HISTORICAL METAMORPHOSIS OF THE ARKANSAS RIVER ON THE KANSAS HIGH PLAINS

BY

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ABSTRACT

River metamorphosis is a well-documented global phenomenon, particularly for the historic period. The Arkansas River in western Kansas is an example of a river channel that has undergone a major historical metamorphosis: the pre-1900's channel was wide, shallow and braided, but subsequently transformed into a narrow, sinuous meandering system. This study establishes the relationship between the hydrology and dynamics of channel morphology, determined the period in which the metamorphosis occurred, and quantified the channel change. In order to document channel change along a reach of the Arkansas River within the Kansas High Plains this study used ArcGIS to evaluate aerial photography for seven discrete years within the past 75 years, USGS stream gages to document the historical decrease in discharge, Public Land Survey records to characterize early settlement channel widths, and lesser sources such as historical ground-based images and bridge construction plans to further document historical changes in channel morphology. Channel width and sinuosity were measured and recorded for each year of aerial photography to quantitatively determine the magnitude of change and to characterize progression of the historical metamorphosis. The river channel has narrowed by about 145 meters and increased in sinuosity from 1.22 to 1.46 since the acquisition of the first

aerial photography (1939). Historical changes in the channel morphology have occurred because of many anthropogenic modifications including a dam, irrigation diversion canals, and groundwater pumping for center pivot irrigation systems. These anthropogenic influences have directly altered the hydrology of the river by decreasing mean annual discharge, reducing peak annual flows, and lowering the water table. The upstream part of the study reach, near the Colorado-Kansas border experiences sporadic flows and has a narrow sinuous channel, where the discharge is actively building and stabilizing the floodplain and channel banks. The downstream reach, below irrigation diversions, channel width increases and sinuosity decreases, where the surface flow is extremely rare, resulting in little or no channel change. Upstream reaches, near Syracuse, have high sinuosity values from riparian vegetation stabilizing point bars and cutbanks, whereas downstream reaches, near Garden City, have low sinuosity values due to minimal riparian vegetation. The character of the Arkansas River channel within the Kansas High Plains may continue its present trajectory as long as the present-day hydrologic regime is maintained and the prevailing climate is unchanged.

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INTRODUCTION

The overall geometry of a river channel is controlled by independent variables, such as the climate and geology of the drainage basin, whereas each river reach is the result of many hydraulic variables, local lithology, and upstream factors (Morisawa, 1985). River channels are dynamic systems that react to numerous changes in discharge and other hydraulic variables caused by internal and external forcings (Schumm, 1973; Hickin, 1974; Schumm, 1979; Knox, 1983; Ritter, 2002; Gregory, 2006). Hydraulic variables and discharge are constantly changing and interdependent, which leads to complexity in fluvial geomorphology. Rivers adjust their hydraulic geometry, channel slope, and channel shape in response to changes in these hydraulic variables in order to reach a quasi-equilibrium state (Schumm, 2005). River channels can adjust to these factors by changing laterally and vertically, where lateral changes occur in channel position, width, and sinuosity (Morisawa, 1985). Channels that experience similar conditions form distinct patterns in map view and can be classified based on numerous metrics. Sinuosity is a useful measure to differentiate between channel patterns, especially in remote sensing research, where particle size and other metrics are not available (Table 1).

Many fluvial geomorphology investigations have focused on channel pattern change, and time series of aerial photography as well as historical maps have often been used to detect this change (Petts et al., 1989; Kondolf, 2003). Large-scale changes in channel shape are usually discernible; however, each image must be georeferenced in order to accurately view and quantify the magnitude of channel change. Many geomorphologists have explored historical channel change using aerial photography along rivers (Braga and Gervasoni, 1989; Bryant and Gilvear, 1999; Juracek, 2000; Tiegs and Pohl, 2005; Wellmeyer et al., 2005; Wallick et al., 2007; Block, 2014; Arnaud et al., 2015). In a study of the geomorphic evolution of the Little Colorado River in Arizona, Block (2014) used historical aerial photographs (1936-2010) to determine that the channel has narrowed by about 90% over the study period, which was attributed to changes in temperature and precipitation. The channel planform changes were hydrologically driven from primarily decreases in precipitation and to a lesser extent from vegetation encroachment; groundwater withdrawals have led to the continued channel narrowing along the Little Colorado River (Block, 2014). Juracek (2000) investigated the Neosho River downstream of John Redmond Dam in southeast Kansas using multiple sets of aerial photography and stream gage data and found minor overall change to the river channel planform. The Neosho River is suspected to be a relatively stable system, and channel changes are not yet recognizable even though the dam was built in 1964 (Juracek, 2000). Wellmeyer et al. (2005) analyzed the downstream impacts of the Livingston Dam on the lower Trinity River in eastern Texas and deduced that the river planform is gradually adjusting to the dam with no major channel changes yet appearing. On the River Dee near the Welsh-English border, Gurnell (1997) used six sets of aerial photographs from the past 50 years to find that the channel had narrowed because of flow regulation. Bryant and Gilvear (1999), employed Airborne Thematic Mapper data to quantify changes on the River Tay in Scotland before and after a flood event, concluded that only subtle channel changes occurred. Gregory et al. (2002) used General Land Office (GLO) maps along with U.S. Army Corps of Engineer surveys to quantify the historical channel pattern changes on the Willamette River, Oregon. In Europe, river regulation has evolved for more than 200 years, where many cartographic sources have assessed channel change in Britain, Italy, and France (Braga and Gervasoni, 1989; Bravard and Bethemont; Hooke and Redmond, 1989; Petts, 1989). In the United States Great Plains, Dort (2009) employed historical maps and early aerial photography to document historical channel change along the Kansas River and its major tributaries.

Metamorphosis

Metamorphosis, a concept introduced by Schumm (1969) in his investigation of the Murrumbidgee River in western Australia, refers specifically to a shift from one channel pattern to another (Figure 1). Hydrology, riparian vegetation, and sediment load are factors that influence a metamorphosis, where a dramatic shift in any of these factors can lead to a complete change in channel pattern. Many studies have reported this phenomenon in historical and Late Quaternary contexts (Table 2). The Mississippi River in the central United States (Rittenour et al., 2007), Murrumbidgee River (Schumm, 1969), the Maas River in the Netherlands (Huisink, 1997), and multiple river systems throughout the southeastern United States (Leigh, 2006) underwent a metamorphosis during the Late Quaternary, whereas the Ain River in France (Marston et al., 1995), Arkansas River in the south-central United States (Nadler and Schumm, 1981), Gilmore Creek (Page et al., 2007) and MacDonald River in Australia (Erskine, 1986), and South Platte River of Nebraska (Nadler and Schumm, 1981) have transformed their channel patterns during the historical period.

Factors such as particle size and riparian vegetation help control channel morphology, but a major shift in the hydrologic regimen alone can trigger a response, which if sufficient, will completely alter channel morphology (Schumm, 1969). Past examples of channel pattern changes occurring due to altered hydrology were reported on river systems in the Southeastern United States (Leigh, 2006) and the Murrumbidgee River (Schumm, 1969) during the Late

Quaternary. Hydrologic fluctuations can be induced by climate, such as the case of the Little Colorado River in Arizona, where a decline in annual precipitation triggered channel narrowing by floodplain accretion and the spread of riparian vegetation (Hereford, 1984). Previous research has demonstrated that a complete transformation of river morphology can occur in response to river regulation, such as dams and diversion canals (Schumm, 1969). Dam construction on river channels regulates discharge downstream, flow regime, sediment transport, and hydraulic gradient (Williams and Wolman, 1984; Mangelsdorf et al., 1990; Brandt, 2000; Graf, 2001). The impact of dam construction often results in changes in planform size, channel sinuosity, and channel stability (Wellmeyer et al., 2005). Diversion canals redirect the flow of the river, which results in channel morphology changes comparable to those of dam emplacement (Schumm, 1969; Nadler and Schumm, 1981). Tiegs and Pohl (2005) analyzed the historical channel planform dynamics of the lower Colorado River in response to river regulation from the Morelos Dam using aerial photography and geographic information systems (GIS); they found that channel contraction dominated but periodic floods result in channel expansion.

Another factor associated with metamorphosis is the sediment particle size and load within the system, which are each key elements in identifying a channel pattern (Brotherton, 1979). Sediment particle size influences channel bank stability, in that channels flowing in silt and clay-rich sediments enable meanders to form, in contrast to sand-rich sediments (Osterkamp, 1977; Schumm and Meyer, 1979). Further, riparian vegetation influences channel morphology, typically width, by promoting deposition of cohesive fine sediment and increasing resistance to erosion (Burkham, 1972; Smith, 1976; Marston et al., 1995). An increase in riparian vegetation can influence channel morphology by reducing the channel capacity, colonizing and stabilizing wet sandy surfaces, thereby modifying islands to become longer and wider, and increasing channel roughness (Gesink et al., 1970; Graf, 1978; VanLooy and Martin, 2005).

Great Plains Historical Channel Change

Historical channel change is an important avenue for river channel investigations due to its many implications, for example flooding, river rehabilitation, stream regulation, and ecological effects (Schumm and Lichty, 1965; Rosgen, 1994; Covich et al., 1997; Friedman et al., 1998; Luttrell et al., 1999; Graf, 2006). Research on historical channel change in the Great Plains was conducted on the North Platte River (Williams, 1978; Eschner et al., 1983), Platte River (Williams, 1978; Eschner et al., 1983), Cimarron River (Schumm and Lichty, 1965; VanLooy and Martin, 2005), Arkansas River (Nadler and Schumm, 1981), Medicine Lodge River (Martin and Johnson, 1987), and South Platte River (Nadler and Schumm, 1981; Eschner et al., 1983). These studies concluded that the majority of Great Plains fluvial systems have decreased in channel width, increased in density of riparian vegetation, and increased in sinuosity since early settlement time (Table 3). These river channels have narrowed and increased in length due to discharge regulation or reduced precipitation, with exception of the Cimarron River, which experienced channel widening due to a large flood event.

Great Plains river systems are highly susceptible to large magnitude events, such as floods and anthropogenic constructs, both of which can take channels decades to recover (Baker, 1977; Richards, 1982). Historical river modifications on the Great Plains can be attributed to anthropogenic activity, where dams, diversion canals, and exotic vegetation growth have altered the channels (Schumm, 1977). Changes on the South Platte and Arkansas rivers were dramatic enough to transform the rivers from braided to meandering systems (Nadler and Schumm, 1981). Despite the growth of vegetation, increased potential of flooding, and significant changes in morphology, fluvial studies on Great Plains rivers are limited (Graf, 2001). Additional research focused on channel morphology and stream-flow regimes is necessary to predict quantitatively future change (Eschner et al., 1983; Dominick et al., 1998).

Arkansas River Metamorphosis

Dramatic channel changes have occurred along the Arkansas River within the Great Plains during the last century (Mead, 1896; Schumm and Meyer, 1979). In western Kansas, the Arkansas River channel was a braided system with wide, sand-bed channels, and sparse vegetation, whereas the present river is meandering with relatively narrow, silt and clay-rich channels, and considerable riparian vegetation (Figure 2). The river previously followed a relatively straight course and had largely intermittent flow, but now the river is meandering and has perennial discharge. Schumm (1969) predicted that anthropogenic influences on the hydrologic regimen of the Arkansas River would change from wide sandy channels to a suspended load system. Many influences on channel morphology are at work on the river, for example, dams in Colorado, numerous diversion canals, invasive riparian vegetation, and groundwater withdrawals. Whereas Schumm's usage of "metamorphosis" is in specific reference to a complete shift in channel pattern (e.g., braided to meandering), this study considers this historical metamorphosis of the Arkansas River channel as a continuum of historical channel change.

STUDY OBJECTIVES

Previous research on historical channel change of the Arkansas River includes that of Nadler and Schumm (1981), who focused on an eastern Colorado reach of the Arkansas and analyzed the metamorphosis through a sedimentology approach. Johnson et al. (1994) concentrated on the historical changes in channel morphology and density of riparian vegetation over a Kansas portion of the Arkansas River. Research is expanded upon from earlier studies by focusing on a reach of the Arkansas River along the Kansas High Plains, extending the period of documented change, assessing the role of hydrology, and quantifying channel change. This study 1) documents and quantifies historical channel change for the past 75 years, 2) establishes a relationship between the hydrology and the dynamics of channel morphology, and 3) develops a time-line of historical change in the channel. Channel change was investigated using successive sets of aerial photography, U.S. Geological Survey stream gage data, Public Land Survey (PLS) records, and lesser sources such as historical ground-based images and bridge construction plans. As the primary data source, aerial photographs were compiled, georeferenced and analyzed using GIS-based methods, with width and sinuosity being measured from the ArcGIS extension XToolsPro. Archival inquiries at the Kansas Historical Society and site-based investigations including a low-altitude flight were conducted to support each objective.

STUDY AREA

Kansas High Plains Reach

The Arkansas River is about 2,364 km long and is the sixth longest river in the United States. Headwaters of the Arkansas River are the Sawatch and Mosquito ranges in eastern Colorado, from which the river flows through Kansas, Oklahoma, and Arkansas, where it joins the Mississippi River. The project study area covers nearly 180 km along the Arkansas River corridor from the Colorado border, east through Hamilton, Kearny, and Finney counties on the Kansas High Plains (Figure 3). Western Kansas lies in the High Plains region of the Great Plains physiographic province, where the climate is semiarid and mean annual precipitation ranges from 43 to 51 cm (Young et al., 2000; Layzell, 2012). Riparian vegetation within the Kansas High Plains is short-grass prairie, which includes salt cedar (*Tamarix ramoissima*), cottonwood (*Aigeiros*), little blue stem (*Schizachyrium scoparium*), sagebrush (*Artemisia*), and blue grama (*Bouteloua gracilis*) (Kuchler, 1974).

Historical Accounts

Spaniards and French trappers were the earliest explorers of the Kansas High Plains, but it was not until the early 1820s that there was a description of the Arkansas River, compiled during the Stephen Long Rocky Mountain Expedition (cited in Nadler and Schumm, 1981; Tomelleri, 1984). The 1820 expedition described the river in western Kansas as “knee deep” and a “bed of sand and gravel.” In his summary of the geology of southwestern Kansas, St. John (1887- as described in the autumn of 1886) characterized the Arkansas River as having few tributaries of considerable size and that much of the water in the tributaries sinks into the sandy river bed. Explorers, in some instances, may have documented abnormal measurements from rare flooding or unusually narrow accounts of the river's width, which vary widely from 137 to 402 m between 1839 and 1846 (cited in Nadler and Schumm, 1981; Parkman, 1948). As early as the 1890s, there were observations that the Arkansas River channel was shrinking from irrigation canal diversions (Haworth, 1897; Mead, 1896). One historian notes that in 1852 plainsmen were able to float down the Arkansas River from Pueblo, Colorado into Arkansas in boats of 15 to 20 men (Mead, 1896). Early records of the Arkansas River morphology are invaluable due to the vivid insight they provide, though these chronicles should be reviewed with discretion due the ambiguous location of descriptions, unique observations of one reach may not necessarily describe the entire region, and the observers' prior experiences.

