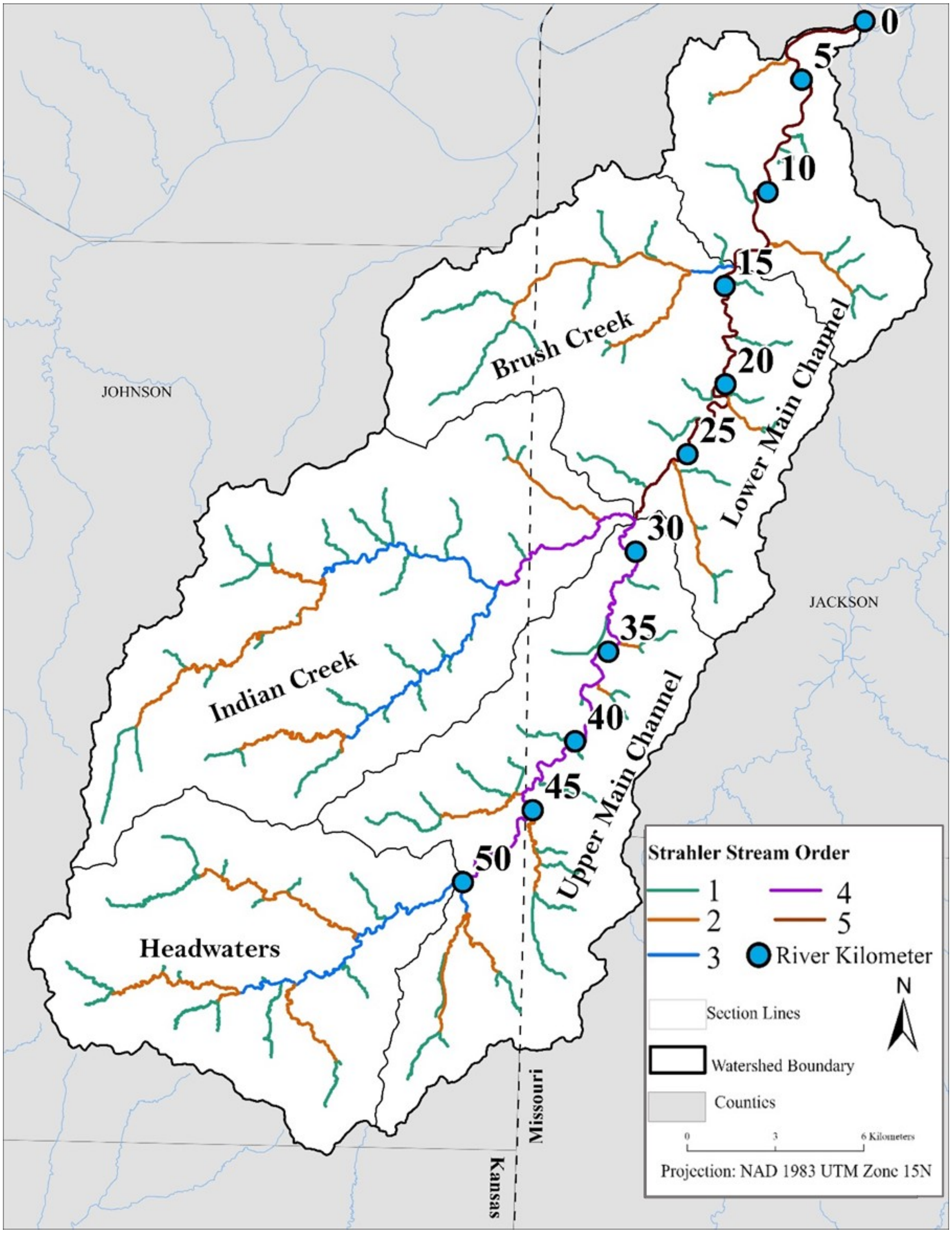

Figure 8. Stream order distribution throughout the Blue River watershed by R-km and subbasin segments.

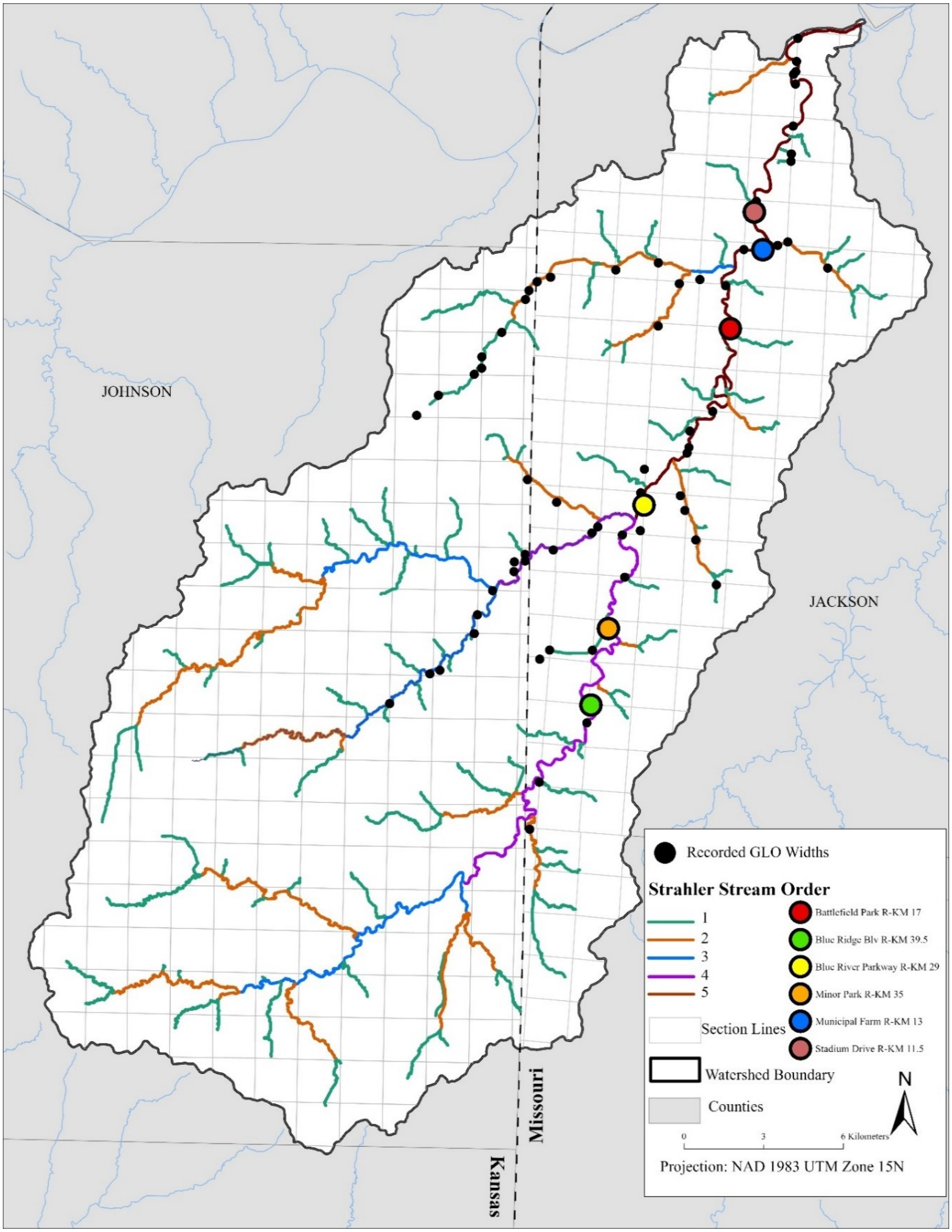

Figure 9. Blue River watershed Strahler stream order with locations of GLO survey and field sites.

RESULTS AND DISCUSSION

Watershed Disturbance History

It is important to review the causes of hydrological disturbance in Blue River before evaluating their effects via channel width changes. There were three main factors that may have affected the flood and sediment regime of the watershed: agricultural expansion, urbanization/industrialization, and channel modifications.

Post-Settlement Agricultural Expansion. Post-agricultural settlement involved early land clearing, logging, and pasture farming practices that potentially contributed to increased runoff, soil erosion, and worsening flood conditions (Wolman 1967; Knox 1977, 1987; Lecce 2013). These practices would be expected to contribute to legacy sediment deposition on the main channel floodplains, possibly narrowing the channel and increasing bank heights in the lower segments of the watershed where increased sediment loads would exceed the transport capacity (James 2013). In this scenario where most of the floodplain features would have been created over the past 150 years, it is expected that floodplain deposits would be little weathered (i.e., young) and poorly developed (i.e., lacking obvious soil horizons) as reported by floodplain soil surveys produced by the USDA for the Blue River for soils along the main channel and tributaries (Figure 4) (Table 3).

Urban Land Development Within the Valley. The impacts of historical post-settlement agricultural activities overlap in time with growing urbanization since the early 1900s in the Blue River watershed. Thus, increased urbanization with the expansion of impervious surface area and drainage systems further contributed to increased flooding and subsequent channel change (Fryirs and Brierley 2012) (Table 4). Urbanization can also decrease sediment loads over time with erosion management practices, concrete armored channels, and increased impervious surfaces (Wolman 1967; James, Lecce, and Pavlowsky 2022). While sediment loads may be reduced, peak discharges are still increased through urban runoff, resulting in channel enlargement through increases in erosion capacity (Fryirs and Brierley 2012). This would be expected to primarily affect the upper and lower segments of the Blue River, where urbanization is more concentrated, drainage systems are more numerous, and channel modifications are more common (Figure 3) (Table 4).

Channel Modifications and Flood Control Measures. In the Blue River watershed, direct channel modifications also exacerbate the effects of historical land use conversion with channel straightening and meander cutoffs further increasing slope and flow velocity (Fryirs and Brierley 2012; Buffington 2012; Bai et al. 2010). The Blue River Channel Modification Project was examined in this study and interpreted as a potential cause of channel width changes. While the project was authorized in 1970, there were no comprehensive records of construction until the 1990s (Table 4). Of the total upper and lower main channel length (50 km), over half (25.5 km) was directly modified by channelization, riprap, or toe protection. Channel straightening was concentrated mostly in the lower 17 km of Blue River which reduced total channel length by 18%, thus further increasing slope, velocity, and both erosion and flooding capacities (Figs. 10 & 11). The modifications, primarily consisting of channel straightening and concrete structures, also extend 20 km up Brush Creek. Additionally, roughly 15 km of the banks of Indian Creek are lined with riprap. The most severe channel modifications were clustered downstream along Blue River near the confluence with the Missouri River and where the highest concentration of urban and industrial development occurs onto the floodplains. Urbanization and industrial development further necessitated measures such as channel deepening and artificial fill on the banks to contain flood waters and prevent channel instability. In attempting to respond to floodplain sedimentation, aggrading channel beds, and reduced channel capacity, historical flood control efforts to encourage or protect developments along the valley floor may have increased the risk of flooding.

Historical Changes in Main Channel Width

Channel Widths have varied significantly over time in the main Blue River channel (Figure 12). While differences of channel widths occurred between 1955, 1995, and 2015 were observable for most sites, the most significant changes occur between GLO widths and the contemporary 1955 channel (Figure 12). From R-km 50 to the upstream extent of the channelization at R-km 20, GLO widths generally range from 30 to 60 m. Lower GLO widths in this portion of the watershed occur at R-km 26, 32, and 44. On average valley widths in these locations narrow by 48% from upstream to downstream. Downstream from R-km 20, GLO widths generally range from 50 to 80 m (Figure 12). In the lower segment of the watershed, valley widths become much wider. However, at approximately R-km 7 where the GLO width significantly narrows, the valley also narrows by about 20% from upstream and downstream. Narrower valley widths in both segments of the watershed may be contributing to the lower GLO widths as a constricted valley restricts channel widening as well as promoting sediment transportation rather than accumulation (Magilligan 1985) (Figure 12).

Triplicate error analysis of width measurements indicated that width ratios probably reflect only a limited influence of measurement error since coefficient of variation (Cv%) values were 19% for 1st, 11-12% for 2nd-4th, and 9% for 5th order sites (Table 9). However, GLO channel widths were typically greater than two-times or 100% of those observed in more recent aerial imagery years (Figure 12). Thus, errors in width measurements were usually <20% of width differences measured between the early 1800s and recent times at GLO sites (Table 9).

Width Changes from Early 1800s to 1955. Width ratios from the early 1800s to 1955 indicate significant narrowing trends along the lower segment and some of the upper segment of the main channel (Figures 12 & 13). On average for the 19 GLO sites below R-km 39, the channel decreased by 33 m or by 47% (Figs. 12 & 13). Channel narrowing along the lower Blue River may be due to floodplain sedimentation, channel-infilling, transformation from a multi-threaded to single channel, or human intervention with channel modifications (Knox 1977, 1987; Lecce and Pavlowsky 2001; Gendaszek, Magirl, and Czuba 2012; Lecce 2013). Few modifications occurred to the channel prior to 1955, with documentation of major construction taking place after 1980 (Driever and Vaughn 1988; USGS 2007). While urban developments including in-filling were probably present in the river valleys before 1955, it appears that width changes from before this time were not related to widespread flood control measures or channelization. The large differences in channel widths from GLO surveys to 1955 were not due to measurement errors due to township and range section line orientation on the channel crossing (Figure 12). A measurement of 84 m was recorded from a section line crossing perpendicular to the channel at R-km 8.5 while a parallel crossing measurement upstream at R-km 9 was similar at 74 m. Further upstream another parallel crossing measurement was recorded at R-km 15.5 as 57 m while at a perpendicular crossing at R-km 17 it was 56 m (Table 10).

Width Changes from 1955 to 1995. Width ratio trends for 1955 to 1995 indicate both widening and narrowing along the main channel (Figure 14). Little to no change is observed above R-km 27, as the historical channel response has slowed and extended downstream (Knox 1977). There is an increase of 20-50% from R-km 27 to 17 and a decrease by 25-45% from R-km 17 to 8. Generally, little change was present from R-km 8 to the mouth of the Blue River (Figure 14). Past research demonstrates disturbances that increase runoff and alter channel form typically result in channel widening (Knox 1977; Hession et al. 2003). However, by 1983, channel straightening, clearing, and deepening had already occurred below R-km 17.5 to the mouth of the river, suggesting these modifications may have contributed to the decrease in channel width seen between R-km 17 and R-km 8 (Table 4). Below Brush creek to R-km 17, decreasing channel slope below a knickpoint may have contributed to the channel widening (Figure 5). The lack of changes below R-km 8 also suggest that severe channelization in the lower main channel, as well as bank armoring, may be acting as a control on channel widening and possibly result in excess stream power from runoff contributing to erosion and flooding problems in the lower segment and where base control is also provided by the Missouri River (Pryor et al. 2014; Heimann, Holmes, and Harris 2018).