Geomorphology and Hydrology

The Arkansas River valley width varies within this reach of the Kansas High Plains: in Hamilton County, the valley width is 3-5 km, though farther east (downstream) to Hartland in Kearny County it narrows to about a kilometer (Figure 3). At Lakin the valley widens to about 8 km until Garden City, where it narrows to about 3 km (Young et al., 2000). Given the pattern of valley width change, the study reach was subdivided into four sections based on width (Figure 3). The river channel bed and banks are composed of mostly coarse sediment and coarse sand channel bars are limited. The wide floodplain dips subtly towards the shallow meandering river, where channel depths do not exceed one meter and the channel width is narrow. Well-developed point bars and cut banks occur frequently in the Hamilton County reach but are rare downstream in Kearny and Finney Counties. The Arkansas River valley has subtle, low-relief loess-mantled uplands to the north and sand dunes bordering the valley to the south (Young et al., 2000). The river gradient over the study reach is about 1.3 m/km (Dunlap et al., 1985), and the valley consists of permeable, poorly sorted, coarse Pleistocene-age alluvium underlain by fine-grained Holocene-age deposits, with most runoff seeping into the alluvium during rainfall events (Dunlap et al., 1985; Young et al., 2000). The maximum depth to bedrock throughout the valley is 20 m, but the thickness of the alluvium varies considerably (Tomelleri, 1984). Sand dunes border the southern extent of the valley and have been intermittently active from the late Pleistocene with various reactivations occurring during the Holocene (Halfen, 2012). Remnants of two or three terrace sequences evident within this reach of the valley were deposited when the ancestral river channel transported much larger volumes of water during the Pleistocene glacial epochs (Smith, 1940; Johnson and Arbogast, 1993; Forman et al., 2008; Halfen, 2012).

The study area has a few minor, ephemeral tributaries from the northern valley uplands: Sand Creek, East and West Bridge Creeks, Shirley Creek, Sandy Creek, and Syracuse Creek contribute scant volumes of water to the Arkansas River within the study reach (Figure 4). Previously the Arkansas River experienced intermittent flows during the spring from snowmelt originating in the Sawatch and Mosquito ranges. John Martin Dam and Reservoir, completed in 1948, altered flow of the Arkansas from seasonal to perennial flow (Nadler and Schumm, 1981). Several floods are documented historically along the Kansas High Plains most notably in 1921, 1942, 1949, 1951, and 1965 (Figures 5 and 6). The High Plains Aquifer is a major source for irrigation within the Kansas High Plains, which has caused the aquifer water level to decline on average by 7.2 m from predevelopment (around 1960) to 2011 due to substantial withdrawals and only minor recharge (McGuire, 2012). Along the Kansas High Plains reach, the USGS maintains a network of stream gages on bridges and diversion canal gates.

Anthropogenic Influences

Numerous anthropogenic influences are cited for altering the landscape on the Kansas High Plains, which then led directly and indirectly to changes in the Arkansas River. In 1873, multiple railways were completed along the Arkansas River valley, at which time settlement populations increased (Tomelleri, 1984). Numerous irrigation canals such as the Amazon Irrigation Canal, Great Eastern Ditch, Frontier Ditch, Southside Ditch, and Farmers Ditch began diverting flow from the Arkansas River by 1895 (Tomelleri, 1984) (Figures 6 and 7). The advent of center pivot irrigation in the 1960s made it economically feasible to water crops with groundwater rather than with surface water from the Arkansas River (Tomelleri, 1984) (Figure 6). As groundwater extraction progressed, the baseflow of the Arkansas River decreased due to the drop in the High Plains aquifer water table (Sherow, 1990; McGuire, 2012).

In Colorado, the Arkansas River flow has also been reduced from irrigation canal diversions and groundwater withdrawals, but in Kansas John Martin Reservoir (JMR) has considerably influenced the Arkansas River discharge. JMR altered the hydrologic regime of the river as to eliminate ephemeral flows, reduce peak flows, and limit volumes of water released to western Kansas beginning in 1948 (Figure 7) (Luckey, 1975). JMR has produced a concomitant reduction in the volume of sediment delivered to the Kansas High Plains reach due to the 85.7% trap efficiency of the dam (cited in Nadler and Schumm, 1981). JMR and irrigation canals have reduced the baseflow of the river and trapped about 4.7 million m^3/yr of sediment (cited in

Nadler and Schumm, 1981). The majority of sediment entering Kansas by way of the Arkansas River is presently silt and clay, in contrast to sand and gravel of the pre-dam era (Osterkamp, 1977). Salt cedar (*Tamarix pentandra*), an invasive phreatophyte from the Mediterranean introduced to stabilize channel banks, was first documented in the Arkansas River valley beginning in 1921 (cited in Nadler and Schumm, 1981; Gesink et al., 1970).

METHODS

Historical channel changes on the Arkansas River in western Kansas were documented by 1) assembling an atlas derived exclusively from seven discrete years of aerial photography, 2) analyzing the hydrology of the river using USGS stream gage data, and 3) quantifying the channel morphology within ArcGIS. Channel width and sinuosity were measured and recorded for each year of aerial photography to determine quantitatively the magnitude of change and to characterize progression of the historical metamorphosis. The procedure for compiling the aerial photography into a map was conducted in three sequential steps: aerial photographs were first scanned, georeferenced, and the river channel boundaries were then digitized. Additionally, hydrology of the river was analyzed using USGS stream gage data to establish the relationship between the river discharge and the dynamics of channel morphology. Stream gages record many different metrics, for example annual and peak discharge as well as frequency of peak flows, all of which were used to determine their individual effect on river width and sinuosity.

Scanning Aerial Photographs

The earliest aerial photography available for the Kansas High Plains Reach was flown in 1939 and the latest images in 2014, a period spanning 75 years. Aerial photography, taken by the United States Department of Agriculture (USDA) Farm Service Agency, was accessed from multiple curators including the Kansas Geological Survey, Kansas Biological Survey, United States National Archives, and Kansas State Historical Society. Channel change in the study reach was documented from aerial photography taken in 1939, 1957, 1965, 1986, 1991, 2003, and 2014 (Table 4). Images from 1991, 2003, and 2014 were available in digital format from the Data Access and Support Center at the Kansas Geological Survey (http://www.kansasgis.org). Printed reproductions (1:20,000) of the 1939, 1957, 1965, and 1986 photographs, taken for the most part in undetermined months, were scanned at a resolution of 300 dpi into a digital file format (.png). The National Agriculture and Imagery Program (NAIP) captured their aerial photography (1991, 2003, and 2014) during June and July at a 1:12,000 scale.

Georeferencing Images

All aerial photographs were georeferenced within the geographic information system of ArcGIS and in the USA Contiguous Albers Equal Area Conic Projection. Each image was georeferenced to the 2014 NAIP imagery base map and rectified based on a minimum of five ground control points (GCPs). Previous studies with similar objectives used on average 20 GCPs for small scale images over urbanized regions; this study justified the use of five GCPs due to the large scale of the images and to the sparse nature of man-made structures in western Kansas

(Leys and Werritty, 1999; Block 2014). Examples of GCPs include crossroads, railroad intersections, permanent structures, and oil well storage tanks, which were spatially distributed across each image to improve locational accuracy.

Digitizing the River Channel

As with georeferencing, digitization of the channel boundaries was also conducted within ArcGIS, where the channel from each year of aerial photography was delineated at the bankfull channel limits (Gurnell, 1997; Surian, 1999; Winterbottom, 2000; Juracek, 2000; VanLooy and Martin, 2005; Wallick et al., 2007). Reliable indicators of the bankfull channel limits were often interpreted as being the first, continuous, clearly demarcated line of woody vegetation. The bankfull channel was digitized following Juracek (2000), using the base of mature trees nearest the channel bank to interpolate the channel boundary. Along reaches with sparse vegetation, physical sedimentary features, such as point bars and cutbanks were used to interpret the channel boundaries. Channel boundaries were determined at 1:2,000 scale in the USA Contiguous Albers Equal Area Conic Projection within an ESRI shapefile. The consistent, previously cited application of these strategies was determined to yield the most accurate channel delineation results possible.

Quantification of Channel Change

Channel change was quantified in regards to sinuosity and width for each year of aerial photography, but a system in which to differentiate channel patterns must be determined before measurements can be classified. Many different classification schemes for channel patterns have been derived and can be differentiated based on methods and metrics used. Leopold and Wolman (1957) identified three channel categories: straight, meandering, and braided, which Ritter (1999) expanded upon by adding the anabranching classification. Subsequently, Morisawa (1985) added a fourth category of sinuous. Schumm (1963) correlated the three previous Leopold and Wolman (1957) qualitative categories with a quantitative approach based on sediment particle size dominating the river's sediment load and concluded there are numerous definable categories of channel patterns (Figure 1). Knighton (1998) classified channel patterns into two groups based on their number of thalwegs, where a single thalweg category would be defined as a straight and meandering channel, and the multiple thalweg category as braided and anastomosing channels.

Fluvial geomorphologists have applied thresholds for each channel pattern, however due to the inconsistent methods in which the thresholds were applied many diverse classifications have been proposed (Lewin and Brewer, 2001). When a river surpasses a threshold, a channel pattern change may be activated and system processes are modified until a new equilibrium can be reached (Schumm and Khan, 1972; Ritter et al., 1999; Ritter et al., 2002). Many of the thresholds are based on metrics such as sinuosity, particle size, and number of thalwegs. Sinuosity is a convenient and widely cited classification metric, especially when studying rivers in map view (Leopold and Wolman, 1957; Schumm, 1963; Moody-Stuart, 1966; Rust, 1977; Rosgen, 1994).

Extensive discussion and research have focused on using sinuosity to differentiate between meandering and braided systems (Rust, 1977). The sinuosity threshold values distinguishing the two channel patterns range from 1.3 to 1.7 and are highly arbitrary, often based on the investigator's preference (Moody-Stuart, 1966; Leeder, 1973; Rust, 1977). The

Schumm (1963) and Moody-Stuart (1966) classifications chose 1.3 as the sinuosity threshold value and as the transitional point between the meandering and braided channel patterns (Table 1). In his study of alluvial river sinuosity on the Great Plains, Schumm (1963) found that a channel with a sinuosity of 1.3 exhibits very flat curves and repetitive meanders. A sinuosity value of 1.3 has been adopted herein because previous research on the Great Plains used the same value, one that has been most widely accepted (Moody-Stuart, 1966; Schumm, 1963; Rust, 1977).

The magnitude of channel change was quantified with the ArcGIS extension XToolsPro, which was employed to measure channel area and channel boundary lengths for each year of aerial photography. Mean channel width was calculated for each year of photography by dividing total area of the channel for each year by the mean channel boundary length. This method was chosen to measure the channel width because it calculated the mean channel as a continuous whole compared to other methods that computed mean channel widths at various discrete cross sections (Leys and Werritty, 1999). As stated previously, sinuosity is a metric often used to differentiate between meandering and braided channel patterns, where a sinuosity greater than 1.3 is considered a meandering system. Sinuosity was computed also for each year of photography by applying the total sinuosity index (TSI) method from Richards (1982). Total sinuosity was calculated as channel boundary length divided by the length between channel endpoints or Euclidean distance, where each channel measurement used the same endpoints. The TSI method was preferred over other sinuosity methods because it is scale-independent and is widely adopted (Juracek, 2000; Marston et al., 2005; Egozi and Ashmore, 2008).

Hydrologic Analysis

Hydrologic records are useful in many applications, such as flood forecasting, reservoir design and operation, and fluvial geomorphic investigations (Juracek and Fitzpatrick, 2009). In this study, hydrologic data were used to detect a large shift in the hydrologic regimen that may have triggered a complete channel pattern transformation (Schumm, 1969). Data from four USGS stream gages on the Arkansas River were utilized to establish a relationship between the hydrology and the dynamics of channel morphology; gages included Below John Martin Reservoir (JMR), Coolidge, Syracuse, and Garden City (Figure 4). The Below JMR gage began collecting hydrologic data in 1938, Coolidge in 1951, Syracuse in 1921, and Garden City in 1923. The stream gage located downstream of JMR is about 400 m from the dam and does not have an associated floodstage. These gages were used to conduct numerous analyses, such as computing 1) mean annual discharge, 2) peak annual discharge, and 3) frequency of high flows. Mean and peak annual discharge were calculated for all four gages using daily flow statistics, where mean discharge is the sum of the daily discharges over a year divided by the number of days and peak discharge is the largest daily flow event of the record year. Frequency of high flows was computed for the Coolidge, Syracuse, and Garden City gages by analyzing daily flow statistics in order to find the number of days where the bankfull depth was met and exceeded. High flows were defined by the National Weather Service’s use of floodstage, which was verified as a height were the lowest lying areas become inundated.

1871 Public Land Survey and KDOT Bridge Crossing Comparisons

Public Land Survey (PLS) maps from 1871 provide an estimate of the early settlement channel widths. Martin and Johnson (1987) utilized channel widths indicated on PLS maps in their study of the Medicine Lodge River historical channel change and noted two inherent problems with the measurements. The 1871 survey is not clear on 1) if the surveyors measured the channel at water widths or bankfull widths and 2) if the channel width measurements were always recorded along section lines or at right angles to the channel banks (Martin and Johnson, 1987). For this study, the perpendicular section line crossings to the river channel were measured, and the survey measurements were interpreted to be taken from one bank to the other regardless of the actual width of the water flowing in the channel bed.

The Public Land Survey indicates measurements of channel width taken at 83 section line crossings, and, in most cases, these crossings were at oblique angles to the river. The 38 section lines that crossed the river in at least a quasi-perpendicular manner provided an opportunity to document the channel width well prior to the first aerial imagery (1939) (Figure 3; Appendix 1). As a result, every section line crossing that was roughly perpendicular to the river channel in the 1871 was compared to the equivalent, perpendicular section line crossing in the subsequent seven years of aerial photography.