Width Changes from 1995 to 2015. Width ratio trends from 1995 to 2015 primarily indicate widening throughout the entirety of the main channel (Figure 15). The most extreme widening between 1995 and 2015 was recorded primarily along the upper main channel from R-km 25 to 40 by an average of 3 m. Above Brush Creek the channel widens by 1.2-1.4 times since 1995. However, below R-km 25 changes in width decrease where channelization has occurred most severely in the watershed, most likely due to design specifications such as bridges, concrete structures, and riprap that stabilize the channel and decrease the rates of width change. In the upper main channel where direct modifications were infrequent, channel widening may have occurred in accordance with the expected response to historical land use conversion widening trends, and contemporary increases in impervious surfaces and runoff (Wolman 1967; James, Lecce, and Pavlowsky 2022).

The influence of channelization can be observed between 1995 and 2015, with channel straightening and meander cutoffs that have been documented as part of the Blue River Channel Modification Project (Figure 10). One of the results from the observed channel straightening and meander cutoffs is the decrease in total main channel length by 11 km from 1955 to 2015, 8 km of which occurred during the period of 1995 to 2015 (Figure 11). Reduction in channel sinuosity as well as length have implications for erosion and flooding, as channel slope may be steeper which contributes to higher stream power, flow velocity, shear stress, and erosion capabilities which may have contributed to the consistent widening trends observed from 1995 to 2015 (Figure 15).

Summary of Main Channel Width Changes. GLO widths were about two-times larger compared to present-day widths along the main channel of the Blue River (Figure 12). However, contemporary width trends indicate some widening since 1955 and more extensive widening since 1995 (Figure 13, 14, 15). Historical narrowing of the channel may have occurred as a response to increased erosion and sediment loads after agricultural expansion which would have filled in the valley and created wider floodplains (Knox 1977; Lecce 2013). Later urbanization in the watershed would have increased runoff and stream power, contributing to the contemporary widening trends observed after 1955, which were later exacerbated by channel modifications. Further, soil conservation practices implemented in the 1930s may have also reduced sediment loads to decrease channel and floodplain sedimentation rates. However, the lack of width changes in the lower main channel below R-km 8 could be expected given the degree of channelization and modifications concentrated in the lower main channel prior to 1995 which may have been designed to a standard width and thus prevented from further adjustments. The widening observed from 1995 to 2015 may be due to channel erosion caused by urban runoff.

Gendaszek, Magirl, and Czuba (2012) found similar patterns of increased stream power in an urban watershed causing the widening of a previously narrowed channel with some reaches restricted from width adjustments by bank armoring and channelization. However, increased runoff due to greater rainfall intensity caused by climate-driven floods may also account for recent channel widening trends (Heimann, Holmes, and Harris 2018).

Historical Changes in Width for the Channel Network

Historical width changes occurred within the entirety of the Blue River watershed at all GLO sites. Evaluating the degree of width adjustment by stream order classes is an effective way to evaluate the influence of watershed scale on geomorphic processes and to organize channel changes using a channel evolution model (Cluer and Thorne 2013) (Figure 16) (Table 6 & 8). From the GLO survey to 2015, channel widening occurred in 1^{st}-3^{rd} order streams and then the trend transitions to channel narrowing downstream in 4^{th}-5^{th} order streams (Figure 17). Compared to average GLO widths**,** average channel widths in 2015 were found to be 25 m (291%) wider in first order streams (all sites widened) and 28 m (47%) narrower in fifth order streams (all sites narrowed) (Figure 17). In contrast to contemporary widening trends of to 50% increase since 1995, the main channel of Blue River showed significant narrowing with mean change ratios of 0.9 for 4^{th} and 0.5 for 5^{th} order channels from pre-settlement conditions to 2015. This watershed scale trend of channel enlargement upstream and channel narrowing along the lower river segments generally follows that expected according to the HCEM (Knox 1977; Lecce 2013) (Figure 1).

Increased runoff due to soil and vegetation disturbances during agricultural development may have caused incision, head-cutting, and headward extension of the channel system (Simon and Hupp 1986). While channel modifications and urbanization may have resulted in some narrowing in the lower main channel, mean width change ratios indicate significantly wider middle segment channels compared to contemporary. This suggests the conversion from a historically wide, multi-threaded riparian wetland channel to a single channel form. This geomorphic transition would have required extensive historical lateral or vertical accretion to fill in the wide channel and raise bank heights (Knox 1977, 1987; Lecce 2013). Additional aggradation in the lower segment could also have resulted from baselevel control from the Missouri River as well as increased historical flooding with higher sediment loads (Yanites and Tucker 2010).

Historical Post-Settlement Deposition on Floodplains

Soil surveys and channel narrowing trends suggest that historical floodplain sedimentation may have infilled wetland areas, raised bank heights, and generated a single-channel form in the Blue River (Wolman 1967; Knox 1977; Knox 1987; James 2013). This suggested increase floodplain sedimentation rates and landform development is indicated by lower channel GLO width ratios for all recent aerial datasets. To further evaluate the presence of legacy sediment deposits along the Blue River, floodplain cores were collected from two sites: one along the lower segment of the main channel below Indian Creek and the other along the middle segment above Indian creek (Figure 9, 18, 19). Soil characteristics were evaluated at approximately 30 cm intervals including texture, Munsell color, OM%, and trace metals (Table 11, 12). The objective was to directly evaluate soil development, look for buried A-horizons, and examine if industrial enrichment of Pb, Zn, and Ca had occurred above expected pre-settlement floodplain surfaces.

The MP1 core is located the farthest upstream above Indian Creek at R-km 35 (Figure 9). While the left bank of the channel is confined by a steep bluff, past the right bank is a wide floodplain sloping downward from a levee, near where the core is located (Figure 18). Surface soil samples indicate average Munsell color and texture as “very dark clay” silty clay loam (Appendix. A). The shift in Munsell color and texture from silt loam, “very dark clay” at a depth of 120 cm to “black” silty clay loam at the depth of 150 cm suggests a possible buried A-horizon (Table 11) (Appendix A). The historical C horizon deposit above 150 cm and below the surface samples was silt loam “very dark grey”. The MP1 core did not show metal a enrichment trend above the possible Ab horizon. With urban and industrial development concentrated in the lower main channel segment, it can be assumed that the upstream location of the MP1 core was not affected significantly by industrial and urban inputs.

Another floodplain site with similar elevation and depositional setting was evaluated near the MP1 site. A cut-bank was observed near Red Bridge at R-km 34 which visually indicated a possible buried A-horizon since a darker and more cohesive unit was present below 100 cm from the top of the bank (Figure 19). Samples were taken from both above and below the possible buried A-horizon. The top sample had higher levels Zn (88 ppm vs. 84 ppm), Pb (32 ppm vs. 15 ppm), and Ca (18,128 ppm vs.7,210 ppm) (Table 12). This floodplain site would have been within 30 m of a relatively important road since the late 1800s, thus the elevated Pb concentrations could have come from exhaust emissions from the burning of leaded gas and higher Ca concentrations from gravel and paved road wear. The anthropogenic record at this site was further supported by glass and construction waste found embedded in the top layer, all of which suggest post-settlement sedimentation above a pre-settlement floodplain surface.

The BP1 and BP2 cores are located downstream of Indian Creek along the main channel which may have been affected by excavations for sewer line installation and toe and bed stabilization structures. Further, an elevated floodplain feature occurred along the transect that may possibly be a fill pile. The left bank of the channel is confined by a steep bluff (Figure 20). In the BP1 core, closest to the right bank, surface soil samples indicate average Munsell color and texture as “very dark gray” silty clay loam and C horizon as “dark grayish brown” (Appendix. A). At a depth of 228 cm, the shift in color from “dark brown” to “very dark gray” could indicate a possible buried A-horizon. In the BP1 core, Zn, Ca, and Pb increase above 150 cm (Figure 21). The presence of a possible buried A horizon can be interpreted from this inflection since legacy sediments would not be expected to be enriched by urban and industrial sediment and pollution (Lecce 2013; James, Beach, and Richter 2020). The BP2 core showed similar trends in color and texture, with a shift from “very dark gray’ silt loam, a possible buried wetland soil, to a “dark brown” silt loam at 190 cm (Figure 21).

Munsell color and texture differences between surface A horizons, historical C horizons, and possible buried A-horizons support the presence of legacy sediment deposition. Darker and grayer shifts in soil colors were found at depths of possible of buried A-horizons in the floodplain profiles. Anthropogenic Zn, Ca, and Pb enrichment above these depths further indicated increasing sedimentation rates during the urban and industrial development periods. While shifts in soil color and texture support the presence of buried A horizons, the lack of highly contrasting darker colors may be due to weaker soil development on a low relief wetland area composed of sand and shifting channel threads (James, Beach, and Richter 2020). More research on historical sedimentation and sediment storage in the Blue River watershed may help better understand processes involved with historical channel response, legacy sediment deposition, and how past disturbances may be affecting water quality and sediment loads today.

Flood History

Analysis of flood hydrology in the Blue River watershed was conducted using the oldest running USGS monitoring station in the watershed beginning in 1939, with a drainage area of 487 km^2. The maximum annual discharge is 1,243 m^3/s and the minimum is 21 m^3/s. In the Blue River watershed, the 2 and 10-year recurrence interval (RI) floods have increased by 19% and 16%, respectively, between 1960-1989 and 1990-2020 (Figure 22). Channel area and bank height typically form to the size of the bankfull flood with a recurrence interval of approximately 1-2 years (Wolman and Leopold 1957; Sherwood and Huitger 2005; Wohl 2014). This hydrogeomorphic analysis indicates that the channel-forming discharge has increased recently, thus supporting the finding of contemporary channel widening because of increased runoff and stream power on channel erosion. However, the additional influence of decreased sediment loads from soil erosion cannot be dismissed (Juracek and Fitzpatrick 2021). Furthermore, while the analysis here evaluated the annual maximum series, the relationship to recent changes in the partial duration series was not investigated. Partial duration analysis accounts for the frequent, low magnitude floods that generate channel erosion and account for a large portion of the annual sediment load but occur at stages below the annual maximum flood (Karim, Hasan, and Marvanek 2017). While this analysis cannot account directly for the specific flood and erosion impacts discussed, it does give insight into the potential cause of channel erosion and observed widening due to the recent increase in flood magnitude and frequency. Floods can also become more frequent or intense due to climate change effects thus maintaining the channel erosion trend in the future (Juracek and Fitzpatrick 2021).

Since the 1970s, climate change effects have contributed to increased flooding with increased rainfall frequency and intensity in the Ozarks, and most likely the Central Osage Plains region of the Blue River (Demaria, Palmer, and Roundy 2016; Pavlowsky, Owen, and Bradley 2016; Byun, Chiu, and Hamlet 2019; James, Lecce, and Pavlowsky 2022). The increased rainfall precipitation has also increased flood magnitude and frequency in many Ozark rivers (Heimann, Holmes, and Harris 2018). So, it is probable that along with land use impacts, climate change has also contributed to erosion and flooding issues within the watershed since the 1970s, primarily in the lower main channel. The increased flood depths and frequencies due to these factors would be expected to cause channel area enlargement, which is evident in the widening trends of the Blue River since 1955 (Wolman and Leopold 1957; Wolman and Miller 1960; Dunne and Leopold 1978; Castro and Jackson 2001; Wohl 2014). More frequent and intense floods also increase erosion rates and contribute to these widening trends through increased velocity, stream power, and reduction of riparian vegetation with urban land use conversion (James 2013; Pavlowsky, Owen, and Bradley 2016; Pavlowsky et al. 2017).

Geomorphic Processes Leading to Channel Change

Incision and Widening in the Headwaters. Bankfull widths have increased in the Blue River watershed headwaters and tributaries since the early 1800s in response to historical agricultural land use conversion and has continued to widen from 1955 to 2015 due to urbanization and channel modifications. In response to increases in magnitude and frequency of post-agricultural settlement flooding, these first and second order streams, comprised primarily of the headwaters and tributaries, experienced headward erosion and incision that first deepened and then widened the channel (Schumm, Mmichael, and Chester 1984; Cluer and Thorne 2013). Lower tributary and upper main channels, comprised primarily of third order streams, have become straighter, and subsequently steeper and wider with increases in stream power resulting in increased runoff and the capacity of the river to transport sediment downstream. Knox (1977) and Lecce (2013) both found the same post-settlement channel conditions in headwater and tributary streams, where agricultural land use increased the width to depth ratio of the channels in these reaches. Increased channel width, usually more pronounced on channel beds in direct contact with bedrock, became wider and shallower with increased transportation of bedload sediment post-agricultural settlement (Knox 1977). Lecce (2013) also found considerable increases in channel width post-settlement being highest in the headwaters and tributaries and decreasing downstream.

Narrowing and Deepening in the Middle Segments. The channel widening trends observed in the headwaters and tributaries follows HCEM assumptions. However, changes in the middle segments indicate a decreasing widening rate downstream and ultimately a narrowing trend in the main channel compared to GLO surveys. Historical narrowing generally occurred as the result of both increased sediment loads and decreasing transport capacity downstream as channel gradient decreases and Blue River approaches the base level of the Missouri River. Riparian vegetation and soil disturbances as well as upland cultivations increased runoff and probably downstream stream power in headwaters and tributaries during the post-settlement period. These changes resulted in the conversion of a wide, multithreaded wetland channel system to a deeper single threaded channel in the upper main channel (Gendaszek, Magirl, and Czuba 2012). Increased sediment from erosion was transported and deposited from overbank floods as legacy sediment, raising the bank heights, and filling in lower wetland areas near the channel. As the channel would have further eroded and laterally migrated in lower stream orders, higher stream order channels would narrow and possibly aggrade with increased suspended sediment loads and higher rates of overbank sedimentation. However, after 1955 or 1995, along with increased urban runoff, direct channel modifications utilized to prevent channel erosion and flooding may now be enhancing channel bed and bank erosion rates and remobilizing stored legacy sediment (Rhoads, 2003).