Bridge construction profiles provided by the Kansas Department of Transportation (KDOT) were compared with on-site inspections. Three bridge plan schematics were used in an effort to reconstruct the historical channel. KDOT completed the bridge at Syracuse during 1952, the Lakin bridge in 1983, and the Garden City bridge in 1973. These bridge cross-channel profiles and accompanying site photographs were examined for evidence of channel migration, artificial stabilization, and downcutting.

Reduction of Errors

Aerial photographs can provide more accurate information about river channel change than historical map sources in that data on aerial photographs is uniformly represented and absent of the inherent distortions present in early maps. Aerial photographs present an impartial, standard depiction of the land surface; however, these images are susceptible to a range of errors that must be addressed. The same operator interpreted each aerial image, and each year of photography was captured at similar baseflow conditions with one exception. The June 1965 aerial photography for the Kansas High Plains Reach reveals high flow conditions; although, data from the USGS stream gages indicate peak flooding occurred in August 1965.

Delineation of the Arkansas River channel followed the bankfull channel technique in order to be as consistent as possible in the interpretation of channel boundaries for each year. Despite this strategy, complications occurred due to the dynamic nature of the metamorphosis and to anthropogenic activity. The changes in channel width did not always coincide with the bankfull channel technique. For example, the first continuous mature line of vegetation was used as a proxy for bankfull channel, although a rapid reduction in channel width was not always recorded due to the delay in time for vegetation to reach maturity. For example, salt cedar was introduced into western Kansas in 1921, but it wasn't prominent until the 1957 aerial photography and was indiscernible in the 1939 imagery (Gesink et al., 1970). Other anthropogenic influences led to complications in channel delineation, such as gravel pits, roads, irrigation canals, center pivots, and vehicle tracks. These structures provided artificial stabilization and controlled flow paths of the river channel especially near urban reaches of the river. Research for this study on the Arkansas River along the Kansas High Plains was largely derived from remote sensing-based techniques. A thorough site-based investigation and low-altitude flight of river reaches with notable change, USGS gages, artificial river barriers, tributaries, and canal diversions was conducted in order to verify the data and results.

RESULTS

Research on the historical metamorphosis of the Arkansas River along the Kansas High Plains has yielded two themes. The first, river hydrology, covers the analysis from USGS stream gage data and presents information from the study area hydrographs. Another theme in the results about channel morphology change details how the sinuosity and channel width have varied with each year of aerial photography. PLS measurements ranging from 1871 to 2014 are also described in the channel morphology change section.

River Hydrology

Peak annual flow (Figure 5), mean annual flow (Figure 8), and frequency of high flows (Figure 9) characterize the hydrologic history of the Arkansas River beginning in 1921, when the stream gage at Syracuse was installed. The mean annual flow hydrograph illustrates that moving downstream from Coolidge and Syracuse to Garden City, the discharge decreases farther downstream (Figure 8). For instance, the mean discharge at Coolidge and Syracuse is on most occasions relatively high, above 100 cfs, but decreases downstream, below 100 cfs, as reflected in the gage data at Garden City. The Coolidge gage was activated in 1951 and since then has similar mean annual discharge values, from 70 to 500 cfs, to that of the Syracuse gage (Figure 8). Mean annual flow values for Garden City are consistently lower than the other three gages (Figure 8). Also, the 1965 flood is visible on each hydrograph as a surge in discharge exceeding 10,000 cfs at Coolidge, Syracuse, and Garden City (Figure 5).

Peak annual flows recorded at the Below JMR and Coolidge gages are dramatically decreased in downstream data at Garden City (Figure 5). The same phenomenon exists in the frequency of high flows, where substantial flows that appear in the Coolidge gage data are not present in the downstream gages. Garden City has not experienced a flow exceeding 2000 cfs since the 2001 flood, and the last instance that this gage exceeded the flood stage of 10 ft was during the 1965 flood. At Syracuse, the flood stage of 10 ft was surpassed in 1965 but not again until 1987, but for only two days. Since 1948 when the John Martin Dam was completed, the flood stage in Garden City has been exceeded for only 11 days. In contrast to the Coolidge data, Garden City has appreciably lower peak annual discharges throughout the period of record. At Garden City, the mean and peak annual flows decrease dramatically from above 100 to below 50 cfs for peak flows and from above 50 to below 1 cfs during 2002 to 2003. At JMR, the discharge is relatively stable, for example, the peak discharge is consistently around 1,500 cfs and the mean annual discharge fluctuates from 150 to 400 cfs (Figures 5 and 8).

Channel Morphology Change

Arkansas River channel morphology within the Kansas High Plains has experienced remarkable changes in the 75-year period of study, where width and sinuosity were used as the primary indicators of such (Figure 10; Appendix 2). The present-day Arkansas River in this reach is a meandering, narrow and entrenched channel, which is in stark contrast to the wide and braided channel of the 1800s and 1939. Width and sinuosity were each quantified as a single measurement for the entire study reach and also for each valley width section for every year of aerial photography (Table 5) (Figure 3). The Public Land Survey Maps from 1871 document the channel width 143 years ago (Figure 11); section line crossings range from 240 to 572 m, with a mean channel width of 363 m. Overall, the river channel has greatly narrowed and increased in sinuosity during the period of study. In 1939, the mean channel width was about 175 m, but by 2014 the mean channel width was around 30 m. Presently the Arkansas River channel is 17% of the 1939 width, and the seven years of aerial photographic documentation show that the channel has progressively narrowed, with the exception of two years: 1965 and 1991. Sinuosity has increased considerably in the last 75 years, resulting in a large increase in river length over the study area: from 296 km (1939) to 355 km (2014). From 1939 to 2014 sinuosity increased by 84%, with the largest increases occurring between 1939 to 1957 and 2003 to 2014.

Maps illustrating the channel courses for each year of aerial photography were compiled with the latest year as top map layer as shown in the sample reach, where the middle portion of the study area reach is depicted (Figure 12). Only a portion of reaches resemble the sample reach, whereas major changes in channel morphology occurred east of Syracuse (western portion of study reach), where the sinuosity increased dramatically and the channel narrowed considerably in comparison to downstream reaches of the river (Figure 13). Minor modifications to the channel were documented at the eastern portion of the study reach in Finney County, where channel sinuosity has remained relatively stable from 1.1-1.2 during the 75 years of record (Figures 14 and 15).

The study area was divided into four sections based on valley width: two relatively wide valley sections and two relatively narrow valley sections (Figure 3). Mean sinuosity measurements for each of these sections for the 75-year period of study suggest that the wide valley sections have exhibited far more sinuous channel morphology (Figure 15). The largest sinuosity increase occurred in section two (1.8), and the least sinuosity increase in section four (1.08). All of the section sinuosity values increase as time progresses, however with 1965 and 2003 again being exceptions. Channel width measurements according to valley width sections were plotted, though no difference or pattern for narrow and wide valleys was recognized.

DISCUSSION

Flow Regime

Analysis of mean and peak flow events provides evidence that change in the hydrologic regime is responsible for channel planform adjustments, where the hydrology and channel width are directly related (Figures 5 and 9) (Wellmeyer et al., 2005). Schumm (1969) predicted that “unstable” rivers of the Western United States were subject to channel pattern transformations following anthropogenic modifications, such as reduced flood peaks and altered sediment particle transport. The Arkansas River channel has narrowed considerably during the period of this study (except for 1965 and 1991), which is attributed to anthropogenic modifications in stream hydrology. High peak discharges from rare hydrologic events were recorded at each study area stream gage during the two exceptional years, which resulted in short-term widening. After the completion of John Martin Dam in 1948 the mean annual discharge was reduced, peaks flows were diminished, and flow became perennial (Figures 5 and 8). At Garden City, the large decrease from in peak annual flows, for instance, above 100 cfs to below 50 cfs during 2003 to 2004 is likely attributed to the sustained use of free flow to the irrigation canals and closed flow to the river due to the drought occurring at that time (Figure 16) (Layzell and Evans, 2013).

The dramatic changes in width and sinuosity for the study reach are not caused by changes in precipitation because no major temporal change is evident (R^2 0.0077) during the period of record (Skaggs, 1978; Garbrecht et al., 2004) (Figure 16). Since 1920 the precipitation values have varied from 5 to 100 cm per year, however due to the valley geomorphology the variation in precipitation is not influencing channel morphology (Figure 16). For example, increases in rainfall will not dramatically shift channel width and sinuosity due to the high infiltration rates from the valley's sandy soils and the limited tributaries within the Kansas High Plains reach of the Arkansas River are short and ephemeral, therefore contributes only minor flow to the river. In comparison, the Little Colorado River narrowed considerably from decreases in precipitation and relatively minor anthropogenic influences on hydrology (Block, 2014).

Other anthropogenic and geomorphic influences were factors affecting hydrology of the Arkansas River within the Kansas High Plains, which then subsequently affected channel morphology. Landscape factors, such as the reduced valley gradient and absence of significant tributaries, have resulted in the study reach channel morphology to be distinctly different from upstream and downstream reaches (Sherow, 1981). For instance, the limited number of tributaries within the Kansas High Plains adds only minor discharge to the river and as result narrow channels, whereas upstream in Colorado the river has contributions from Cheyenne Creek, Pauls Arroyo, and Buffalo Creek and downstream near Larned and Great Bend the Arkansas River has contributions from the Pawnee River and Walnut Creek. Effects of irrigation canal diversions and wells to supply groundwater for center-pivot irrigation in the Arkansas River valley are evident in the river hydrographs. The peak annual flow hydrograph indicates a decrease in discharge from below JMR relative to Garden City for each year (Figure 5). The High Plains aquifer has been extensively used for irrigation, with dramatic increases in use from 2.1 million acres in 1949 to 13.7 million acres in 1980 (McGuire, 2012). In 1940 alone, 520 irrigation wells were drilled in southwestern Kansas, withdrawing 90,000 acre-feet/yr (Pabst and Gutentag, 1979). This increased dependence on the High Plains aquifer has lowered the water table in eastern Kearny County and Finney County in extreme cases by up to 31 m (McGuire, 2012). As a result of groundwater pumping, the river in the study reach has lost its baseflow. An important temporal change in the hydrologic regime is present at Coolidge and Garden City gage locations, which display a pronounced decrease in annual mean discharge, peak discharge, and flood events (Figures 5, 8, and 9). This decrease in peak discharge at these two locations is due to 1) the lack of large tributaries in this reach of the river and 2) diversions for four canals between these two gage locations (Figure 6). Furthermore, years in which the discharge was fairly consistent, such as in 1957, 2003, and 2014, the channel responded to the absence of peak flows by narrowing. The notion that an altered hydrologic regime can bring about changes in channel morphology on the Arkansas River was previously predicted by Nadler and Schumm (1981) for a river reach in eastern Colorado and holds true along the Kansas High Plains.

Historical Channel Planform Change

The Arkansas River channel narrowed during the 75-year period of study, though some deviations from that trend did occur during the seven discrete years of photographic documentation. When the 1939 photographs were taken, the mean Arkansas River channel width was about 175 m with a sinuosity of 1.22. By 1957, channel sinuosity increased slightly to 1.28, and mean width decreased by 60%. The completion of John Martin Dam in 1948 and the widespread extraction of groundwater for center pivot irrigation starting in the 1960s modified the hydrologic regime, which then transformed the channel morphology (Pabst and Gutentag, 1979). The third year of aerial photography, 1965, indicated a reversal of the previous trend: sinuosity decreased slightly (1.27) and mean channel width increased by 23 m from the previous year of aerial photography. The large-magnitude flood event of 1965 was responsible for increasing channel width by destroying existing riparian growth and removing the previously constructed floodplain. Aerial photographs from 1986 indicated that mean channel width had decreased by 49 m and sinuosity increased to 1.30. The changes in width and sinuosity during this time are likely due to the fact that in 1980 the recorded use of the High Plains Aquifer for irrigation levels off in use with 13.7 million acres (McGuire, 2012). By the 1991 aerial photography, mean channel width had increased by about 2 m and sinuosity continued increasing to 1.32. The frequency of high-flow events in 1987 at Coolidge and a surge in mean annual flow produced this reversal to an increase in width. The 2003 mean channel width was similar to that of the 1991 channel, which may be a result of peak flow events in 1999 at Coolidge. The last year of photographic documentation, 2014, indicated the largest periodic increase in channel sinuosity (to 1.46 from 1.35 in 2001) and a decrease in mean channel width by about 16 m. The lack of peak flow events along the entire study reach and the highest recorded rate of groundwater for irrigation in 2005 (15.5 million acres irrigated) were the drivers of these morphologic changes.

Changes in Arkansas River channel morphology have also varied spatially along this Kansas High Plains reach. Previous research reported that clusters of riparian vegetation, such as cottonwood trees and salt cedar, were prevalent on the south side of the channel in Hamilton County and became increasing sparse to the east in Finney County. Channel sinuosity is appreciably greater in Hamilton County than in eastern Kearny County and Finney County, a pattern that is due to vastly reduced riparian vegetation growth in the latter area (Figure 17). The difference in riparian vegetation growth is due to a number of irrigation canals between Hamilton and Finney Counties, which limits water available for plants. For example, the Amazon and Southside irrigation canals near the town of Hartland and the Farmers irrigation canal at the Kearny-Finney County border divert considerable water (Sherow, 1990) (Figure 7).

Channel change analyses from seven years of aerial photography indicate a substantial downstream narrowing of the Arkansas River following the construction of JMR. JMR and irrigation diversion canals control discharge on the Arkansas River, which then dictates in-channel processes and influences channel morphology. Riparian vegetation coverage and channel sediment availability are dependent on artificially-controlled flow conditions, where river reaches close to the Colorado border and JMR have a different channel morphology compared to those reaches downstream (Figure 18). Reaches that experience sporadic flows, for example around Coolidge and Syracuse, have narrow sinuous channels, where the discharge is actively building and stabilizing the floodplain and channel banks. Downstream, below the irrigation diversions, the channel is wider and follows a relatively straight course. Near Holcomb and Garden City channel-forming flows are rare. Diversion canals, occurring at two locations in the study reach, one west of Hartland and another west of Holcomb have resulted in morphologic changes in the channel immediately downstream (Figure 7). Upstream of Holcomb above the

Farmers Ditch diversion, the channel is fairly sinuous (1.47), somewhat narrower (20m), and has vegetated banks, but below the diversion the channel is wide (55m) and artificially-straightened (1.15) with only sparse riparian vegetation.

The density and channel juxtaposition of riparian growth enhances sinuosity, though valley width is also a major controlling factor. The two relatively wide valley sections, one in the western half of Hamilton County and the other in the eastern half of Kearny County, accommodate large increases in sinuosity due to the 3-8 km valley widths (Figure 3). Narrow valley width imposes a constraint on the width of the meander belt, but changes in sinuosity are also dependent on channel-forming flows. Sinuosity may have the lateral space to increase but without an increased discharge sufficient to affect modifications in channel position sinuosity will not change. The first section from Coolidge to Kendall has a wide valley section with frequent channel-forming flows, which results in a larger sinuosity value than the other wide valley section, section 3, which rarely experiences any channel-forming discharge. Valley width is a factor contributing to the variation in the sinuosity; however, the hydrology or occurrence of channel-forming flows has a larger influence (Figure 15). Multiple factors, such as riparian vegetation growth, artificial stabilization from center pivots and rip rap, and the locations of irrigation canals all influence the channel morphology and cannot be differentiated.

Cross-channel profiles of bridge crossings from KDOT and ground truthing images show that the channel near Garden City has entrenched roughly a 1.5 m over time (Figure 19). The timing and magnitude of downcutting is beyond the scope of this study and the necessary data sources to systematically characterize the vertical changes are not available. Anecdotal evidence, however from bridge construction profiles and ground-based observations reveal that the modern channel has entrenched below the pre-development channel. Entrenchment is difficult to assess at bridge crossings due to the emplacement of rip rap, Kellner jetty jacks, and other channel control methods, but entrenchment is evident on each of the bridges where one or more support columns are within the river channel. Bridges often create atypical flow conditions; there is consistency among the study area bridges as to the evidence for entrenchment. Upstream from all the study area diversion canals (Hamilton County), channel entrenchment is greatest due to the frequent channel-forming flows.

Chronology of Channel Pattern Change

A result of this research is that of developing the chronology of channel change in this reach of the Arkansas River. Schumm (1963) and Moody-Stuart (1966) classifications for channel patterns and the total sinuosity index were used to quantitatively determine the time period in which the river shifted from braided to meandering. The channel pattern change occurred between the years of 1986 and 1991 when the sinuosity crossed the 1.3 value, where the channel transitioned from a braided classification to a meandering one (Table 1). After 1991 the sinuosity began to increase relatively quickly to 1.35 in 2003 and 1.46 in 2014. No one event led to the time in which the river experienced a complete channel pattern change but a culmination of events. Together the absence of peak flow events, such as in 1965, have not occurred, groundwater withdrawals have increased, salt cedar has become ubiquitous for stabilizing channel banks, and the continued use of numerous irrigation diversion canals has resulted in the complete channel pattern change between 1986 and 1991.

The shift from the braided to meandering channel pattern for the Kansas High Plains reach did occur between the 1986 and 1991 period, however as previously noted channel changes have varied based on study area location (Figures 13,14 and 18). Upstream sections have sinuosity values above 1.6 in some cases, whereas downstream sections have mean sinuosity values of 1.2 (Figure 15). These differences between upstream and downstream sinuosity values are attributed to the locations of the Farmers and Amazon Irrigation Diversion Canals, which have limited the flows reaching downstream (Figures 4 and 7). Sections 1, 2, and the majority of section 3 receive channel forming flows, where as section 4 rarely experiences flows exceeding bankfull depths (Figure 9). Upstream reaches near Syracuse have well-defined cutbank and pointbar sequences in comparison to downstream reaches near Garden City where the channel is fairly straight (Figure 20). This contrast in sinuosity between sections 1, 2, and 3 from section 4 occurred between 1965 and 1986 when the majority of sinuosity values for the first three sections are above 1.3 (Figure 15). The metamorphosis of the Kansas High Plains is shown to occur earlier, during the 1965-1986 period, when the downstream reach, near Garden City, exhibiting minor change is not included in the analysis.

CONCLUSIONS

River metamorphosis has been documented in global river systems during the historical and Late Quaternary contexts. For example, during the Late Pleistocene to Holocene transition many rivers underwent a metamorphosis, such as the Mississippi River (Rittenour et al., 2005), Murrumbidgee River (Schumm, 1969), Maas River (Huisink, 1983), and multiple rivers in the southeastern U.S. (Leigh, 2006). At this time, around 20 ka, the Arkansas River appears to have changed its channel pattern from a highly sinuous meandering stream channel to a braided system (Johnson and Dort, 1988; Jaumann, 1991). While these late-Pleistocene changes in channel patterns were climatically induced, the historical changes in the Arkansas River channel within the Kansas High Plains are being driven by anthropogenic influences, but the changes are equally dramatic in regards to the large degree of channel change over a small expanse of time.

This study of historical channel change along the Kansas High Plains reach of the Arkansas River has documented the channel as it relates to surface-water and groundwater hydrology for the past 75 years. The hydrologic history of the Arkansas River explains the major significant changes in sinuosity and width changes. The Arkansas River metamorphosis was observed along with other rivers on the Great Plains such as the North and South Platte Rivers, where a dramatic change in the hydrologic regimen transformed the channel morphology. In most cases, as with the North and South Platte Rivers, tributary streams below the point of main-channel regulation still contribute water and sediment to the main channel (Schumm, 2003). The metamorphosis of the Arkansas River channel is especially intense and more developed compared to downstream and upstream reaches due to local conditions, such as minor tributary inputs and the large amount of diversion canals. Along the Kansas High Plains reach of the Arkansas River anthropogenic influences from irrigation diversion canals to groundwater pumping are extensive and compound the hydrological effects of upstream dams and limited local tributary input.

The recent history of the Arkansas River along the Kansas High Plains and any indications of possible future behavior will impact, directly or indirectly a substantial number of people and a large portion of the state's economy (Dort, 2009). Therefore, in order to predict future changes in the Arkansas River channel one should appreciate the channel transformation that occurred historically. Research regarding the historical channel changes along the Kansas High Plains reach is intended to aid future river engineering decisions from the U.S. Army Corps of Engineers and KDOT. The Arkansas River along the Kansas High Plains has experienced changes in width, depth, and sinuosity; therefore, in light of channel entrenchment and meander migration, erosion of the channel bed and bank is anticipated. Government agencies can utilize this research to mitigate erosion levels and propose solutions to stabilize the channel banks by limiting the proximity of center pivot irrigation systems and gravel pit operations to the river channel and allowing riparian vegetation to mature. Channel change research is also exceptionally valuable to natural resource management agencies to maintain watershed conditions, wildlife habitat, and the aesthetic value of fluvial landscapes.

The GIS-derived analysis of the Arkansas River channel morphology produced from aerial photographs has confirmed trends predicted by previous studies regarding channel narrowing and sinuosity increases (Schumm, 1969; Nadler and Schumm, 1981; Schumm, 2003). As a result of documenting and quantifying the historical channel change for the past 75 years this study indicates that 1) the Arkansas River along the Kansas High Plains is a relatively unstable system adjusting to changes in hydrology and 2) the river has experienced a historical metamorphosis from anthropogenic modifications of surface-water and groundwater hydrology. The Arkansas River channel will likely continue its current trend of increasing sinuosity and narrowing as long as the present-day hydrologic regime is maintained. Subsequent research on the Arkansas River historical channel change should determine if these morphologic patterns occur upstream and downstream of the Kansas High Plains reach.

REFERENCES

Baker, V. R. 1977. Stream-channel Response to floods, with examples from central Texas. Geological Society of America Bulletin 88, 1057-1071.

Block, D. 2014. Historical Channel-Planform Change of the Little Colorado River near Winslow, Arizona. United States Geological Survey Scientific Investigation Report 2014-5112, 1-24.

Braga, G., & Gervasoni, S. 1989. Evolution of the Po River: an example of the application of historic maps. Historical Change of Large Alluvial Rivers: Western Europe. Chichester: Wiley, 113-126.

Bravard, J. P., & Bethemont, J. 1989. Cartography of Rivers in France. Historical Change of Large Alluvial Rivers: Western Europe. Chichester: Wiley, 95-111.

Brandt, S. A. 2000. Classification of geomorphological effects downstream of dams. Catena 40, 375-401.

Brotherton, D. I. 1979. On the origin and characteristics of river channel patterns. Journal of Hydrology 44, 211-230.

Bryant, R. G., & Gilvear, D. J. 1999. Quantifying geomorphic and riparian land cover changes either side of a large flood event using airborne remote sensing: River Tay, Scotland. Geomorphology 29, 307-321.

Burkham, D.E. 1972. Channel changes of the Gila River in Safford valley, Arizona, 1846-1970. United States Geological Survey Professional Paper 655, 1-23.

Covich, A. P., Fritz, S. C., Lamb, P. J., Marzolf, R. D., Matthews, W. J., Poiani, K. A., & Winter, T. C. 1997. Potential effects of climate change on aquatic ecosystems of the Great Plains of North America. Hydrological Processes 11, 993-1021.

Dominick, D. S., & O'Neill, M. P. 1998. Effects of flow augmentation on stream channel morphology and riparian vegetation: Upper Arkansas River Basin, Colorado. Wetlands 18, 591-607.

Dort, W. 2009. Historical channel changes of the Kansas River and its major tributaries. American Geographical Society, 1-80.

Dunlap, L. E., Lindgren, R. J., & Sauer, C. G. 1985. Geohydrology and model analysis of stream-aquifer system along the Arkansas River in Kearny and Finney counties, southwestern Kansas. United States Geological Survey Water-Supply Paper, 1-52.

Egozi, R., & Ashmore, P. 2008. Defining and measuring braiding intensity. Earth Surface Processes and Landforms 33, 2121-2138.

Erskine, W. D. 1986. River metamorphosis and environmental change in the Macdonald Valley, New South Wales, since 1949. Australian Geographical Studies 24, 88-107.

Eschner, T. R., Hadley, R. F., & Crowley, K. D. 1983. Hydrologic and morphologic changes in channels of the Platte River basin: a historical perspective. United States Geological Survey Open-File Report, 81-1125.

Forman, S. L., Marín, L., Gomez, J., & Pierson, J. 2008. Late Quaternary Eolian Sand Depositional Record for southwestern Kansas: Landscape Sensitivity to Droughts. Palaeogeography, Palaeoclimatology, Palaeoecology 265, 107-120.

Friedman, J.M., Osterkamp, W. R., Scott, M. L., & Auble, G. T. 1998. Downstream effects of dams on channel geometry and bottomland vegetation: regional patterns in the Great Plains. Wetlands 18, 619-633.

Garbrecht, J., Van Liew, M., & Brown, G. O. 2004. Trends in precipitation, Streamflow, and Evapotranspiration in the Great Plains of the United States. Journal of Hydrologic Engineering 9, 360-367.

Gesink, R. W., Tomanek, G. W., & Hulett, G. K. 1970. A descriptive survey of woody phreatophytes along the Arkansas River in Kansas. Transactions of the Kansas Academy of Science, 55-69.

Graf, W. L. 1978. Fluvial adjustments to the spread of tamarisk in the Colorado Plateau region. Geological Society of America Bulletin 89, 1491-1501.

Graf, W. L. 2001. Damage control: restoring the physical integrity of America's rivers. Annals of the Association of American Geographers 91, 1-27.

Graf, W. L. 2006. Downstream hydrologic and geomorphic effects of large dams on American rivers. Geomorphology 79, 172-191.

Gregory, S., Ashkenas, L., Oetter, D., Minear, P., &Wildman, K. 2002. Historical Willamette River Channel Change. Oregon State University Press, 18-24.

Gregory, K. J. 2006. The human role in changing river channels. Geomorphology 79, 172-191.

Gurnell, A. M. 1997. Channel change on the River Dee meanders, 1946–1992, from the analysis of air photographs. Regulated Rivers: Research & Management 13, 13-26.

Halfen, A.F. 2012. Aeolian Dunefields of Kansas and their Response to Late-Quaternary Drought. Doctoral Dissertation. Lawrence: University of Kansas.

Haworth, E. 1897. Underground waters of southwestern Kansas. Kansas State Printing Office, 1-69.

Hereford, R. 1984. Climate and Ephemeral-stream Processes: Twentieth-century Geomorphology and Alluvial Stratigraphy of the Little Colorado River, Arizona. Geological Society of America Bulletin 95, 654-668.

Hickin, E. J. 1974. The development of meanders in natural river-channels. American Journal of Science 274, 414-442.

Hooke, J. M., & Redmond, C. E. 1989. Use of Cartographic Sources for Analysing River Channel Change with Examples from Britain. Historical Change of Large Alluvial Rivers: Western Europe. Chichester: Wiley, 79-93.

Huisink, M. 1997. Late-glacial sedimentological and morphological changes in a lowland river in response to climatic change: the Maas, southern Netherlands. Journal of Quaternary Science 12, 209-223.

Jaumann, P.J. 1991. Evidence for late Quaternary Boreal Environments in the Arkansas River valley, south-central Kansas: Theoretical Aspects of Paleoecology and Climatic Inferences. Master's Thesis. Lawrence: University of Kansas.

Johnson, W.C., Arbogast, A.F. 1993. Geologic Map of Finney County, Kansas (southern part). Kansas Geologic Survey Map Series M-28B.

Johnson, W.C., Dort Jr., W. 1988. Paleochannels of the Arkansas River, Western Kansas, and Hydrologic Implications. Abstract from Association of American Geographers Annual Conference: Phoenix, Arizona, USA.

Johnson, W.C., Spray, K.L., Dort, W. 1994. Impact of Surface-Water and Groundwater Withdrawal on Riparian Vegetation and Stream Channel Morphology in the Arkansas River Valley, western Kansas. Kansas Geological Survey Open File Report 94-39, 1-128.

Juracek, K. E. 2000. Channel Stability Downstream from a Dam Assessed using Aerial Photographs and Stream Gage Information. Journal of the American Water Resources Association 36, 633-645.

Juracek, K. E., & Fitzpatrick, F. A. 2009. Geomorphic applications of stream- gage information. River research and applications 25, 329-347.

Kellerhals, R., Bray, D. I., & Church, M. 1976. Classification and analysis of river processes. Journal of the Hydraulics Division 102, 813-829.

Knighton, D. 1998. Fluvial Forms and Processes: A New Perspective. Routledge: Hodder Education, 1-383.

Knox, J. C. 1983. Responses of river systems to Holocene climates. Late Quaternary Environments of the United States. Ed. By H.E. Wright and S.C. Porter. University of Minnesota Press 2, 26-41.

Kondolf, G. M. 2003. Tools in Fluvial Geomorphology. Chichester: Wiley, 1-396.

Layzell, A.L. 2012. A Thousand Years of Drought and Climatic Variability in Kansas: Implications for Water Resources Management. Kansas Geological Survey Open File Report 2012-18, 1-23.

Leeder, M. R. 1973. Fluviatile Fining-upwards Cycles and the Magnitude of Palaeochannels. Geological Magazine 110, 265-276.