Lower Main Channel Alluviation. Historical narrowing of the main Blue River channel can be attributed to alluviation in response to higher suspended sediment loads, decreased slopes downstream, and floodplain construction and artificial infilling (Knox 1977, 1987; Lecce and Pavlowsky 1977, 2001; Lecce 1997, 2013). Channel widening has occurred since 1955 in response to additional stormwater discharges and related flooding due to increasingly more impervious areas and, potentially, higher rainfall intensity. Increased flood risks were mitigated by anthropogenic modifications to the channel to prevent channel erosion and flooding in the increasingly populated and urbanized portions of the watershed. In accordance with this pattern, urban soils are mapped in the valley floor for most of the lower main channel below Indian Creek (Figure 4). This further suggests the use of artificial fill to try and raise bank elevations above flood stages in response to the effects of post-settlement agricultural land use conversion. In the lower channel valley bottoms, the presence of urban soils supports the idea that artificial fill overlies legacy sediment on the banks. Thus, the additional fill may have made flood problems worse. Recent increases in valley floor obstructions by artificial fill and structures had the consequence of further increasing flood heights and worsening conditions. Thus, progressively more fill was required to continually raise bank elevations to meet the worsening floods, which was then exacerbated by growing urbanization (Pryor et al. 2014; Pavlowsky, Owen, and Bradley 2016; Heimann, Holmes, and Harris 2018). This cycle of increasing flood response and anthropogenic modifications prompted a large-scale channelization project to enlarge the channel and reduce flood stages to avoid flooding of urban and industrial development due to aggradation, artificial fill, and ongoing urbanization.

Development of a Historical Channel Evolution Model

The findings of this study are generally supported by the HCEM developed in the Driftless area in Wisconsin (Knox 1972, 1977, 1987; Lecce 1997, 2013; Lecce and Pavlowsky 1977, 2001). However, more recent channel modifications and urbanization in the Blue River watershed have resulted in contemporary channel conditions and problems in the lower main channel not typical of other studies—thus this study adds a new component to the model involving more recent human disturbances of floodplains. The consistency between the original HCEM model and the Blue River watershed from this study are most clearly observed in headwater and tributary widening (Figure 16,17). Increased channel capacity in response to post-settlement agricultural activities increased sediment loads to the lower gradient downstream channel and most likely resulted in significant rates of overbank sedimentation and legacy deposits downstream (Schumm, Michael, and Chester 1984) (Table 11). However, significant urbanization, channelization, and artificial fill in the Blue River valleys have resulted in channel confinement, flooding, and erosion issues not typical of contemporary channels in the agricultural regions where the original historical channel response and HCEM studies were completed. While a trend of widening since 1955 is present, channel confinement and increased bank heights below Indian Creek have further decreased flood capacity, already lessened by historical agricultural settlement period activities (Figure 13). With increased precipitation in the Ozarks due to climate change and significant urbanization and impervious surface in the watershed, decreased flood capacity has limited the ability of the channel to widen in response, leading to documented worsening erosion and flooding problems (Figure 22).

A GLO survey quote from the notes by a field surveyor at R-km 17 along the Blue River suggests a geomorphic shift from a wide, shallow, multi-threaded system to a narrower, deeper, single-channel stream. This lends support to the idea of legacy sediment deposits filling in the valleys and narrowing the main channel width (Figure 19, 23). The quote is as follows:

> Edge of high bank on the island… enter a low boggy place… the greater part of the island connects to a sand bar, the greater part of which has not been covered by water within the last two years. The main island is high, level, and has not been overflowed, from the best information I could gain, since 1851. Soil rich sandy bottom, fit for cultivation. – 1856. (Vol. 277).

The location described above is at the Battlefield Park site evaluated by this study. This today is occupied by a single incised channel, with a bedrock and rocky bed, relatively wide and high floodplain overlain with possibly >1.5 m of legacy sediment, and lacking "islands" and "boggy places".

While developed in the Upper Midwest, the HCEM presented here may have applications for other watersheds beyond the Blue River, making further contributions this topic for understanding the variations in geomorphic response in river systems due to human activities. This study expanded upon the general agricultural disturbance response model to suggest a historical channel change for Blue River from a multi-threaded, wetland channel system to a single channel primarily through legacy sediment as described in previous studies in the eastern US (Jacobson and Coleman 1986; Walter and Merritts 2008). Further, beyond the hydrological disturbance of agricultural settlement, the impacts of historical valley in-filling for land use development and more recent channel modifications for flood and erosion control may have contributed to channel form adjustments and increased flood risk along lower Blue River as well. However, the degree of channelization influence on geomorphic behavior is not yet clear and the timing of when historical aggradation may have occurred before urban and industrial expansion onto the filled valley is not well understood. Nevertheless, this study suggests that watershed scale changes in the Blue River system have occurred by both indirect and direct disturbances and showed that historical and present-day channel morphology has adjusted to anthropogenic factors. Further, these types of river changes may be inferred to have occurred for other rivers with similar geology, climate, and land use history. While the effects of climate change on floods to date may be inconclusive, these results suggest the interaction of increased flood frequency and magnitude coupled with urban development has contributed to channel instability. In this way, it is essential to further understand how both land use and climate change effects have influenced channel evolution and may continue to do so in the future.

Table 10. Historical widths for the main channel of Blue River.

R-km	GLO Width (m)	1955 Width (m)	1995 Width (m)	2015 Width (m)
3	65.4	33.5	33.3	44.0
4	73.6	23.0	64.9	66.4
4.5	82.9	19.4	63.7	63.7
5	65.2	22.2	33.2	29.0
7	49.7	25.3	23.1	27.2
8.5	84.1	27.5	19.8	21.6
9	73.6	30.3	22.7	23.1
11	65.4	29.7	20.2	26.5
12.5	60.4	28.7	18.6	24.1
13.5	51.9	23.8	17.4	16.8
15.5	56.9	14.3	9.6	12.9
17	56.3	10.7	14.9	23.6
23	46.1	11.2	12.2	19.7
24.5	54.3	15.8	23.5	22.9
26	30.2	16.0	21.3	19.2
26.5	30.2	16.4	19.8	26.1
28.5	63.2	16.9	16.3	22.8
30	45.1	15.3	13.0	16.1

Table 10-Continued. Historical widths for the main channel of Blue River.

R-km	GLO Width (m)	1955 Width (m)	1995 Width (m)	2015 Width (m)
32.5	28.2	16.4	15.4	24.5
39	10.1	15.8	14.2	12.1
40	60.4	19.7	21.3	28.3
44	10.1	13.7	15.1	19.2

Table 11. Munsell color and texture for sediment cores where possible buried A horizons occur.

Core	Min Depth	Max Depth	Hand-Texture	Munsell Color Name
MP1	90	120	Silt Loam	Very Dark Clay
MP1	120	150	Silty Clay Loam	Black
BP1	194	228	Silt Loam	Dark Brown
BP1	228	256	Silty Clay Loam	Very Dark Clay
BP2	162	190	Silt Loam	Very Dark Gray
BP2	190	228	Silty Clay Loam	Dark Brown

Table 12. Oakfield probe sediment core samples from Blue River watershed.

Core Location	R-km	Core Number	n	Max Depth (cm)	Pb (ppm) Mean Range	Zn (ppm) Mean Range	Ca (ppm) Mean Range	Fe (ppm) Mean Range
Municipal Farm	13	MF 1	2	30	28 (27-30)	115 (93-138)	18,849 (18,435-19,265)	17,974 (17,531-18,417)
Municipal Farm	13	MF 2	3	48	27 (25-28)	123 (104.4-136)	15,825 (12,793-18,795)	17,274 (16,938-17,575)
Municipal Farm	13	MF 3	1	10	22	122	10,890	14,154
Municipal Farm	13	MF 4	1	10	33	146	18,261	18,834
Municipal Farm	13	MF 5	1	10	29	145	18,722	16,804
Municipal Farm	13	MF 6	2	70	28 (27-29)	129 (123-136)	13,353 (12,997-18,723)	19,933 (19492-20,374)

Table 12- Continued. Oakfield probe sediment core samples from Blue River watershed.

Core Location	R-km	Core Number	n	Max Depth (cm)	Pb (ppm) Mean Range	Zn (ppm) Mean Range	Ca (ppm) Mean Range	Fe (ppm) Mean Range
Minor Park	35	MP 1	9	270	19 (15-25)	90 (81-100)	7,426 (6,321-8,966))	18,789 (16,914-20,109)
Minor Park	35	MP 2	2	160	24 (15-32)	86 (84-90)	12,669 (7,210-18,128)	16,129 (15,377-16,882)
Battlefield Park	17	BP 1	9	270	22 (13-36)	89 (68.7-121.7)	6,693 (4,887.7-9,583.8)	17,503 (15,4544-18,936)
Battlefield Park	17	BP 2	8	258	24 (15-37)	101 (95.3-111)	6,823 (5,559-8,838)	17,819 (15,266-19,896)
Battlefield Park	17	BP3	4	128	22 (16-31)	93 (84-105)	6,356 (5,715-7,237)	17,115 (15,920.2-17,840)
Red Bridge	35	RB1	2	160	23 (15-32)	86 (84-88)	12,669 (7,210-18,128)	16,129 (15,377-16,882)

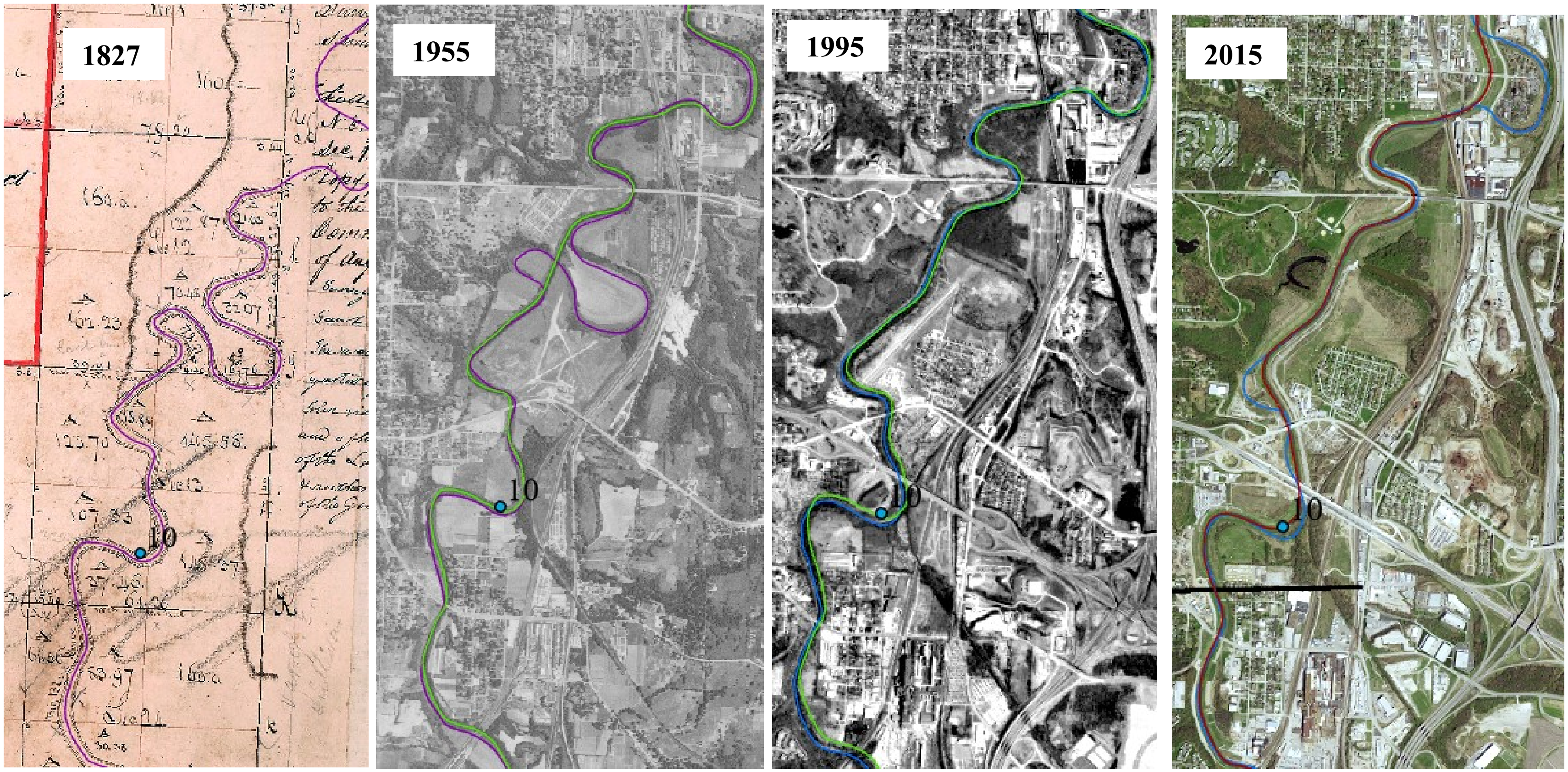

Figure 10. Historical planform comparison near R-km 10. Between 1827 and 1955, meander cutoffs and channel straightening were observed from R-km 8. Few changes in planform are present between 1955 and 1995 in the lower main channel. However, the influence of channelization can be observed between 1995 and 2015, with channel straightening and meander cutoffs that have been documented as part of the Blue River Channel Modification Project.