Leopold, L. B., & Wolman, M. G. 1957. River channel patterns: braided, meandering, and straight. United States Geological Survey Professional Paper 282-B, 1-50.

Leigh, D. S. 2006. Terminal Pleistocene braided to meandering transition in rivers of the Southeastern USA. Catena 66, 155-160.

Lewin, J., & Brewer, P. A. 2001. Predicting channel patterns. Geomorphology 40, 329-339.

Leys, K.F. & Werritty, A. 1999. River Channel Planform Change: Software for Historical Analysis. Geomorphology 29, 107-120.

Luckey, R.R., 1975. Hydrologic Effects of Reducing Irrigation to maintain a permanent pool in John Martin Reservoir, Arkansas River Valley, Colorado. United States Geological Survey Open File Report 75-214, 1-26.

Luttrell, G. R., Echelle, A. A., Fisher, W. L., & Eisenhour, D. J. 1999. Declining status of two species of the Macrhybopsis aestivalis complex (Teleostei: Cyprinidae) in the Arkansas River Basin and related effects of reservoirs as barriers to dispersal. Copeia, 981-989.

Mangelsdorf, J., Scheurmann, K., & Weiss, F. H. 1990. River Morphology: a Guide for Geoscientists and Engineers. Berlin: Springer Science & Business Media, 1-235.

Marston, R. A., Girel, J., Pautou, G., Piegay, H., Bravard, J. P., & Arneson, C. 1995. Channel metamorphosis, floodplain disturbance, and vegetation development: Ain River, France. Geomorphology 13, 121-131.

Marston, R. A., Mills, J. D., Wrazien, D. R., Bassett, B., & Splinter, D. K. 2005. Effects of Jackson Lake Dam on the Snake River and its floodplain, Grand Teton National Park, Wyoming, USA. Geomorphology 71, 79-98.

Martin, C. W., & Johnson, W. C. 1987. Historical channel narrowing and riparian vegetation expansion in the Medicine Lodge River Basin, Kansas, 1871–1983. Annals of the Association of American Geographers 77, 436-449.

McGuire, V. L. 2012. Water-level and storage changes in the High Plains aquifer, predevelopment to 2011 and 2009–11. United States Geological Survey Scientific Investigations Report 2012-5291, 1-15.

Mead, J. R. 1896. A dying river. In Transactions of the Annual Meetings of the Kansas Academy of Science. Kansas Publishing House, 111-112.

Moody-Stuart, M. 1966. High-and low-sinuosity stream deposits, with examples from the Devonian of Spitsbergen. Journal of Sedimentary Research 36, 1102-1117.

Morisawa, M. 1985. River Form and Process. Geomorphology Texts 7, Rivers. New York: Longman Group Ltd., 1-222.

Nadler, C. T., & Schumm, S. A. 1981. Metamorphosis of South Platte and Arkansas Rivers, eastern Colorado. Physical Geography 2, 95-115.

Osterkamp, W.R. 1977. Fluvial Sediment in the Arkansas River Basin, Kansas. Bulletin 19 of the Kansas Water Resources Board, 1-33.

Pabst, M.E.; and Gutentag, E.D. 1979. Water-level changes in southwestern Kansas, 1940-78. Kansas Geological Survey Journal, 1-29.

Page, K., Frazier, P., Pietsch, T., & Dehaan, R. 2007. Channel change following European settlement: Gilmore Creek, southeastern Australia. Earth Surface Processes and Landforms 32, 1398-1411.

Parkman, F. 1948. The Oregon Trail. New York: Signet Classic, 1-363.

Petts, G.E. 1989. Historical Analysis of Fluvial Hydrosystems. Historical Change of Large Alluvial Rivers: Western Europe. Chichester: Wiley, 1-18.

Petts, G.E., Moller, H., & Warner, R.F. 1989. Historical Change of Large Alluvial Rivers: Western Europe. Chichester: Wiley, 1-365.

Richards, K. S. 1982. Rivers: Form and Process in Alluvial Rivers. London: Methuen, 1-358.

Rittenour, T. M., Blum, M. D., & Goble, R. J. 2007. Fluvial evolution of the lower Mississippi River valley during the last 100 ky glacial cycle: Response to glaciation and sea-level change. Geological Society of America Bulletin 119, 586-608.

Ritter, D. F., Kochel, R. C., & Miller, J. R. 1999. The disruption of Grassy Creek: implications concerning catastrophic events and thresholds. Geomorphology 29, 323-338.

Ritter, D. F., Kochel, R. C., & Miller, J. R. 2002. Process Geomorphology. New York: McGraw-Hill, 1-652.

Rosgen, D. L. 1994. A Classification of Natural Rivers. Catena 22, 169-199.

Rust, B. R. 1977. A Classification of alluvial Channel Systems. Canadian Society of Petroleum Geologists, 187-198.

Schumm, S. A., & Khan, H. R. 1972. Experimental Study of Channel Patterns. Geological Society of America Bulletin 83, 1755-1770.

Schumm, S. A., & Meyer, D. F. 1979. Morphology of Alluvial Rivers of the Great Plains. In Riparian and wetland habitats of the Great Plains: proceedings of the 31st annual meeting, Great Plains Agronomy Council Publication 91, 9-17.

Schumm, S. A., & Lichty, R. W. 1965. Time, space, and causality in geomorphology. American Journal of Science 263, 110-119.

Schumm, S. A. 1963. Sinuosity of alluvial rivers on the Great Plains. Geological Society of America Bulletin 74, 1089-1100.

Schumm, S. A. 1969. River Metamorphosis. In Journal of the Hydraulics Division, American Society of Civil Engineers 95, 255-273.

Schumm, S. A. 1973. Geomorphic Thresholds and Complex Response of Drainage Systems. Fluvial geomorphology. Ed. By M. Morisawa, 299-309.

Schumm, S. A. 1977. The Fluvial System. New York: Wiley, 1-338.

Schumm, S. A. 1979. Geomorphic Thresholds: the concept and its applications. Transactions of the Institute of British Geographers, 485-515.

Schumm, S. A. 2005. River Variability and Complexity. Cambridge: University Press, 1-220.

Sherow, J. E. 1990. Watering the valley: development along the High Plains Arkansas River, 1870-1950. Lawrence: University Press of Kansas, 1-222.

Skaggs, R. H. 1978. Climatic Change and Persistence in western Kansas. Annals of the Association of American Geographers 68, 73-80.

Smith, H. T. U. 1940. Notes on historic changes in stream courses of western Kansas, with a plea for additional data. Transactions of the Kansas Academy of Science, 299-300.

Smith, D. G. 1976. Effect of vegetation on lateral migration of anastomosed channels of a glacier meltwater river. Geological Society of America Bulletin 87, 857-860.

St John, O. 1885. Notes on the geology of southwestern Kansas. Fifth Biennial Report of State Board of Agriculture, 140-142.

Tomelleri, J. R. 1984. Dynamics of the woody vegetation along the Arkansas River in western Kansas, 1870-1983. Doctoral Dissertation. Hays, KS: Fort Hays State University.

Tiegs, S.D. & Pohl, M. 2005. Planform Channel Dynamics of the lower Colorado River: 1976-2000. Geomorphology 69, 14-27.

VanLooy, J. A., & Martin, C. W. 2005. Channel and vegetation change on the Cimarron River, southwestern Kansas, 1953–2001. Annals of the Association of American Geographers, 95, 727-739.

Wallick, J. R., Grant, G. E., Lancaster, S. T., Bolte, J. P., & Denlinger, R. P. 2007. Patterns and controls on historical channel change in the Willamette River, Oregon, USA. Large rivers: geomorphology and management. John Wiley & Sons, 491-516.

Wellmeyer, J. L., Slattery, M. C., & Phillips, J. D. 2005. Quantifying downstream impacts of impoundment on flow regime and channel planform, lower Trinity River, Texas. Geomorphology 69, 1-13.

Williams, G. P. 1978. The case of the shrinking channels: The North Platte and Platte Rivers in Nebraska. United States Geological Survey, 1-48.

Williams, G.P, and Wolman, M.G. 1984. Downstream effects of dams on alluvial rivers. United States Geological Survey Professional paper 1286, 1-111

Young, D.P., Whittemore, D.O., Grauer, J.L., Whitmer, J.M. 2000. Lithologic Characterization of Unconsolidated along the Arkansas River Corridor in southwest Kansas. Kansas Geological Survey Open File Report 43, 1-14.

TABLES

Table 1: Classification and parameters for alluvial river channel patterns within the Great Plains (Schumm, 1963).

Channel Pattern	# of Channels	Sinuosity	Stream Slope (ft/ft)	Valley Slope (ft/ft)	Width -Depth Ratio	Weighted Means Silt-Clay (%)	Silt-Clay Bank (%)	Median Grain Size (mm)	Mean Annual Discharge (cfs)
Tortuous	10	2.3	0.00095	0.00223	5.2	43.4	89	0.42	70
Irregular	9	1.8	0.00062	0.00116	19.0	14.0	82	0.71	149
Regular	4	1.7	0.00077	0.00132	25.5	8.8	72	0.74	209
Transitional	7	1.3	0.00154	0.00193	56.0	4.9	54	0.45	255
Straight	11	1.1	0.00145	0.00175	43.0	3.4	41	0.35	370
Straight (islands)	6	1.1	0.00148	0.00170	52.0	4.1	45	0.37	421

Table 2: Complete channel pattern change studies.

River Name	Period of Metamorphosis	Author(s) and Year	Study Area	Pattern Change	Cause of Change
Ain River	Historical	Marston et al., 1995	France	braided to meandering	humans built a reservoir, artificial cutoffs, lateral embankments
South Platte River	Historical	Nadler and Schumm, 1981	southwestern Kansas	braided to meandering	humans and climate changed hydrology and sediment load
Arkansas River	Historical	Nadler and Schumm, 1981	eastern Colorado	braided to meandering	humans and climate changed hydrology and sediment load
Gilmore Creek	Historical	Page et al., 2007	Australia	meandering to braided	humans influenced riparian zone and sediment input
MacDonald River	Historical	Erskine, 1986	Australia	braided to meandering	humans and climate changed hydrology and sediment load
Mississippi River	Late Quaternary	Rittenour et al., 2005	central United States	meandering to braided to meandering	climate modified sea level and discharge
Murrumbidgee River	Late Quaternary	Schumm, 1969	Australia	meandering to braided	climate altered sediment load and discharge
Maas River	Late Quaternary	Huisink, 1983	Netherlands	braided to meandering	climate altered sediment load and discharge
Multiple Rivers	Late Quaternary	Leigh, 2006	southeastern United States	braided to meandering	climate modified sediment load and vegetation

Table 3: Central Great Plains river systems where historical river channel change has been documented.

River Name	River Length (km)	Author(s) and Year	Study Area	Documented Change	Cause of Change
North Platte River and Platte River	499	Eschner et al., 1983	Colorado, Wyoming, and Nebraska	channel narrowing, sinuosity increase	regulation in discharge
Cimarron River	1123	VanLooy and Martin, 2005	southwestern Kansas	channel narrowing, riparian density increase	decreased discharge from climatic variability
North Platte River	1152	Williams, 1978	western, central Nebraska	channel narrowing, riparian density increase	regulation in discharge
Cimarron River	1123	Schumm and Lichty, 1963	southwestern Kansas	channel widening	large flooding event
Platte River	499	Williams, 1978	western, central Nebraska	channel narrowing, riparian density increase	regulation in discharge
South Platte River	707	Eschner et al., 1983	Colorado, Wyoming, and Nebraska	channel narrowing, sinuosity increase	regulation in discharge
Medicine Lodge River	210	Martin and Johnson, 1987	South central Kansas	channel narrowing, riparian density increase	decreased discharge from less precipitation

Table 4: Aerial photography from which channel courses were digitized.

Year of Aerial Photography	Scale	Type
1939	1: 20,000	Black and White
1957	1: 20,000	Black and White
1965	1: 20,000	Black and White
1986	1: 20,000	Black and White
1991	1: 12,000	Black and White
2003	1: 12,000	Color
2014	1: 12,000	Color

Table 5: Sinuosity and mean width calculations derived from digitized channel courses.

Year of Arkansas River Channel	Sinuosity (Total Sinuosity Index)	Average Width (m)
1939	1.22	174.93
1957	1.28	69.72
1965	1.27	92.51
1986	1.30	43.94
1991	1.32	46.27
2003	1.35	46.22
2014	1.46	29.81

FIGURES

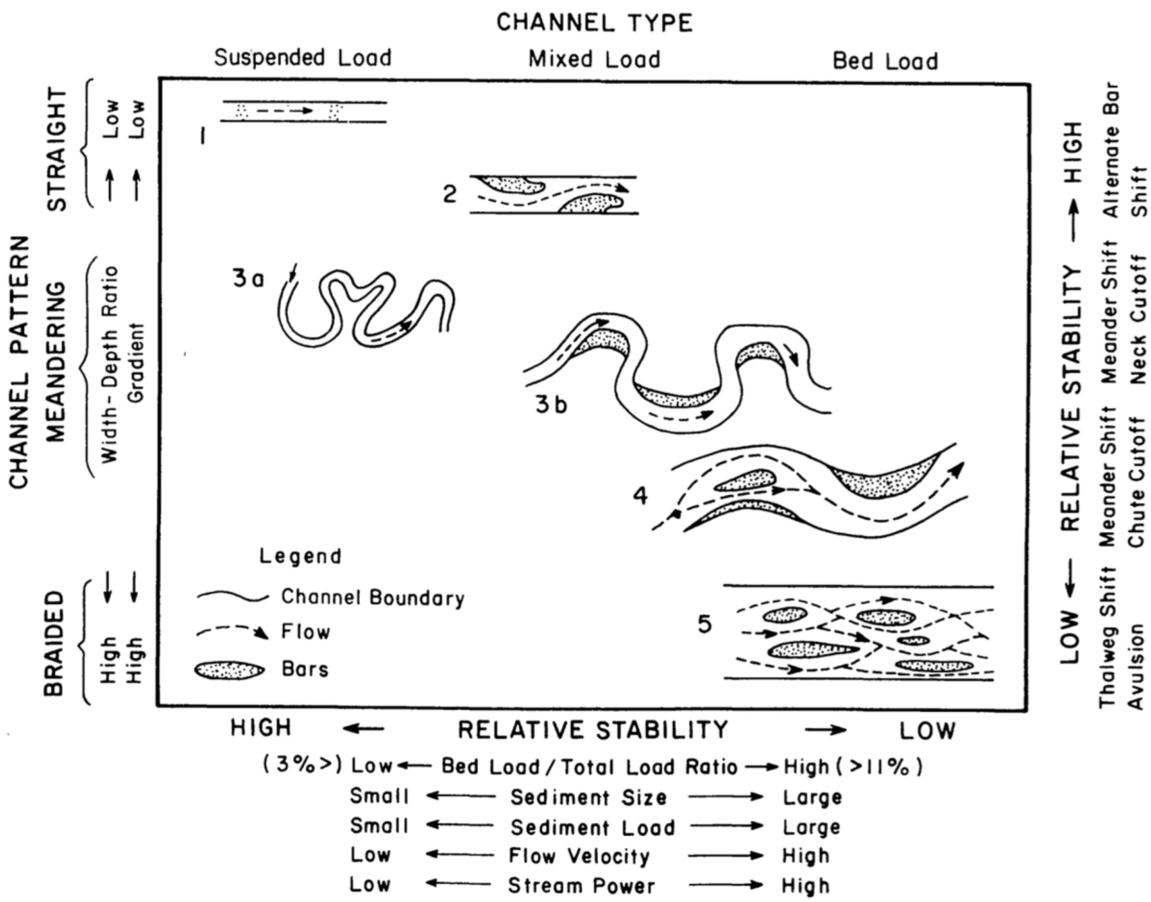

Figure 1: Channel pattern classification and relative stability of alluvial channels for the Great Plains (Schumm and Meyer, 1979).