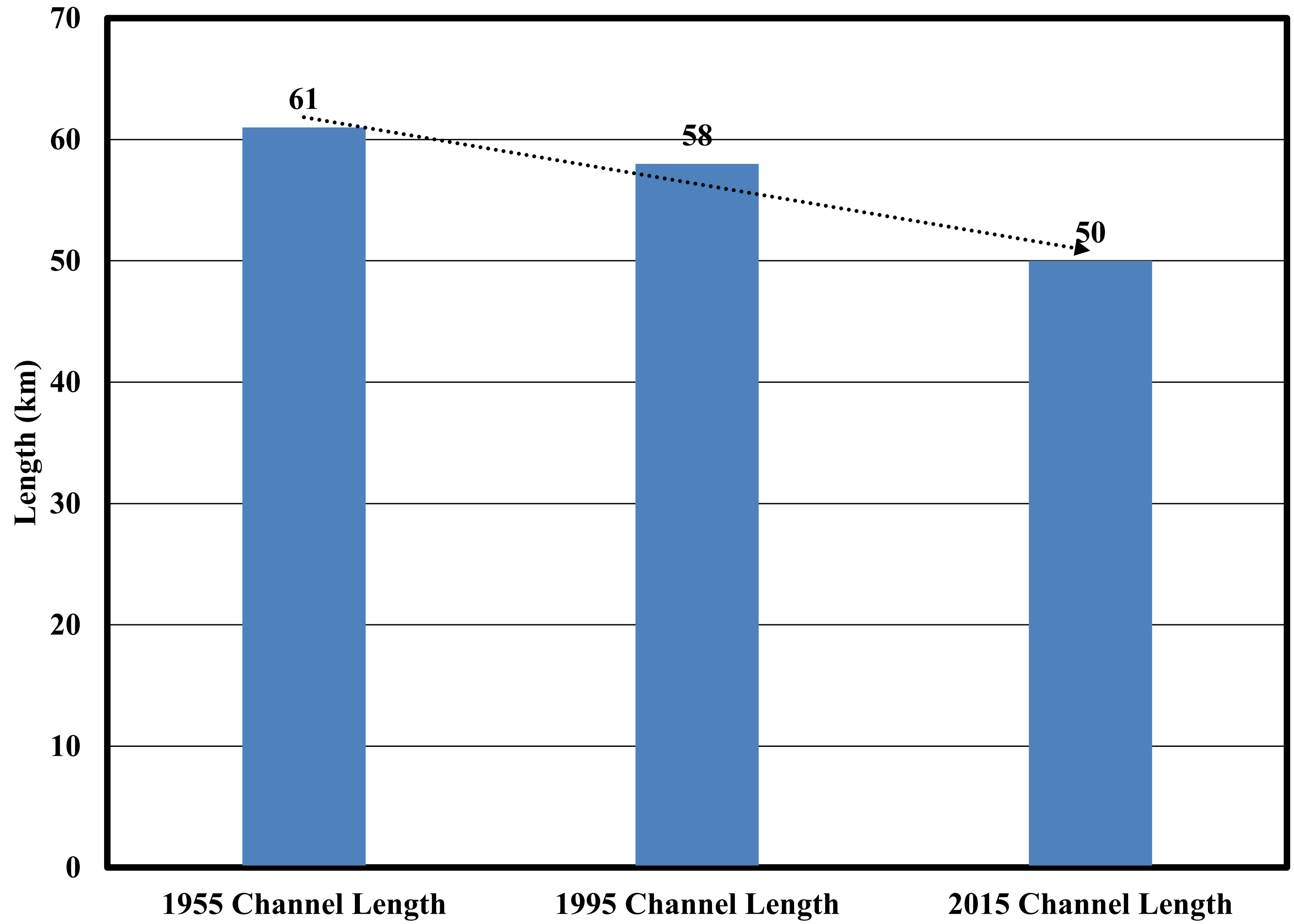

Figure 11. Historical reduction in main channel length by 18% due to flood and channel erosion control measures. Channel length decreased by 5% between 1955 and 1995 and 14% more between 1995 and 2015.

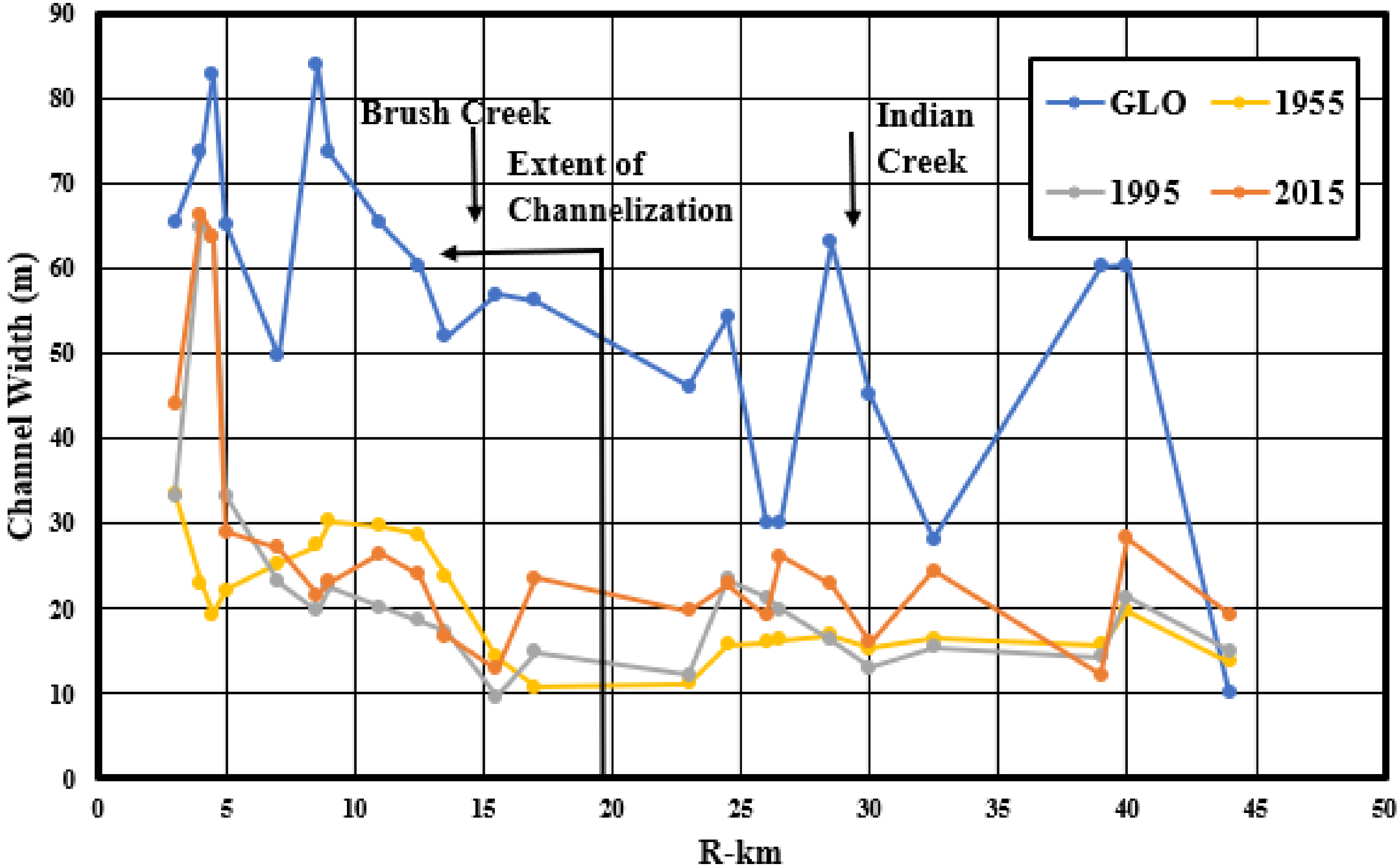

Figure 12. Main channel width measurements from the GLO survey and 1955, 1995, and 2015 aerial photographs.

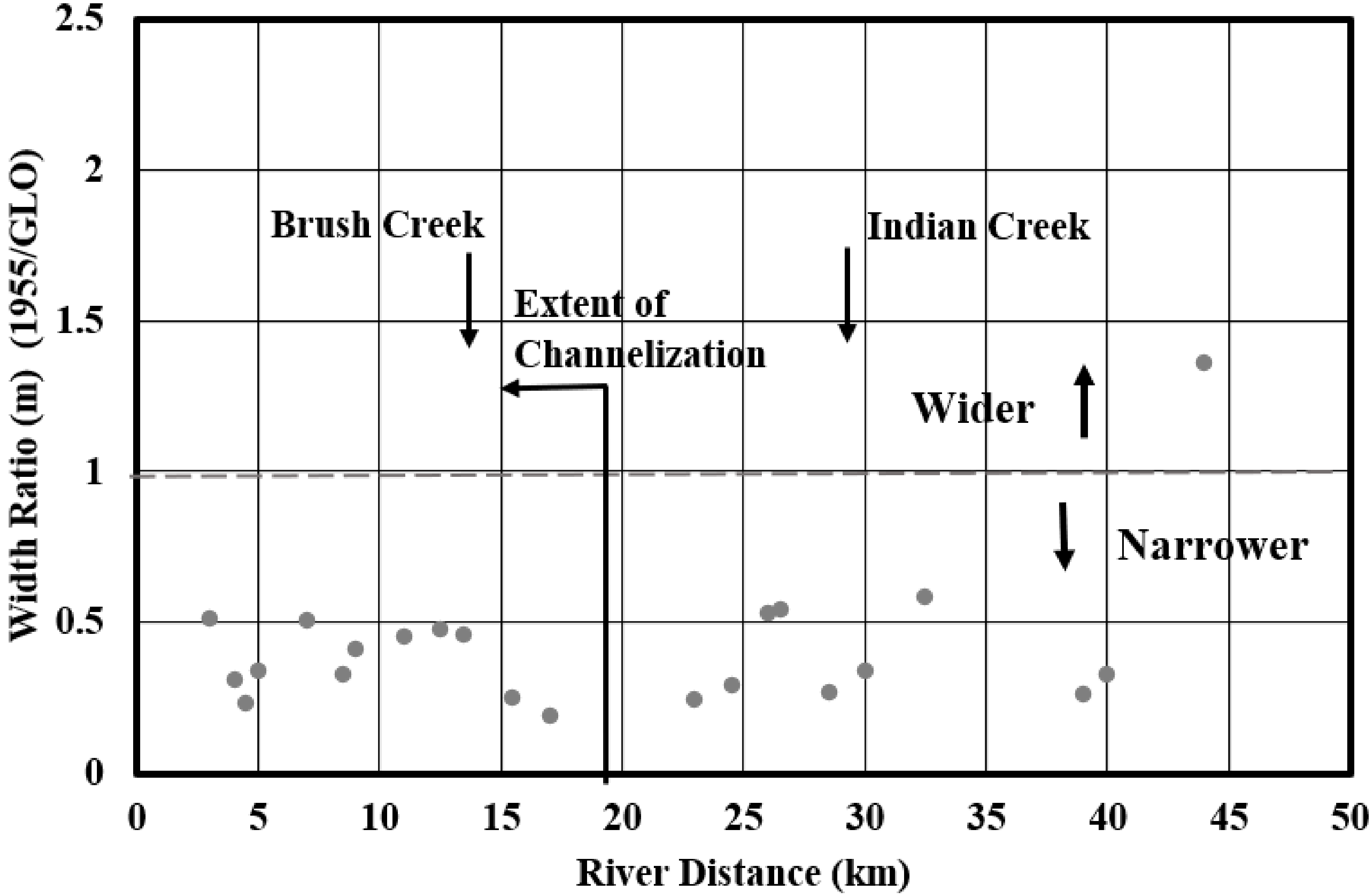

Figure 13. Channel width ratios by R-km comparing GLO and 1955.

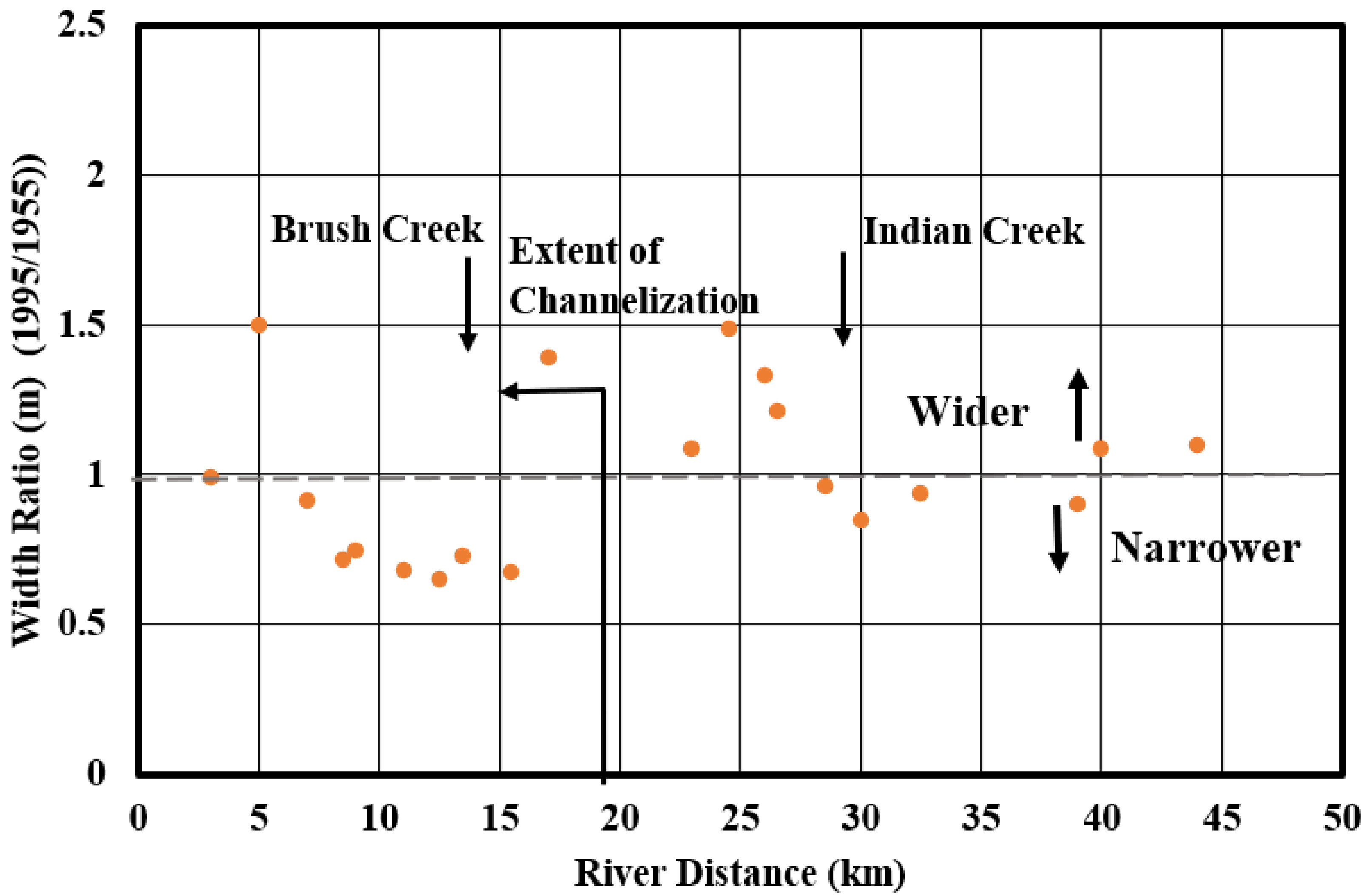

Figure 14. Channel width ratios by R-km comparing 1955 and 1995.

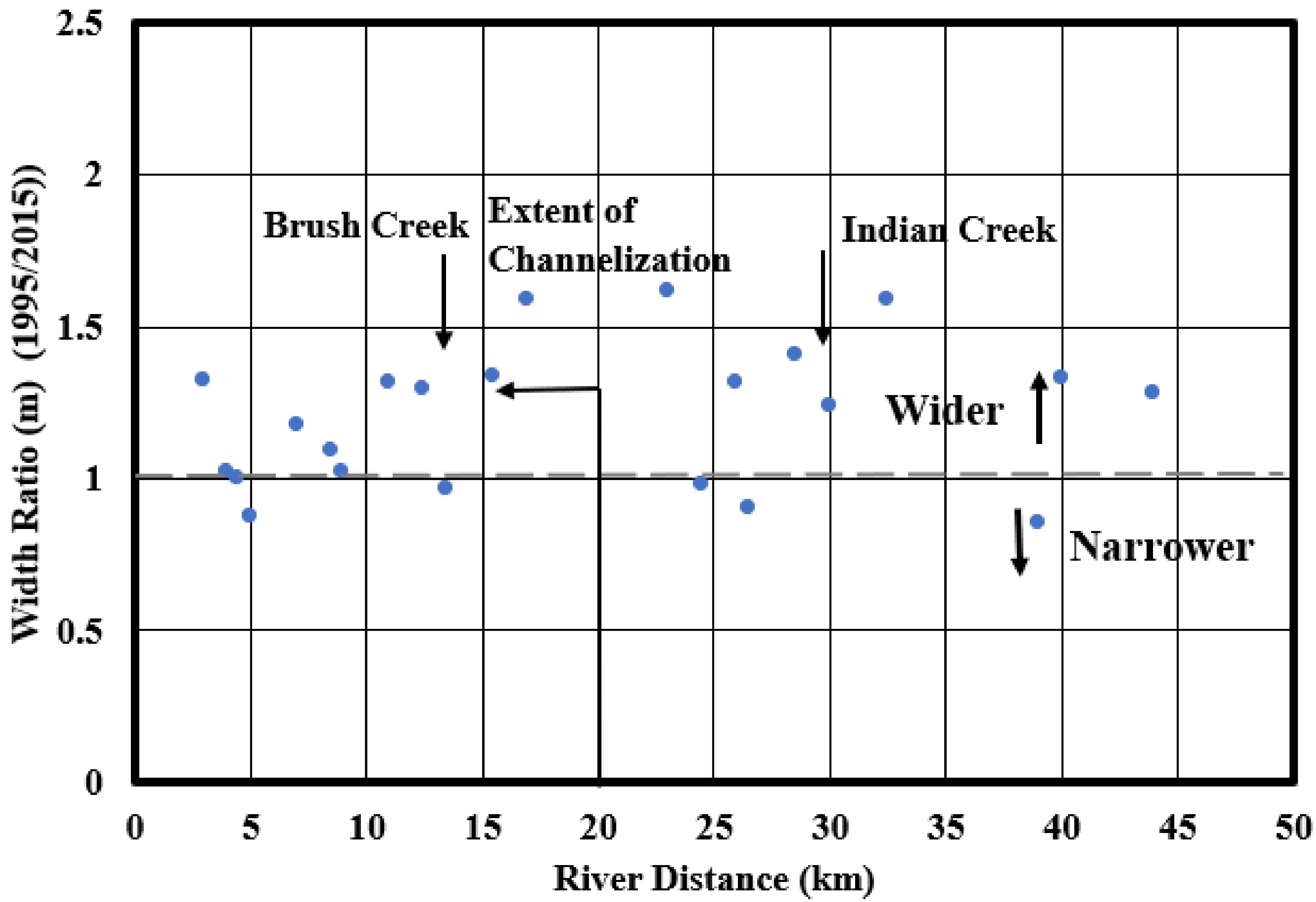

Figure 15. Channel width ratio by R-km comparing 1995 and 2015.

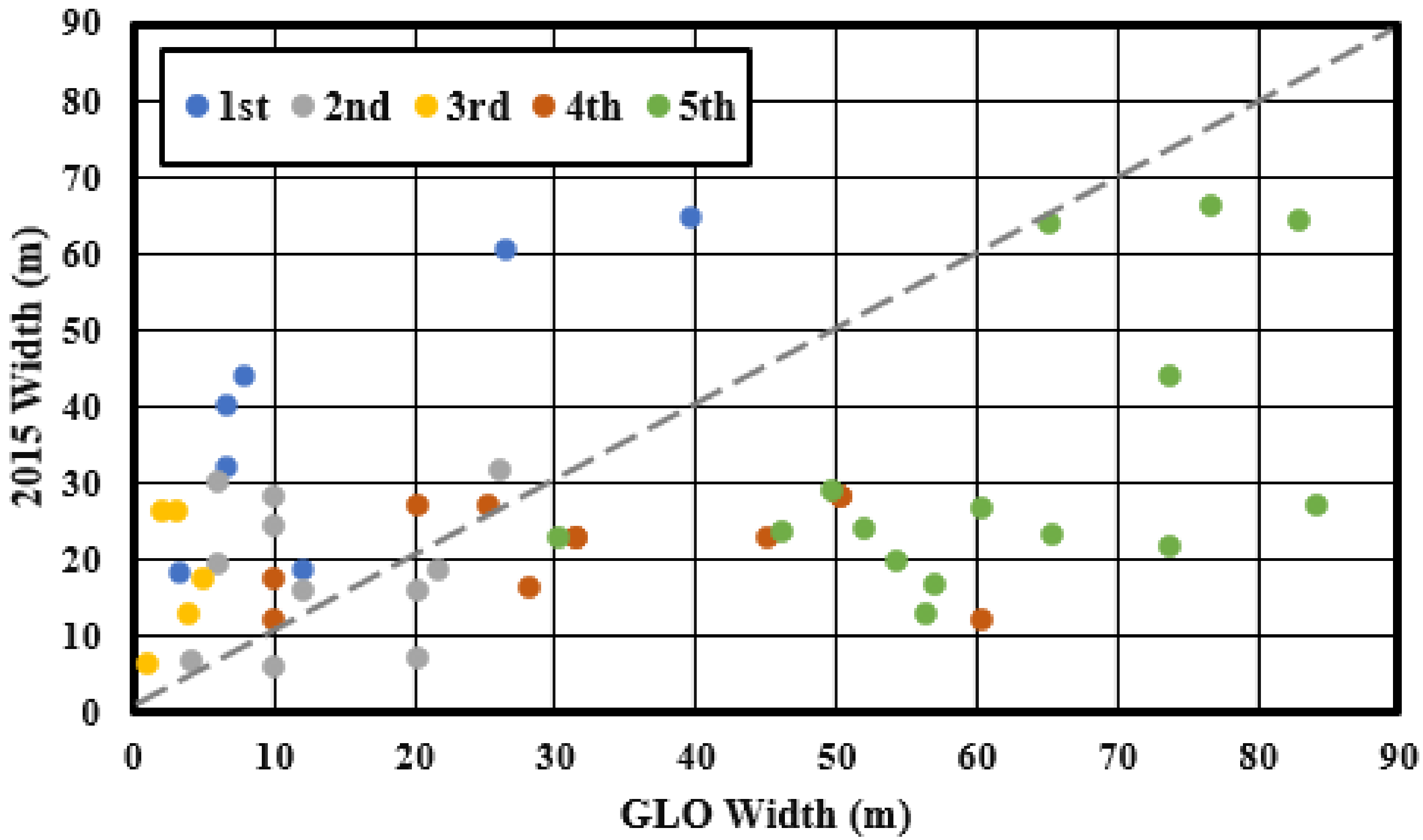

Figure 16. Relationship between GLO and 2015 channel widths for all GLO sites by stream order. Trendline indicates a 1:1 relationship.

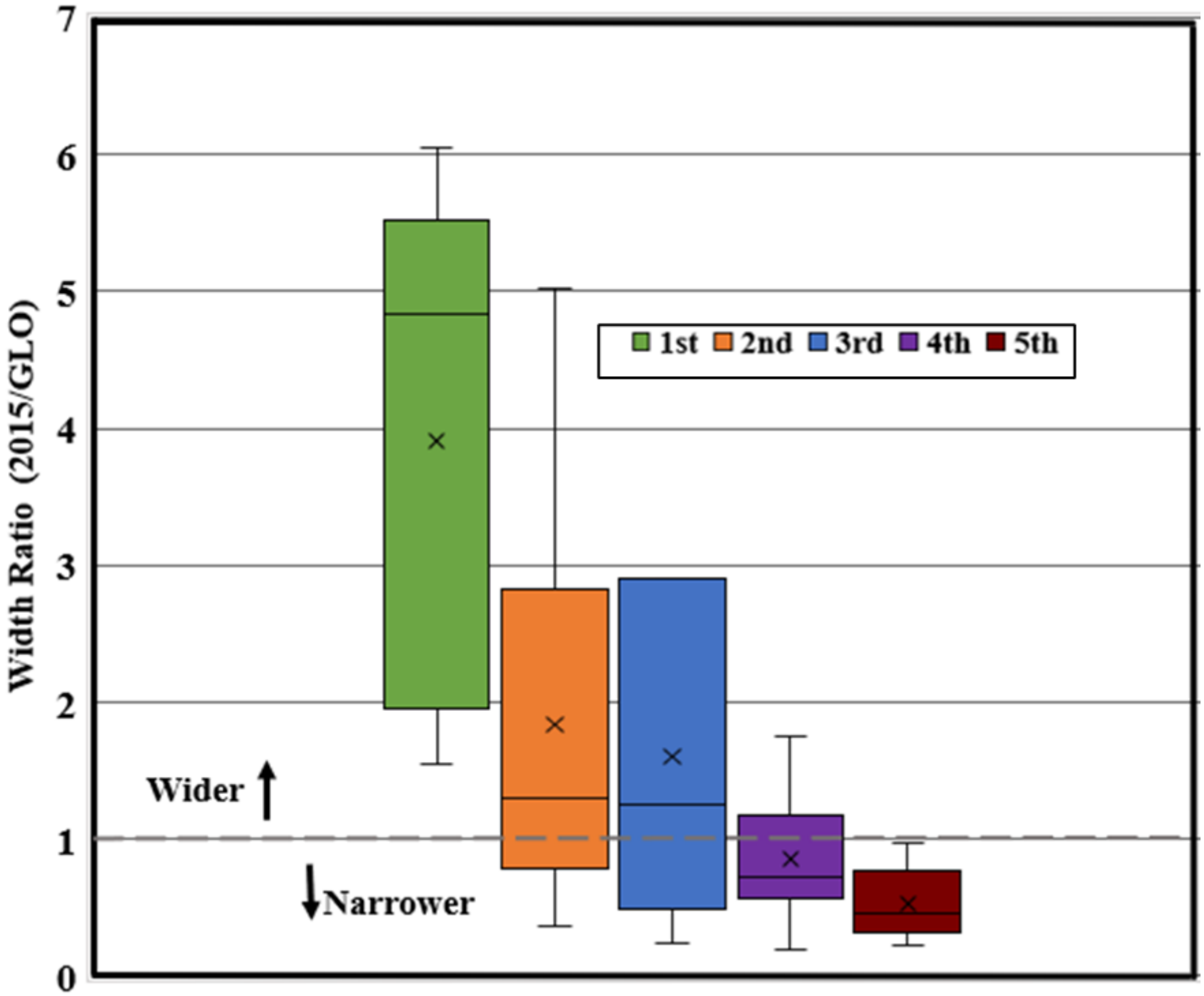

Figure 17. Boxplots of width change ratios by stream order for GLO and 2015. Lower main channel sites are composed of all 5th order streams. Upper Blue River sites are composed of 55% 4th, 11% 2nd, and 33% 1st order streams. Indian Creek sites are composed of 40% 4th, 40% 3rd, 13% 2nd and 6% 1st order streams. Brush Creek sites are composed of 6% 3rd, 53% 2nd, and 40% 1st order streams (Table 8).

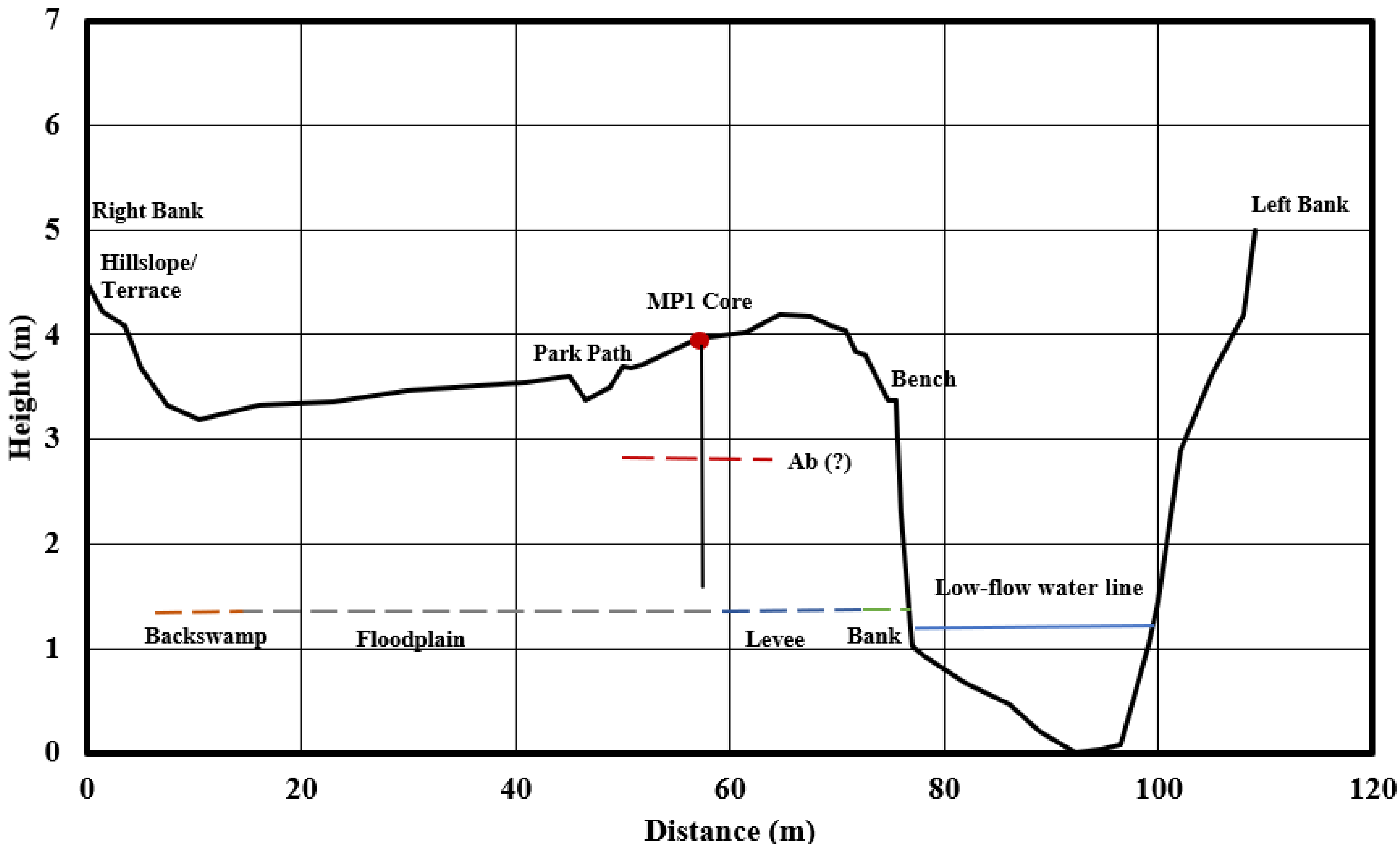

Figure 18. Cross section of Minor Park site. Field data collected 12/22/22 with MP1 core (38°55'00.5"N 94°34'23.8"W).