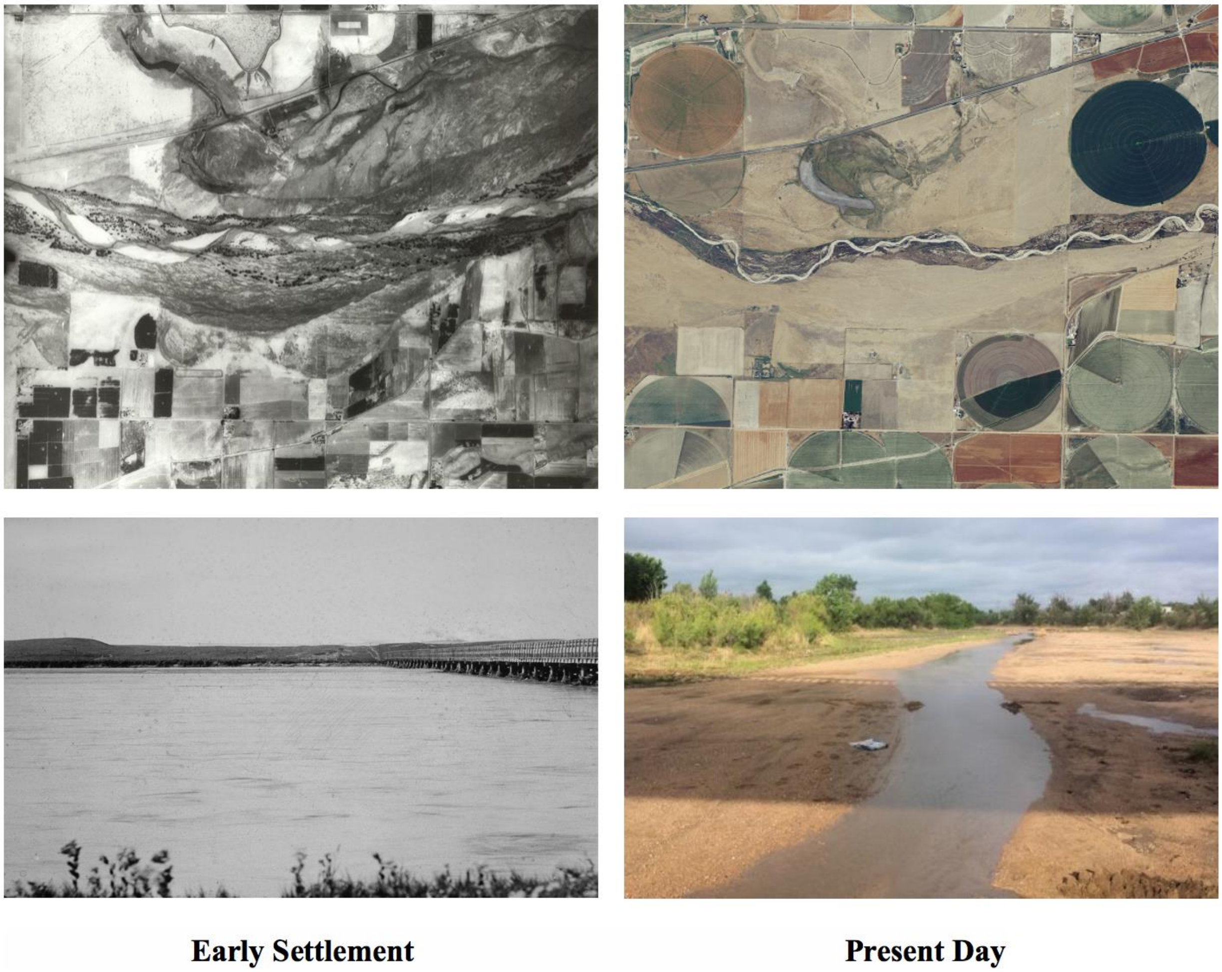

Figure 2: Past (left) and present (right) comparison of the Arkansas River in western Kansas. Top Left- 1939 aerial image of the Arkansas River as a braided channel pattern in Finney County (National Archives). Top Right- 2012 aerial image depicting the same reach of the Arkansas River as the top left image but as a meandering pattern (National Agriculture Imagery Program). Bottom left- Historical ground perspective image of the Arkansas River bridge at Garden City (view south/southwest) during the late 1800s (Kansas State Historical Society). Bottom right- Present day upstream (west) view from the Garden City bridge at U.S. Highway 83 (United States Geological Survey).

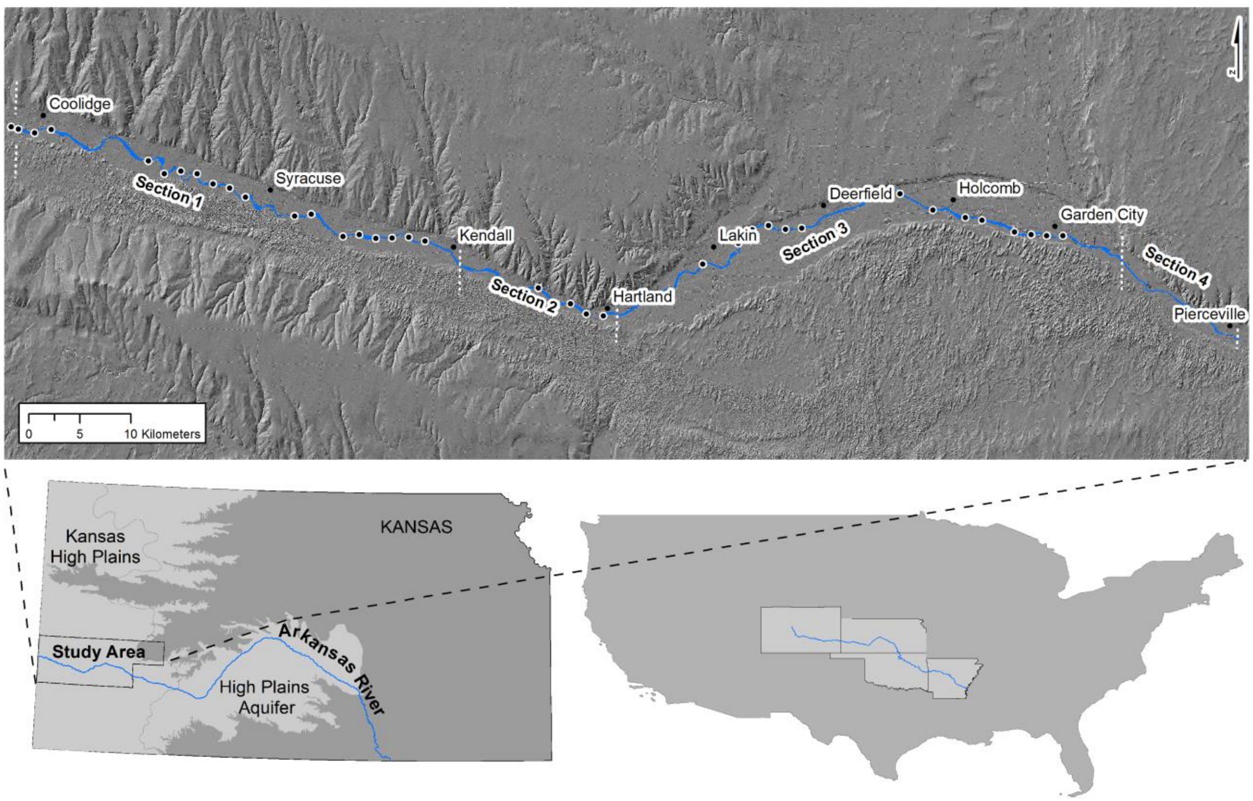

Figure 3: Kansas High Plains reach of the Arkansas River in western Kansas. The top image is a LiDAR-derived, hillshade-digital elevation model (DEM) of the study area. Highlighted black dots represent selected Public Land Survey (PLS) locations. Dotted white lines delineate each study area section based on valley width.

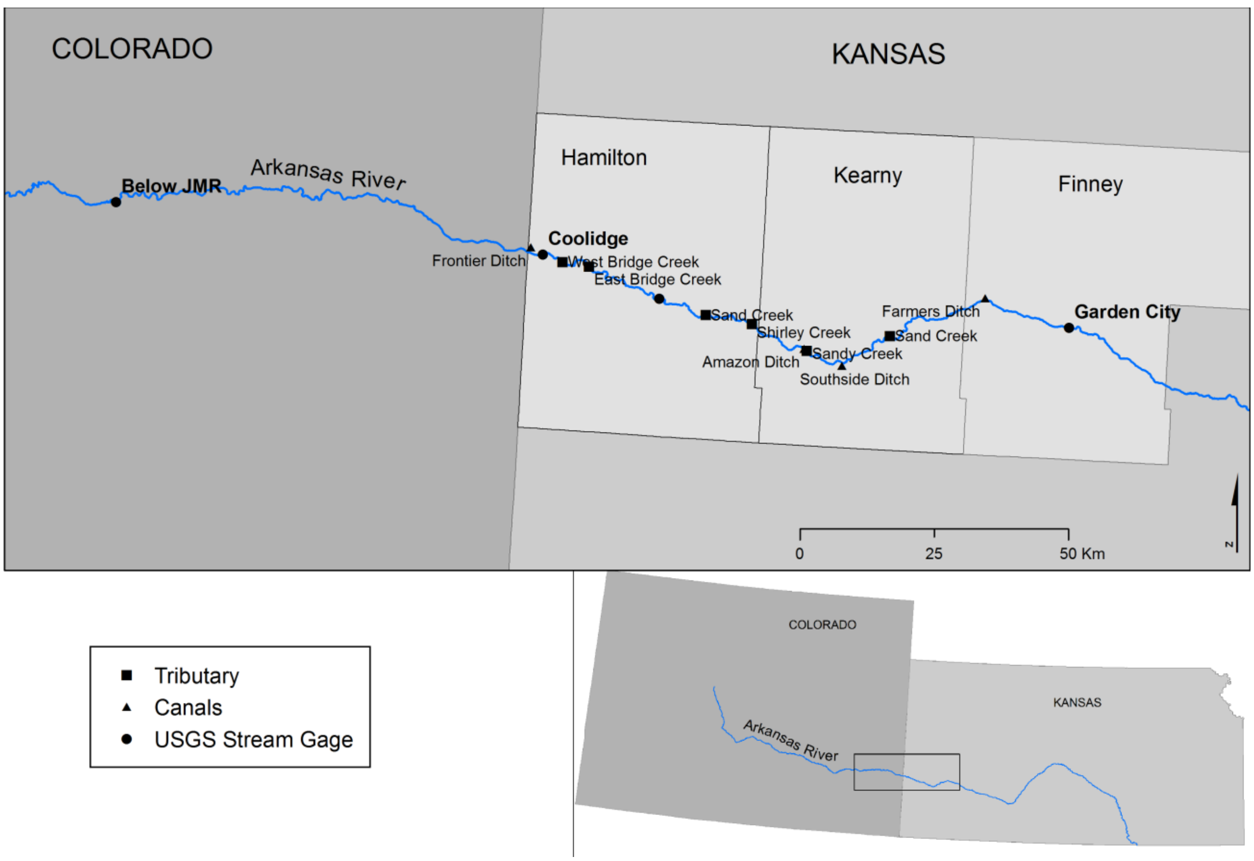

Figure 4: Locations of USGS stream gages, irrigation diversion canals, and tributaries along the Kansas High Plains reach of the Arkansas River.