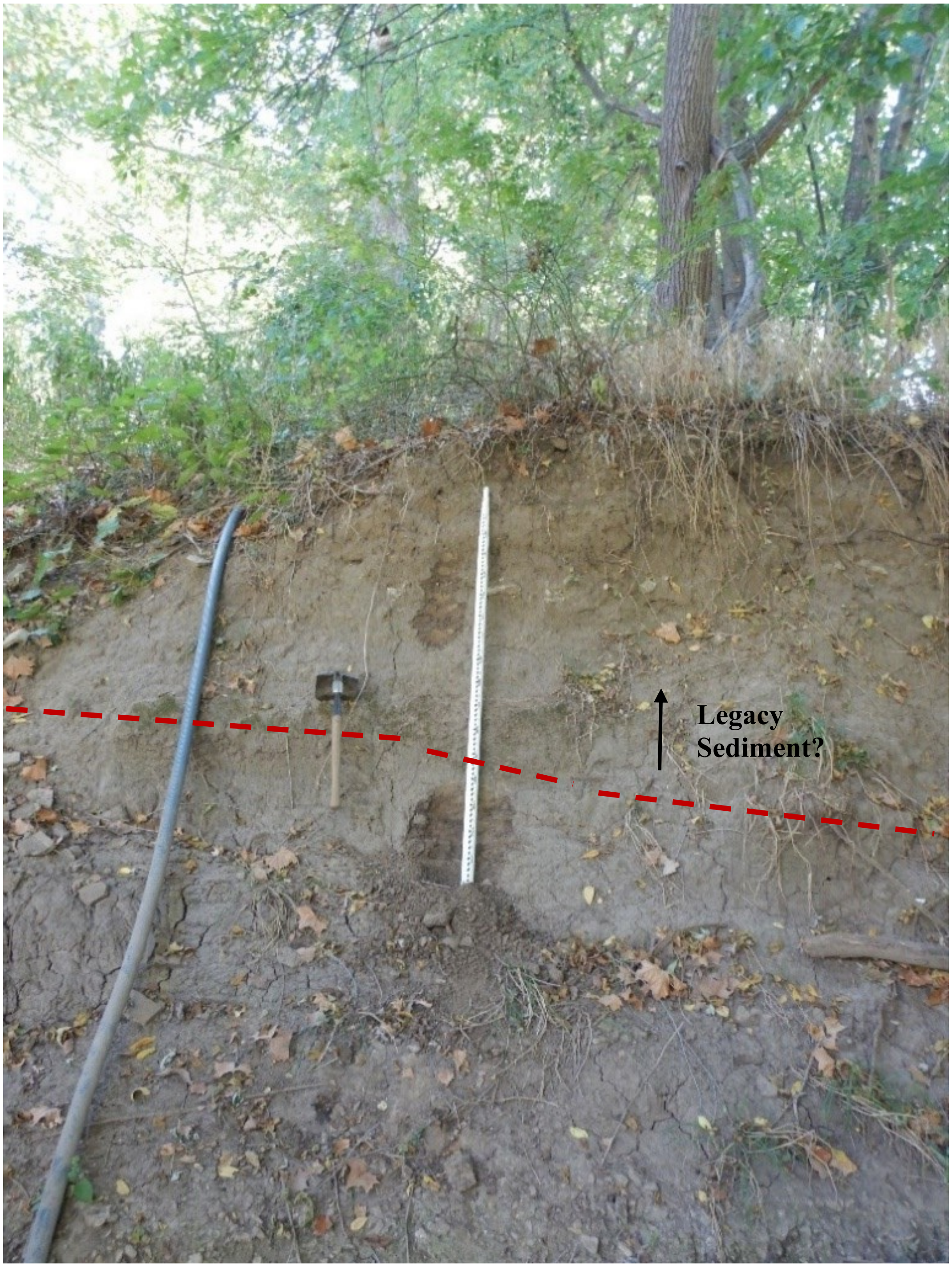

Figure 19. Cut bank exposure from R-km 35 at Red Bridge showing possible legacy deposit. Dotted red line indicates the top of a darker and more cohesive unit (probable Ab horizon). The top sample has higher levels of both Zn (88-84 ppm) and Pb (32-15 ppm) than the lower which may indicate sedimentation from an urban period. This is further supported by the glass and construction waste found in the top layer.

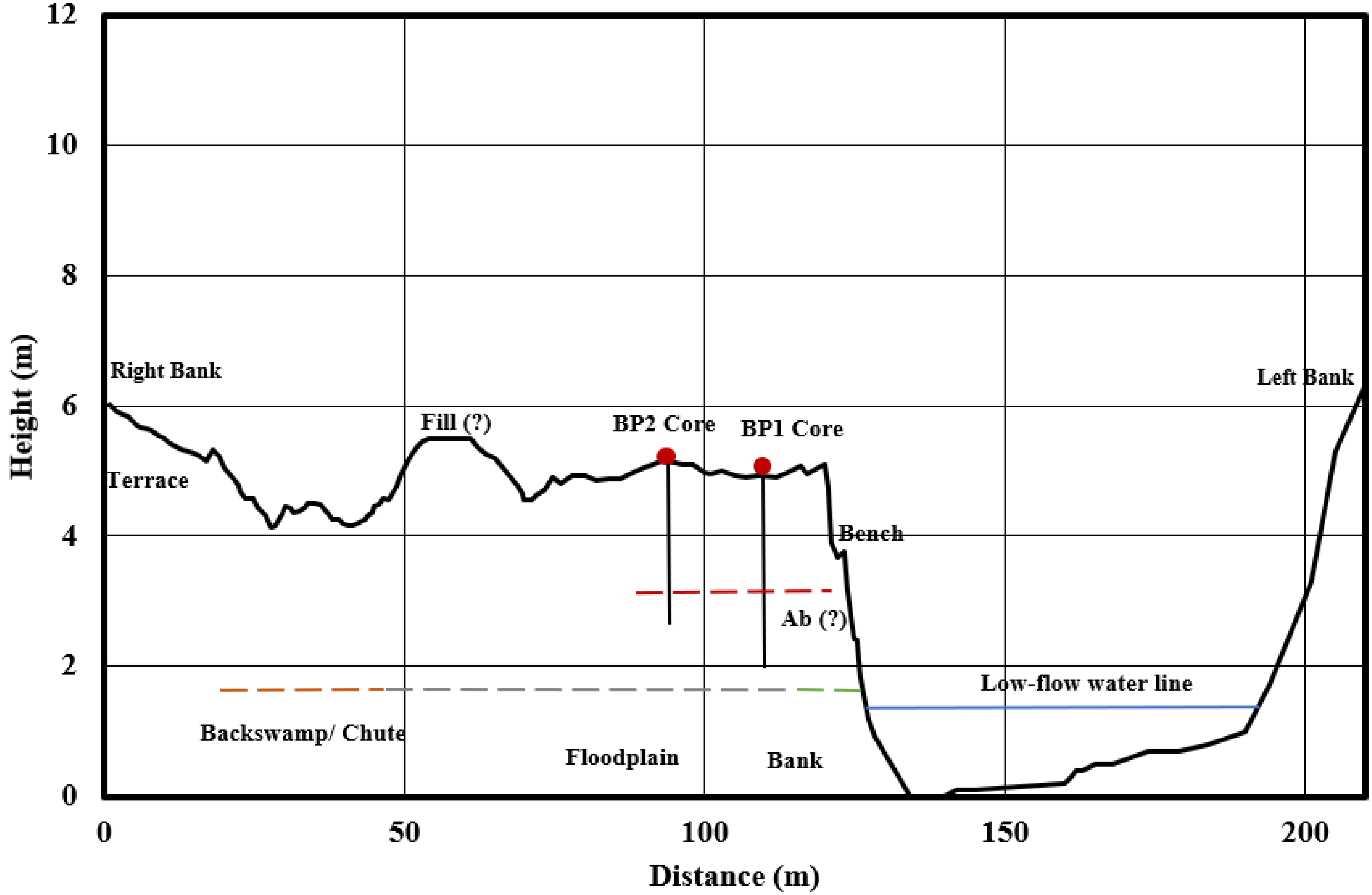

Figure 20. Cross section of Battlefield Park site. Field data collected 12/22/22 with BP1 core (39°01'08.1"N 94°31'20.7"W) and BP2 core (39°01'08.0"N 94°31'19.9"W).

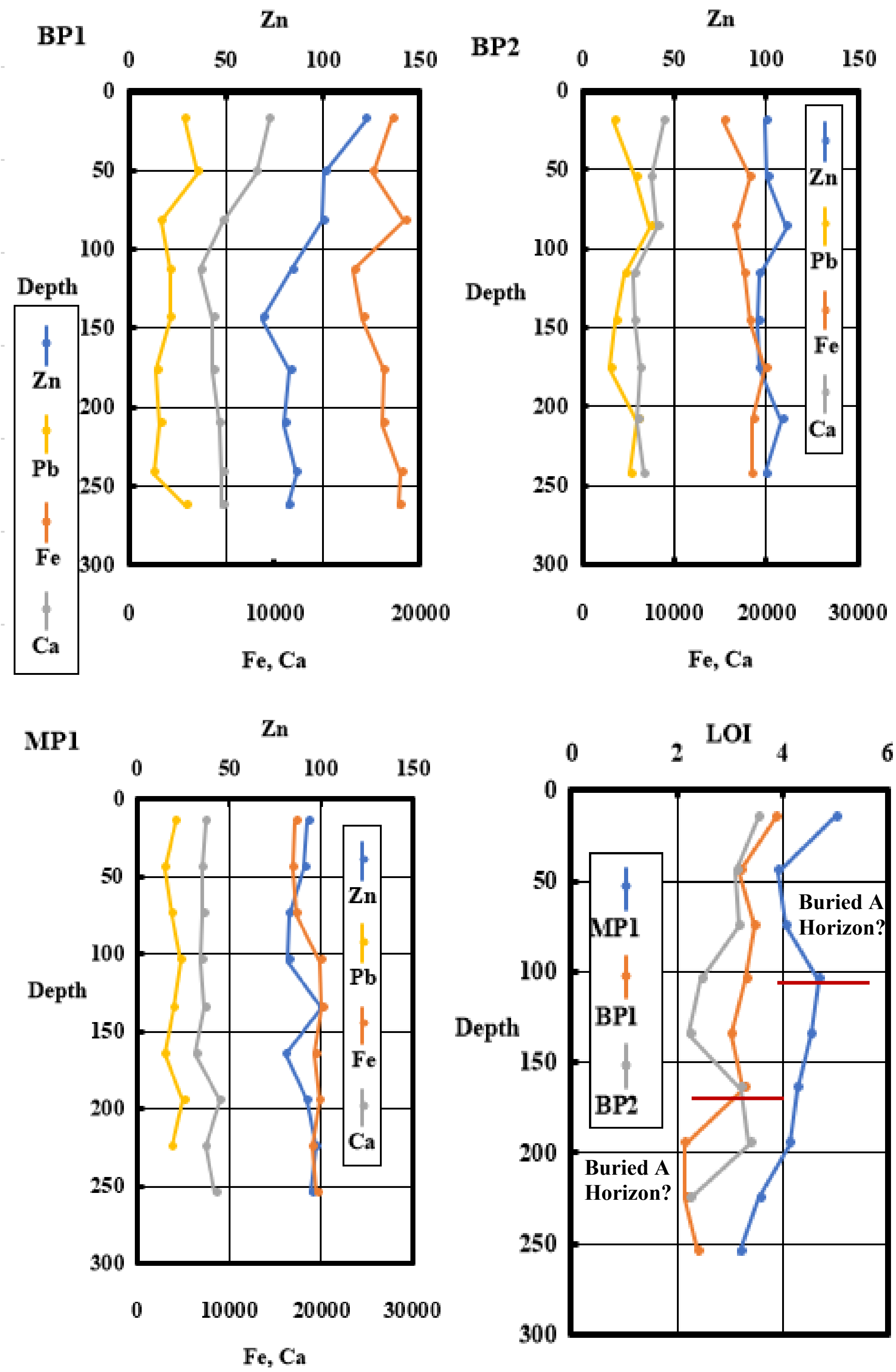

Figure 21. XRF and LOI results from Oakfield sediment cores (see Table 12).

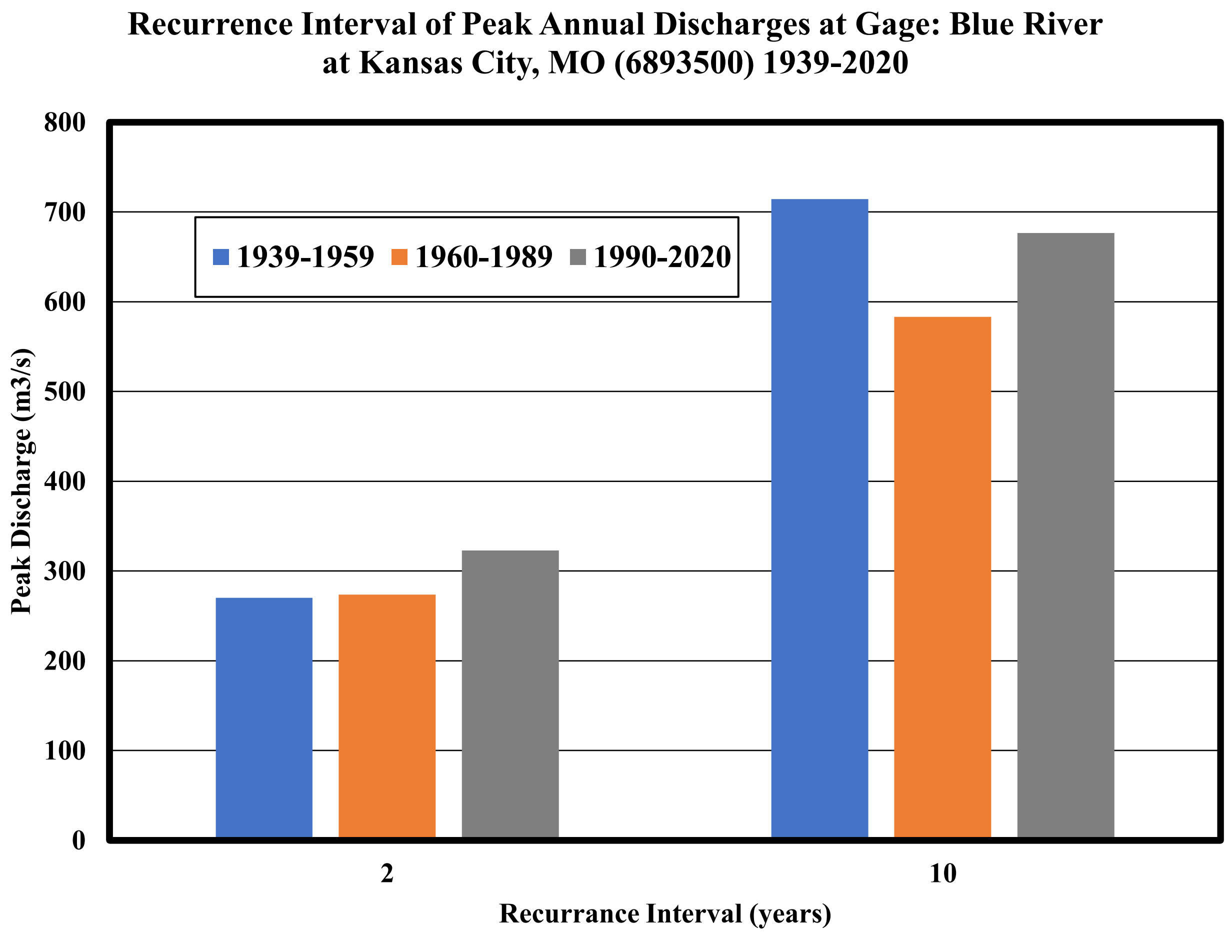

Figure 22. Flood frequency comparison for the longest running gage in the Blue River watershed.

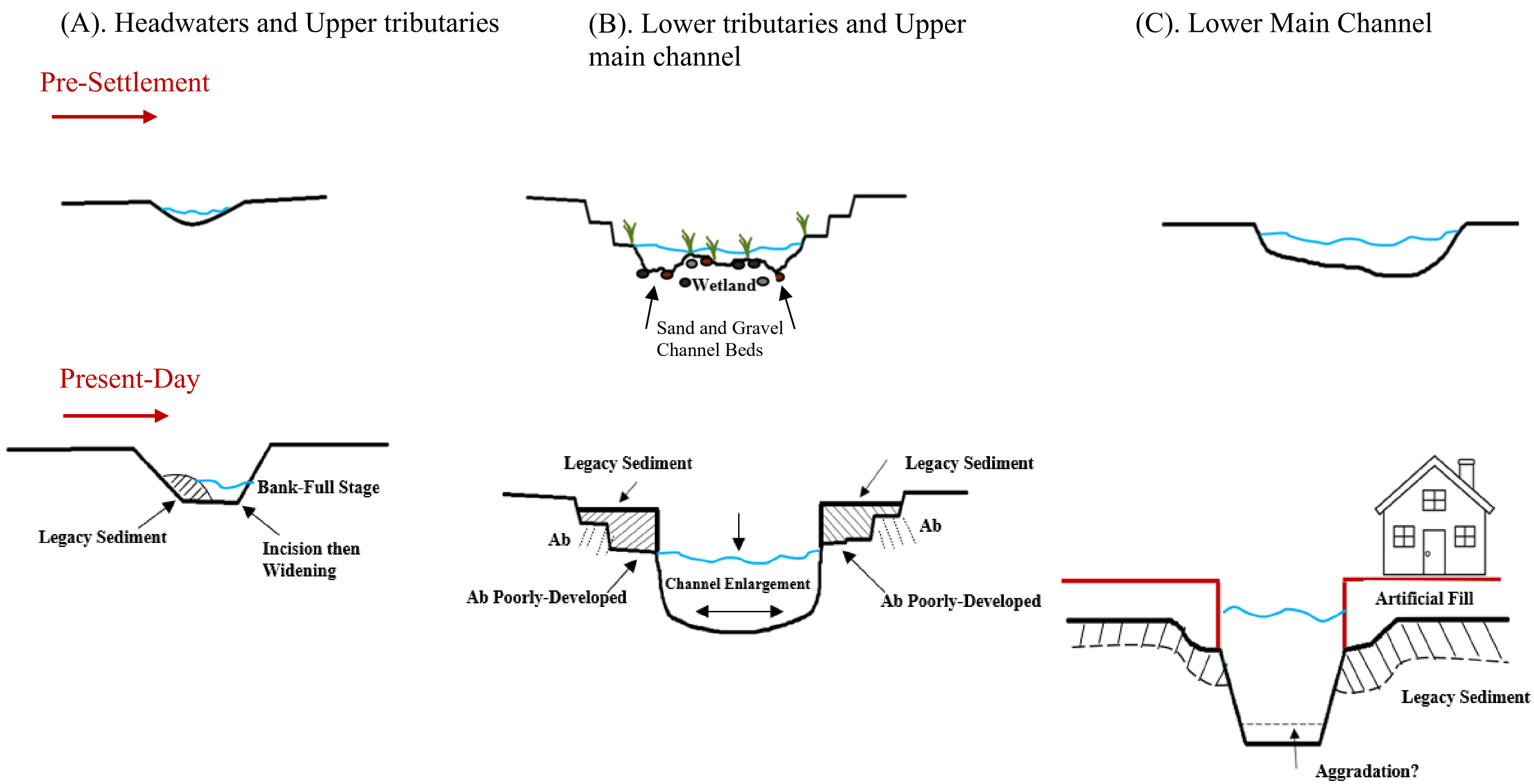

Figure 23. Channel evolution model for the Blue River watershed illustrating changes from pre-settlement channel conditions to present-day. (A). Headwater and tributary incision and subsequent channel widening and legacy sediment deposits (Schumm 1984; Simon and Hupp 1986). (B). Conversion from wide, shallow wetland environment to deeper, incised channel with floodplain sedimentation. Potential for A-horizon development on higher, less flooded surface, but not well developed on lower wetland bar and bench areas (Lecce 2013). (C). Legacy sediment deposits narrowing the channel and raising bank heights. Artificial fill of valley floor combined with channel aggradation may have increased flood risk and further need for flood control structures in the lower Blue River (Knox 1977, 1987).

CONCLUSION

The purpose of this study was to use historical data from General Land Office (GLO) surveys and aerial photographs to assess downstream changes in channel width and form in response to early historical settlement and more recent urban development and channel engineering practices. Channel widths from 1826, 1827, and 1836 were compared to widths obtained from 1955, 1995, and 2015 aerial photography to analyze spatial and temporal trends related to land use change and direct modifications. Along with historical width analysis, soil surveys and field data indicated historical channel widening upstream and narrowing downstream in Blue River watershed in response to increased runoff and sediment loads. In addition, this study has probably documented the presence of legacy sediment deposits in the upper and lower main channel floodplains, fitting with the proposed historical channel evolution model (HCEM) for the Upper Midwest USA (figs. 1 & 23). This study has five main findings:

1. Historical land use changes were significant and capable of transforming the channel morphology of the Blue River and its tributaries. Historical agricultural land use conversion increased runoff, headwater erosion, and sediment loads in the Blue River, possibly leading to downstream sediment deposition that narrowed the channel and raised bank heights. Urbanization and expansion of impervious surface probably contributed to recent increases in flooding and flow velocity that, along with decreased sediment loads, have resulted in recent downstream channel widening. In response to historical urban development and avoidance of flood risk, valley filling occurred in the lower segment to artificially raise bank heights as a flood control measure. As flood conditions continued to worsen, direct channel modifications were implemented in the lower 20 km of the main Blue River channel and Brush Creek, primarily between 1990 and 2010. These modifications included channel straightening and deepening which further confined the valley and reduced flood capacity.

2. Total river distance decreased by 11 km from 1955 to 2015 (18%) and 8 km from 1995 to 2015 (14%) due to channel straightening and meander cutoffs. This suggests the channel slope may be steeper which contributes to higher stream power, flow velocity, shear stress and higher erosion capabilities.

3. Channel widths in the headwaters and tributaries widened from the early 1800s to 2015. First and second order streams incised and widened approximately 25 m (35%) and 5 m (27%) respectively, while third order widened on average by 3 m (6%), primarily due to initial incision and then lateral expansion (Schumm, Mmichael, and Chester 1984; Simon and Hupp 1986). This is consistent with the HCEM created from findings proposed primarily by Knox (1977) and Lecce (2013) in the Driftless area of Wisconsin showing the highest increases in channel width in smaller headwater streams.

4. Channel widths in the upper and lower main channel have significantly narrowed in the period from the GLO surveys to 2015. Fourth order streams narrowed on average 10 m (31%) and fifth order streams narrowed approximately 29 m (52%). Limited GLO survey notes confirm this and suggest there was a geomorphic shift from a wide, shallow, multi-threaded wetland system to a narrower, deeper, single-channel stream. This is consistent with the findings from Gendaszek, Magirl, and Czuba (2012) suggesting post-agricultural settlement aggradation and legacy sediment deposition narrowed channels, creating flooding and erosion issues exacerbated by artificial fill, channelization, and urban expansion.

5. It is highly probable that legacy sediment deposits occur to some degree on most tributary and main channel floodplains in Blue River watershed. Mapped soils analysis and accompanying floodplain sediment core samples indicate legacy sediment deposition as a factor in channel narrowing. Urban soils mapped on the valley floor of the lower main channel further indicate the presence, and role, of direct modifications in altering historical channel response trends.

This study shows that the Blue River today was significantly modified by human action both directly and by historical land use conversion. This is evidenced by the presence of legacy sediment, channel width changes, artificial fill, and direct channel modifications in the watershed. This study provides support for an historical channel evolution model for evaluating historical and contemporary channel response to land use change and the effects of direct modifications in an urban watershed. In general, the Blue River HCEM was consistent with the upper Midwest HCEM. However, this study added a new component regarding the possible geomorphic influence of channel modifications and urban land infilling on contemporary floodplain processes. A better understanding about how land use conversion affects watersheds can aid in reducing future negative impacts. As climate change progresses it is essential to study how land use changes in the past and future affect watersheds to inform management efforts to mitigate adverse environmental impacts. Therefore, further work needs to be completed to evaluate the validity of the channel evolution model for the Blue River and test its approach and application to other watersheds in the region.

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APPENDICES

Appendix A. GPS coordinates for each floodplain sediment core.

Core Site	Depth (cm) Min	Max	GPS Coordinates Lat° Long°
MP1	0	30	38°55'00.6"N 94°34'23.2"W
MP1	30	60	38°55'00.6"N 94°34'23.2"W
MP1	60	90	38°55'00.6"N 94°34'23.2"W
MP1	90	120	38°55'00.6"N 94°34'23.2"W
MP1	120	150	38°55'00.6"N 94°34'23.2"W
MP1	150	180	38°55'00.6"N 94°34'23.2"W
MP1	180	210	38°55'00.6"N 94°34'23.2"W
`MP1	210	240	38°55'00.6"N 94°34'23.2"W
MP1	240	270	38°55'00.6"N 94°34'23.2"W
BP1	0	37	39°01'08.1"N 94°31'20.7"W
BP1	37	66	39°01'08.1"N 94°31'20.7"W
BP1	66	99	39°01'08.1"N 94°31'20.7"W
BP1	99	128	39°01'08.1"N 94°31'20.7"W
BP1	128	160	39°01'08.1"N 94°31'20.7"W
BP1	160	194	39°01'08.1"N 94°31'20.7"W
BP1	194	228	39°01'08.1"N 94°31'20.7"W
BP1	228	256	39°01'08.1"N 94°31'20.7"W
BP1	256	270	39°01'08.1"N 94°31'20.7"W
BP2	0	39	39°01'08.0"N 94°31'19.9"W

Appendix A-Continued. GPS coordinates for each sediment core.

Core	Depth (cm)		GPS Coordinates
Site	Min	Max	Lat° Long°
BP2	39	71	39°01'08.0"N 94°31'19.9"W
BP2	71	102	39°01'08.0"N 94°31'19.9"W
BP2	102	132	39°01'08.0"N 94°31'19.9"W
BP2	132	162	39°01'08.0"N 94°31'19.9"W
BP2	162	190	39°01'08.0"N 94°31'19.9"W
BP2	190	228	39°01'08.0"N 94°31'19.9"W
BP2	228	258	39°01'08.0"N 94°31'19.9"W

Appendix B. Munsell color and hand texturing for all cores.

Core	Min Depth	Max Depth	Hand-Texture	Munsell Color Name
MP1	0	30	Silt Loam	Very Dark Clay
MP1	30	60	Silty Clay Loam	Black
MP1	60	90	Silt Loam	Very Dark Clay
MP1	90	120	Silt Loam	Very Dark Clay
MP1	120	150	Silty Clay Loam	Black
MP1	150	180	Silt Loam	Very Dark Clay
MP1	180	210	Silty Clay Loam	Black
`MP1	210	240	Silty Clay Loam	Black
MP1	240	270	Silty Clay Loam	Black
BP1	0	37	Silt Loam	Very Dark Grey
BP1	37	66	Silt Loam	Very Dark Grey
BP1	66	99	Silt Loam	Very Dark Grey
BP1	99	128	Silt Loam	Very Dark Grey
BP1	128	160	Silt Loam	Very Dark Grey
BP1	160	194	Silt Clay Loam	Black
BP1	194	228	Silt Loam	Dark Brown
BP1	228	256	Silty Clay Loam	Very Dark Grey
BP1	256	270	Silt Clay Loam	Dark Grayish Brown
BP2	0	39	Silty Clay Loam	Very Dark Gray
BP2	39	71	Silt Loam	Very Dark Clay

Appendix B-Continued. Munsell color and texture for all floodplain sediment cores.