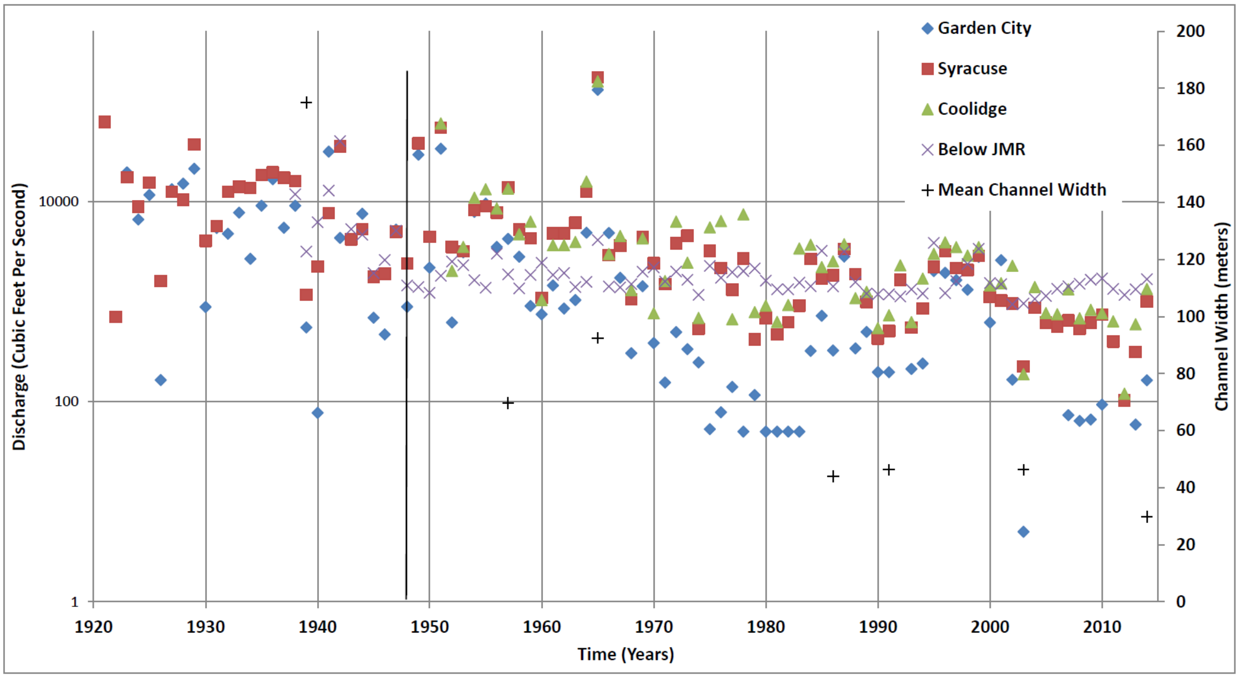

Figure 5: Maximum annual discharge events for the Arkansas River from four stream gages within the study area reach. The vertical black line on year 1948 indicates the completion of John Martin Dam. Note that the Coolidge gage began collecting data in 1951, and the Below John Martin gage started recording in 1938. (USGS: http://waterdata.usgs.gov/ks/nwis/rt)

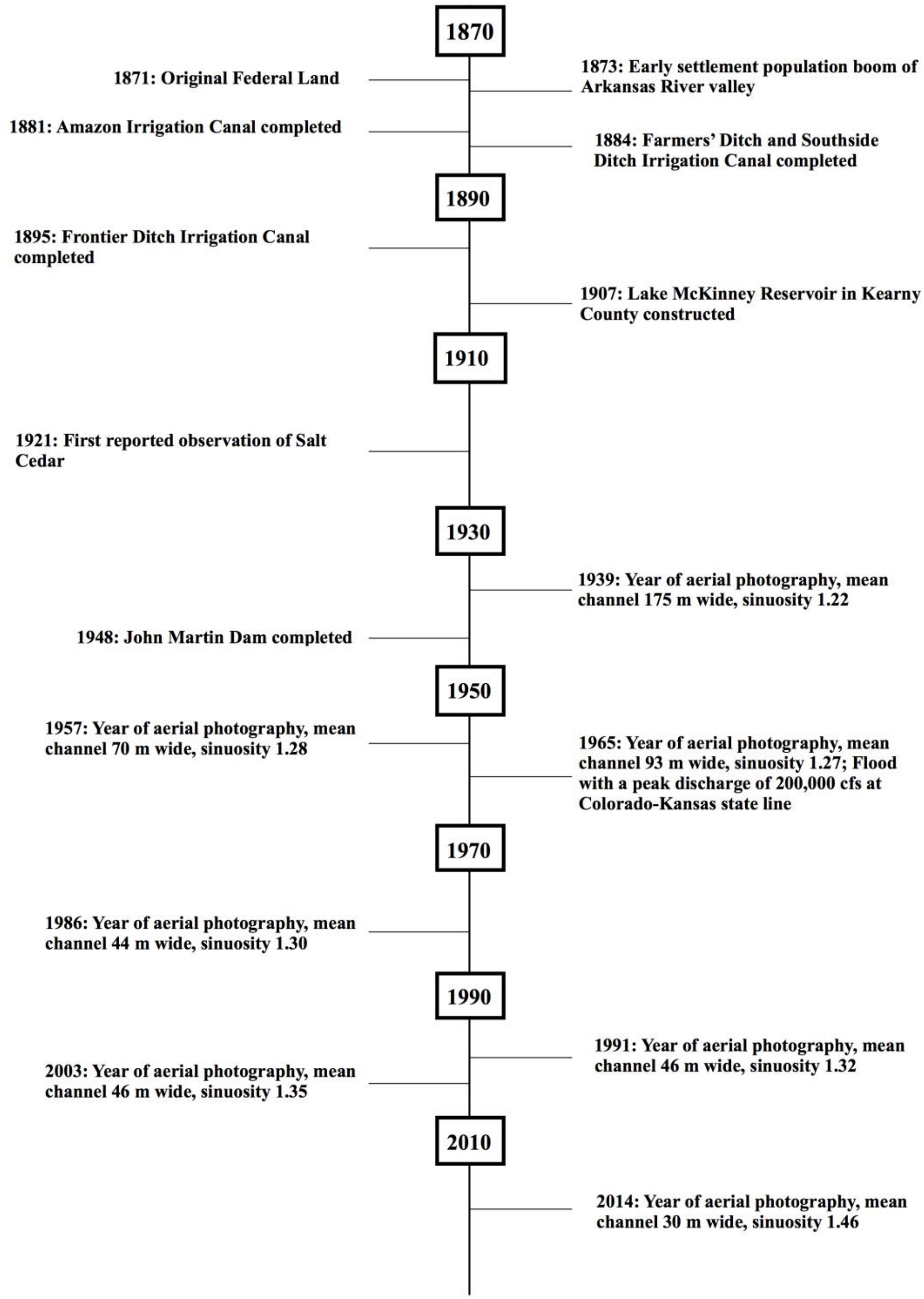

Figure 6: Timeline of the major floods, river engineering projects, and years of aerial photography for the study reach of the Arkansas River valley.

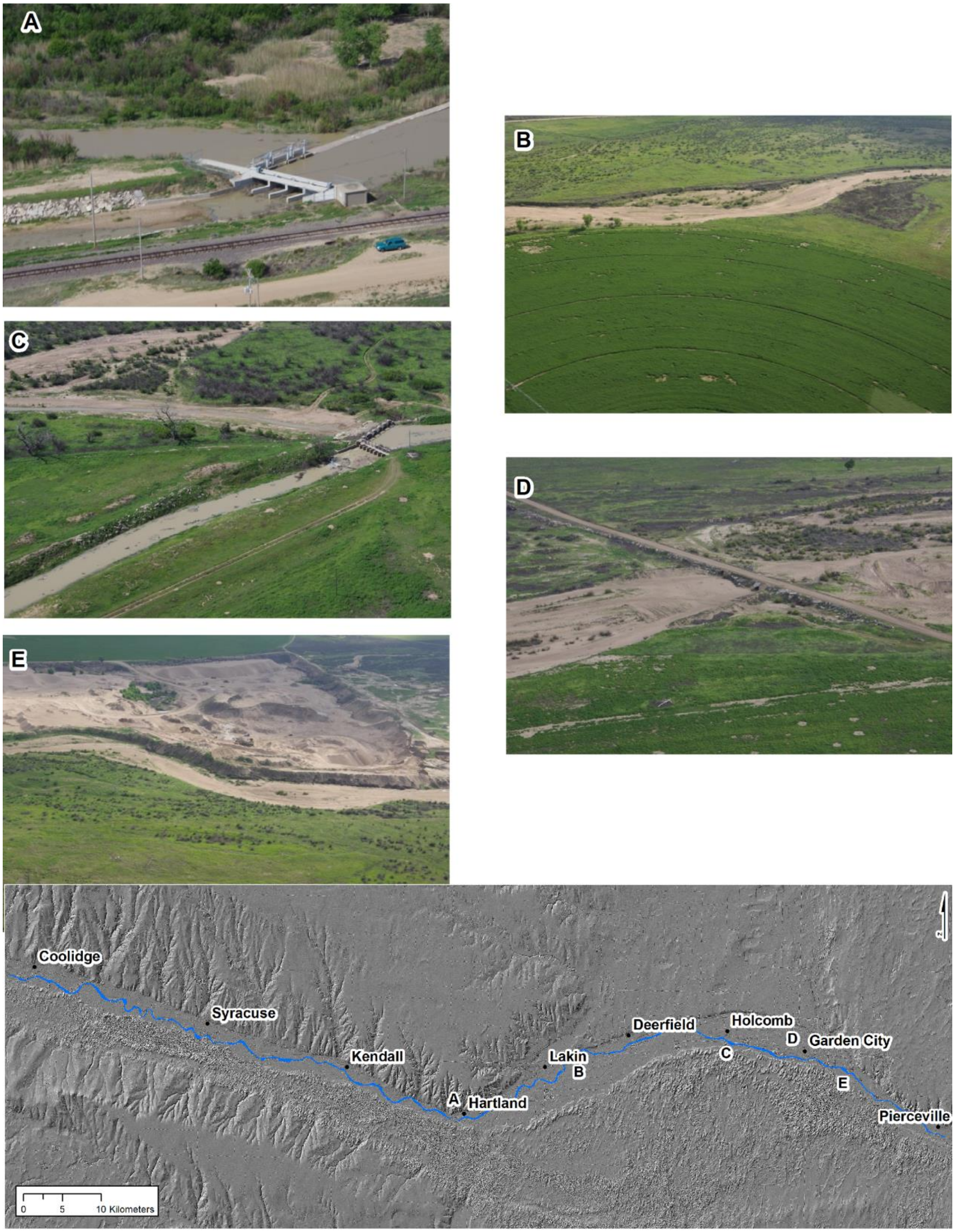

Figure 7: Locations where the Arkansas River channel is artificially stabilized or controlled: A) Amazon irrigation diversion canal, B) center pivot irrigation system, C) Farmers irrigation diversion canal, D) gravel road build up by riprap crossing the channel, and E) construction pit building up the channel bank.

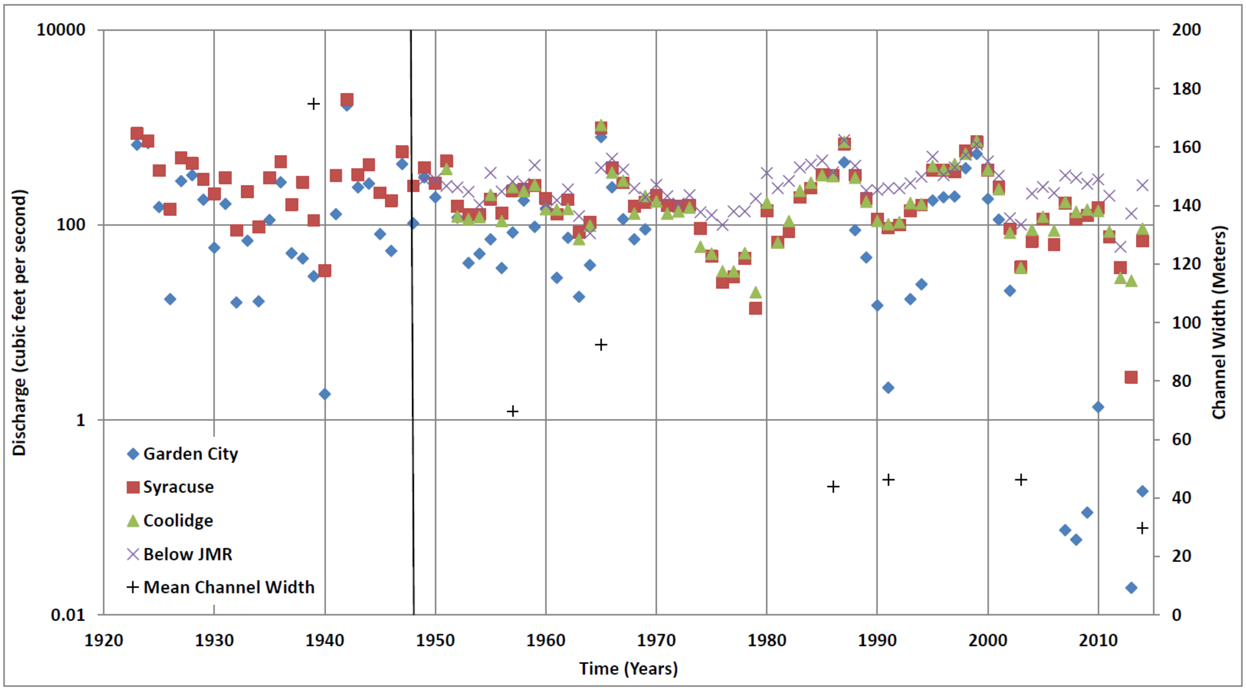

Figure 8: Mean annual discharge for the Arkansas River from four stream gages along the study area. The vertical black line on year 1948 indicates the completion of John Martin Dam. Note that the Garden City gage does not have data from 1969 to 1987, the Coolidge gage began collecting data in 1951, and the Below John Martin gage started recording in 1949. (USGS: http://waterdata.usgs.gov/ks/nwis/rt)

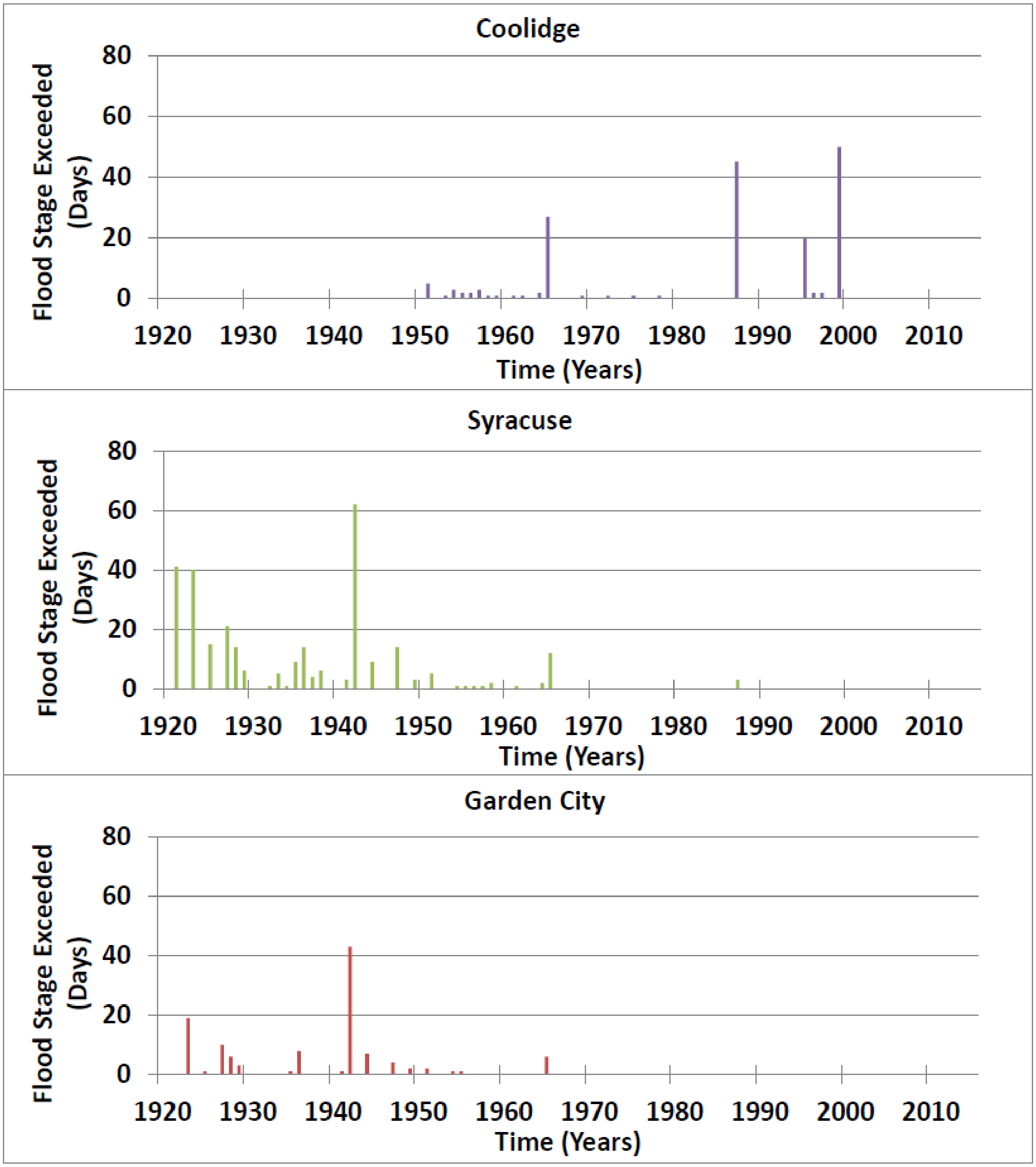

Figure 9: Frequency of flows that exceeded bankfull depth at each study area stream gage that had a specified National Weather Service floodstage. (USGS: http://waterdata.usgs.gov/ks/nwis/rt)