Core	Depth (cm)		Hand-Texture	Munsell Color Name
Site	Min	Max		
BP2	71	102	Silty Clay Loam	Very Dark Grey
BP2	102	132	Silt Loam	Very Dark Gray
BP2	132	162	Silt Loam	Very Dark Gray
BP2	162	190	Silt Loam	Very Dark Gray
BP2	190	228	Silty Clay Loam	Dark Brown
BP2	228	258	Silty Clay Loam	Dark Brown

Appendix C. Organic Matter-LOI percentage, and metal concentrations for all cores.

Core Site	Depth (cm) Min	Max	OM %	Pb (ppm)	Zn (ppm)	Fe (ppm)	Ca (ppm)
MP1	0	30	5	20	93	17,164	7,358
MP1	30	60	4	15	91	16,914	6,973
MP1	60	90	4	19	83	17,303	7,101
MP1	90	120	5	23	82	19,857	6,939
MP1	120	150	5	19	100	20,109	7,298
MP1	150	180	4	14	80	19,312	6,321
MP1	180	210	4	25	92	19,849	8,966
`MP1	210	240	4	<LOD	98	19,066	7,413
MP1	240	270	3	18	95	19,528	8,465
BP1	0	37	4	30	122	18,055	9,584
BP1	37	66	3	29	101	16,784	8,706
BP1	66	99	3	36	100	18,936	6,451
BP1	99	128	3	17	83.81	15,454	4,888
BP1	128	160	3	21	69	16,046	5,791
BP1	160	194	3	21	83	17,492	5,752
BP1	194	228	3	14	80	17,479	6,228
BP1	228	256	2	16	86	18,707	6,418
BP1	256	270	2	13	82	18,572	6,420

Appendix C- Continued. Hue, Value, Chroma, Organic Matter-LOI percentage, and metal concentrations for all cores.

Core	Depth (cm)		OM%	Pb (ppm)	Zn (ppm)	Fe (ppm)	Ca (ppm)
Site	Min	Max					
BP2	0	39	4	17	99	15266	8,838
BP2	39	71	3	29	100	18193	7,471
BP2	71	102	3	37	111	16568	8,149
BP2	102	132	2	23	96	17630	5,559
BP2	132	162	3	18	95	18165	5,670
BP2	162	190	3	15	96	19896	6,309
BP2	190	228	2	30	108	18446	5,947
BP2	228	258	2	26	100	18385	6,640

Appendix D. Cross section data. Battlefield Park at R-km 17 (12/22/2022).

Tape distance (m)	Rod Height	Elevation	Landform
1	0.87	6.03	Terrace
2	0.98	5.92	Terrace
3	1.02	5.88	Terrace
4	1.06	5.84	Terrace
5	1.15	5.75	Terrace
5.5	1.2	5.7	Terrace
6	1.22	5.68	Terrace
7	1.26	5.64	Terrace
8	1.28	5.62	Terrace
9	1.35	5.55	Terrace
10	1.4	5.5	Terrace
10.7	1.46	5.44	Terrace
11.3	1.5	5.4	Terrace
12	1.52	5.38	Terrace
13	1.58	5.32	Terrace
14	1.59	5.31	Terrace
15	1.62	5.28	Terrace
16	1.68	5.22	Backswamp
17	1.76	5.14	Backswamp

Appendix D-Continued. Cross section data. Battlefield Park at R-km 17 (12/22/2022).

Tape distance (m)	Rod Height	Elevation	Landform
18	1.58	5.32	Backswamp
19.2	1.67	5.23	Backswamp
20	1.85	5.05	Backswamp
21	1.98	4.92	Backswamp
21.7	2.01	4.89	Backswamp
22.5	2.11	4.79	Backswamp
22.75	2.21	4.69	Backswamp
23.5	2.32	4.58	Backswamp
24	2.33	4.57	Backswamp
24.8	2.33	4.57	Backswamp
25.6	2.46	4.44	Backswamp
26.5	2.54	4.36	Backswamp
27	2.6	4.3	Chute
27.4	2.71	4.19	Chute
27.75	2.76	4.14	Chute
28.15	2.77	4.13	Chute
28.7	2.73	4.17	Chute
29.1	2.65	4.25	Chute
29.6	2.57	4.33	Backswamp
30.2	2.43	4.47	Backswamp
31	2.46	4.44	Backswamp

Appendix D-Continued. Cross section data. Battlefield Park at R-km 17 (12/22/2022).

Tape distance (m)	Rod Height	Elevation	Landform
31.5	2.53	4.37	Backswamp
32.5	2.51	4.39	Backswamp
33.4	2.47	4.43	Backswamp
34	2.39	4.51	Backswamp
35	2.4	4.5	Backswamp
36	2.41	4.49	Backswamp
36.8	2.51	4.39	Backswamp
37.5	2.56	4.34	Chute
38	2.63	4.27	Chute
39	2.63	4.27	Chute
39.9	2.72	4.18	Chute
40.6	2.73	4.17	Chute
41.5	2.73	4.17	Chute
42.5	2.7	4.2	Chute
43.5	2.64	4.26	Chute
44	2.59	4.31	Floodplain
44.6	2.54	4.36	Floodplain
45	2.44	4.46	Floodplain
45.7	2.41	4.49	Floodplain
46.6	2.33	4.57	Floodplain
47.3	2.35	4.55	Floodplain

Appendix D-Continued. Cross section data. Battlefield Park at R-km 17 (12/22/2022).

Tape distance (m)	Rod Height	Elevation	Landform
50.6	1.76	5.14	FP/ upland
51.5	1.63	5.27	FP/ upland
52.3	1.52	5.38	FP/ upland
53	1.46	5.44	FP/ upland
54	1.41	5.49	FP/ upland
55	1.4	5.5	FP/ upland
56	1.39	5.51	FP/ upland
56.7	1.4	5.5	FP/ upland
58.3	1.39	5.51	FP/ upland
61	1.4	5.5	FP/ upland
62.2	1.52	5.38	FP/ upland
63.7	1.64	5.26	FP/ upland
65	1.7	5.2	FP/ upland
66.3	1.84	5.06	Backswamp
67.5	1.98	4.92	Backswamp
68.7	2.13	4.77	Backswamp
69.5	2.24	4.66	Backswamp
70	2.35	4.55	Backswamp
71.3	2.35	4.55	Backswamp
72.1	2.26	4.64	Backswamp
73.3	2.19	4.71	Backswamp

Appendix D-Continued. Cross section data. Battlefield Park at R-km 17 (12/22/2022).

Tape distance (m)	Rod Height	Elevation	Landform
74.7	1.99	4.91	Backswamp
76	2.09	4.81	Backswamp
78	1.97	4.93	Backswamp
80	1.96	4.94	Backswamp
82	2.04	4.86	Backswamp
84	2.02	4.88	Backswamp
86	2.02	4.88	Backswamp
88	1.93	4.97	Backswamp
90	1.86	5.04	Backswamp
93	1.74	5.16	Edge of sidewalk
95	1.78	5.12	Edge of sidewalk
96.3	1.79	5.11	Edge of sidewalk
98	1.8	5.1	Levee
100	1.93	4.97	Levee
101	1.95	4.95	Levee
103	1.9	5	Levee
105	1.97	4.93	Levee
107	2	4.9	Levee
109	1.96	4.94	Levee
112	1.99	4.91	Levee
114	1.92	4.98	Levee

Appendix D-Continued. Cross section data. Battlefield Park at R-km 17 (12/22/2022).

Tape distance (m)	Rod Height	Elevation	Landform
116	1.83	5.07	Levee
117	1.95	4.95	Levee
119	1.86	5.04	Levee
120	1.79	5.11	Levee/Bank edge
120.6	2.14	4.76	
121.1	3.01	3.89	Levee/ lower bank
121.6	3.11	3.79	Bench
122.3	3.23	3.67	Mid bench
123.2	3.14	3.76	Bench top edge
123.9	3.74	3.16	Bank
125	4.47	2.43	Bank
125.3	4.49	2.41	Bank
126	5.06	1.84	Mid bank
127.2	5.7	1.2	Lower bank
128.3	5.98	0.92	Waterline
134.3	6.9	0	Water depth is 6 m
140	6.9	0	Bed
142	6.8	0.1	Bed
143.3	6.8	0.1	Bed
145.2	6.8	0.1	Bed
160	6.7	0.2	Bed

Appendix D-Continued. Cross section data. Battlefield Park at R-km 17 (12/22/2022).

Tape distance (m)	Rod Height	Elevation	Landform
161	6.6	0.3	Bed
161.8	6.5	0.4	Bed
163	6.5	0.4	Bed
165	6.4	0.5	Bed
168	6.4	0.5	Bed
174	6.2	0.7	Bed
179	6.2	0.7	Bed
184	6.1	0.8	Bed
190	5.9	1	Start of Bluff
194	5.2	1.7	Bluff
201	3.6	3.3	Bluff
205	1.6	5.3	Bluff
210	0.6	6.3	Bluff

Appendix D-Continued. Cross section data. Minor Park at R-km 35 (12/22/2022).

Tape distance (m)	Rod Height	Elevation	Landform
0	1	4.48	Hillslope
1.4	1.25	4.23	Terrace
3.5	1.4	4.08	Edge of terrace
5	1.8	3.68	Mid bank
7.5	2.15	3.33	Floodplain
10.5	2.29	3.19	Backswamp
16	2.15	3.33	Floodplain
23	2.12	3.36	Floodplain
30	2.02	3.46	Floodplain
41	1.93	3.55	Floodplain
45	1.87	3.61	Floodplain
46.5	2.1	3.38	Trail edge (1)
48.8	1.98	3.5	Trail edge (1)
50	1.78	3.7	Levee starts
50.8	1.8	3.68	Trail edge (2)
51.8	1.77	3.71	Trail edge (2)
57	1.52	3.96	Levee
61.5	1.46	4.02	Levee
64.7	1.29	4.19	Levee
67.5	1.31	4.17	Levee
69.5	1.4	4.08	Levee

Appendix D-Continued. Cross section data. Cross section data. Minor Park at R-km 35 (12/22/2022).

Tape distance (m)	Rod Height	Elevation	Landform
70.8	1.44	4.04	Levee
71.8	1.64	3.84	Levee edge
72.6	1.68	3.8	Levee edge
74.7	2.11	3.37	Bench Edge
75.5	2.11	3.37	Bench
76	3.18	2.3	Mid bank
77	4.45	1.03	Water edge
78	4.55	0.93	toe
82	4.81	0.67	Channel
86	5.01	0.47	Channel
89	5.27	0.21	Channel
92.2	5.48	0	Thalweg
94.7	5.45	0.03	Boulders in channel
96.5	5.39	0.09	Toe (boulders)
99	4.45	1.03	Water edge (boulders)
100	4.04	1.44	Lower bank
102	2.58	2.9	hillslope
105	9.4	3.6	Bluff
108	10	4.2	Bluff
109	10.8	5	Bluff

Appendix E. Historical widths for the main channel of Blue River with triplicate measurements.

RKM	Stream Order	GLO Width (m)	1955 Width (m)	1955 Average Triplicate (m)	1995 Width (m)	1995 Average Triplicate (m)	2015 Width (m)	2015 Average Triplicate (m)
3	5	65.4	33.5	33.5	33.3	31.6	44.0	42.6
4	5	73.6	23.0	16.9	64.9	64.1	66.4	64.1
4.5	5	82.9	19.4	22.7	63.7	63.7	63.7	63.7
5	5	65.2	22.2	19.8	33.2	33.2	29.0	29.0
7	5	49.7	25.3	25.7	23.1	23.1	27.2	27.2
8.5	5	84.1	27.5	25.6	19.8	19.8	21.6	21.6
9	5	73.6	30.3	30.3	22.7	22.7	23.1	23.1
11	5	65.4	29.7	31.3	20.2	20.2	26.5	26.5
12.5	5	60.4	28.7	28.2	18.6	18.6	24.1	24.1
13.5	5	51.9	23.8	27.8	17.4	17.4	16.8	16.8
15.5	5	56.9	14.3	15.9	9.6	9.6	12.9	12.9
17	5	56.3	10.7	11.3	14.9	14.9	23.6	23.6
23	5	46.1	11.2	9.4	12.2	12.2	19.7	19.7
24.5	5	54.3	15.8	15.9	23.5	23.5	22.9	22.9

Appendix E-Continued. Historical widths for the main channel of Blue River with triplicate measurements.

RKM	Stream Order	GLO Width (m)	1955 Width (m)	1955 Average Triplicate (m)	1995 Width (m)	1995 Average Triplicate (m)	2015 Width (m)	2015 Average Triplicate (m)
26	5	30.2	16.0	15.1	21.3	19.8	19.2	26.1
26.5	5	30.2	16.4	15.9	19.8	21.3	26.1	19.2
28.5	5	63.2	16.9	15.1	16.3	16.3	22.8	22.8
30	5	45.1	15.3	15.9	13.0	13.0	16.1	16.1
32.5	4	28.2	16.4	19.6	15.4	15.4	24.5	24.5
39	4	10.1	15.8	12.4	14.2	14.2	12.1	12.1
40	4	60.4	19.7	19.1	21.3	21.3	28.3	28.3
44	4	10.1	13.7	12.0	15.1	15.1	19.2	19.2

Appendix F. Historical widths for main tributaries of Blue River. Average triplicate measurment used for 2015.

RKM	Stream	Stream Order	GLO Width (m)	2015 Width (m)
1.8	Brush Creek	2	6.0	6.5
3.5	Brush Creek	3	4.0	6.3
6.2	Brush Creek	2	10.1	5.9
10.1	Brush Creek	2	10.1	31.6
10.8	Brush Creek	4	26.2	27.2
11.3	Brush Creek	2	20.1	18.6
11.7	Brush Creek	2	21.7	15.7
14	Brush Creek	1	20.1	18.7
15.1	Brush Creek	1	14.1	64.6
15.3	Brush Creek	1	6.6	60.4
15.5	Brush Creek	1	6.6	44.1
16.2	Brush Creek	1	12.1	39.9
6.2	Indian Creek	2	10.1	30.2
10	Indian Creek	2	6.0	7.3
4.3	Indian Creek	4	20.1	22.8
5	Indian Creek	4	31.6	28.4
10.4	Indian Creek	4	50.3	27.2
15	Indian Creek	3	25.1	26.3
16.3	Indian Creek	3	9.1	12.9
30.2	Indian Creek	3	17.5	17.6