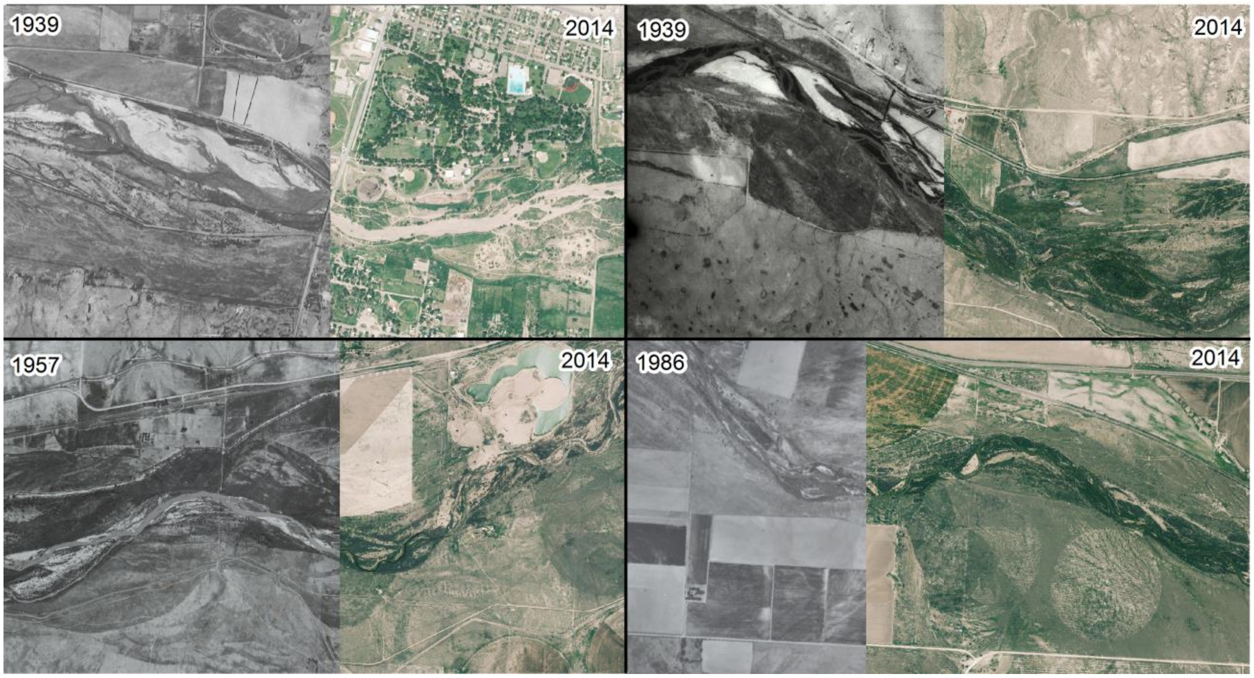

Figure 10: Image pairs depicting river reaches that illustrate temporal change in channel morphology. Upper left-south of Garden City; upper right-west of Hartland; bottom left-east of Hartland; bottom right-southeast of Syracuse.

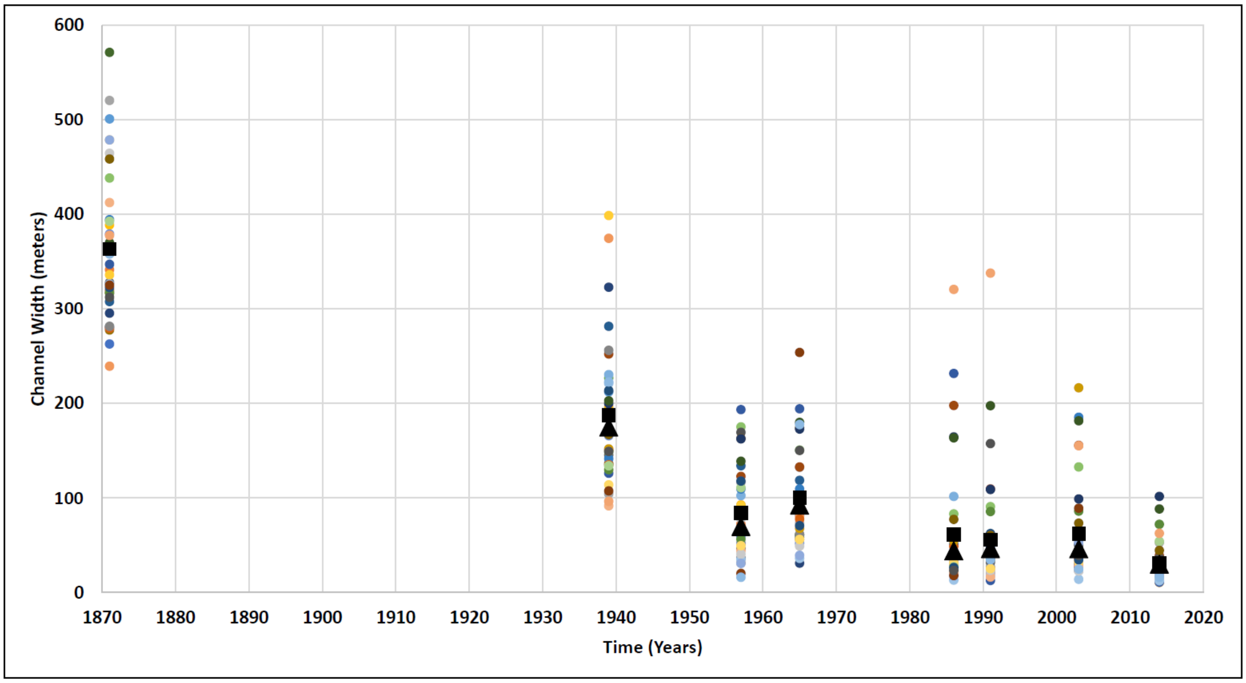

Figure 11: 38 selected Public Land Survey (PLS) measurements (color dots), mean PLS measurements (black squares), and aerial photograph mean calculations (black triangles) within the study reach from 1871 to 2014.

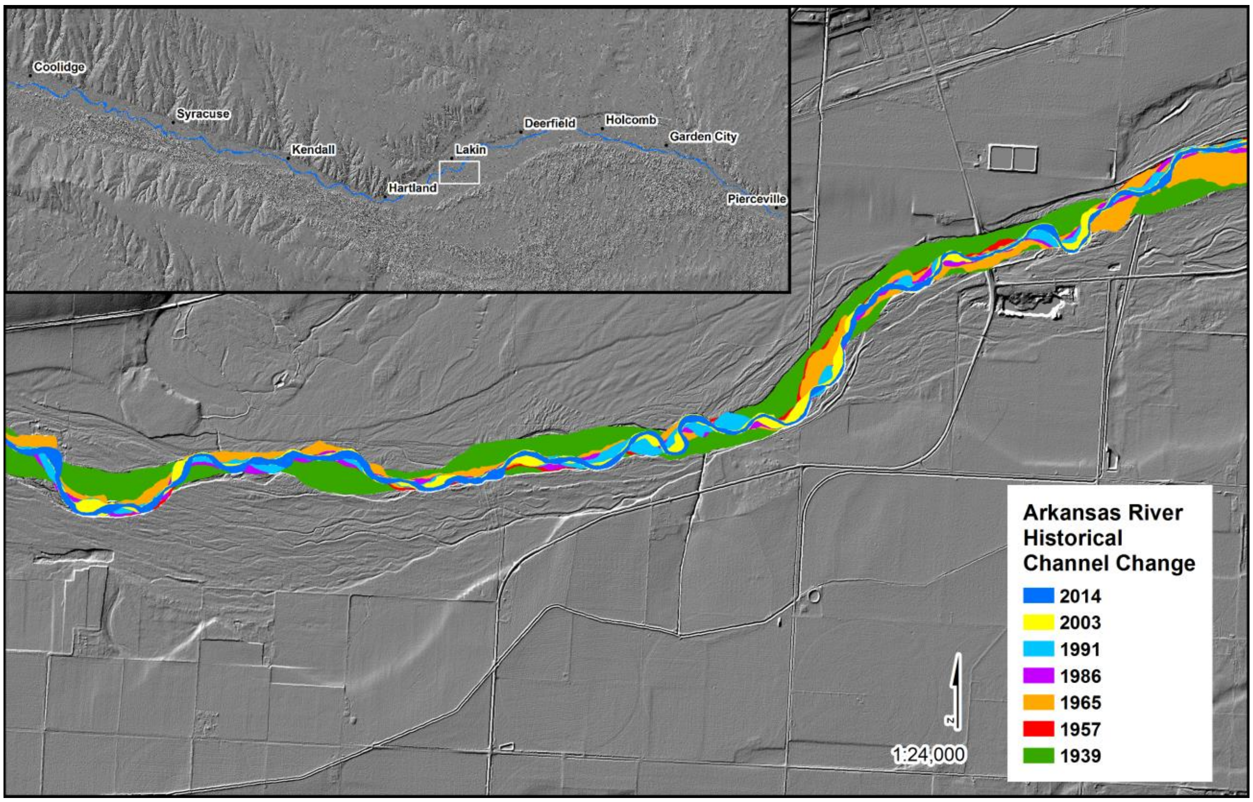

Figure 12: Sample reach of the Arkansas River southwest of Lakin, Kansas. While not typical of the entire Arkansas River channel of the Kansas High Plains, this reach exemplifies historical channel changes from 1939 to 2014.

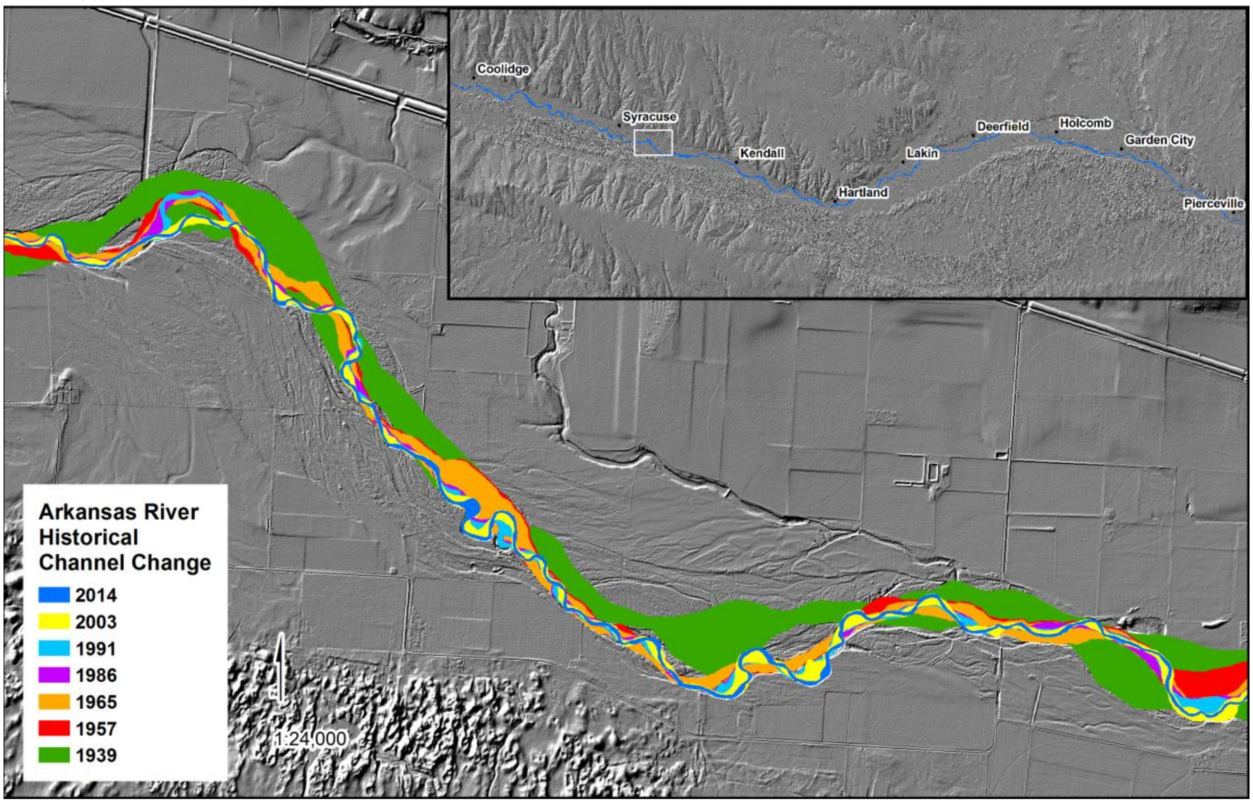

Figure 13: Reach of the Arkansas River exhibiting major historical channel changes (1939-2014), here southeast of Syracuse in Hamilton County.

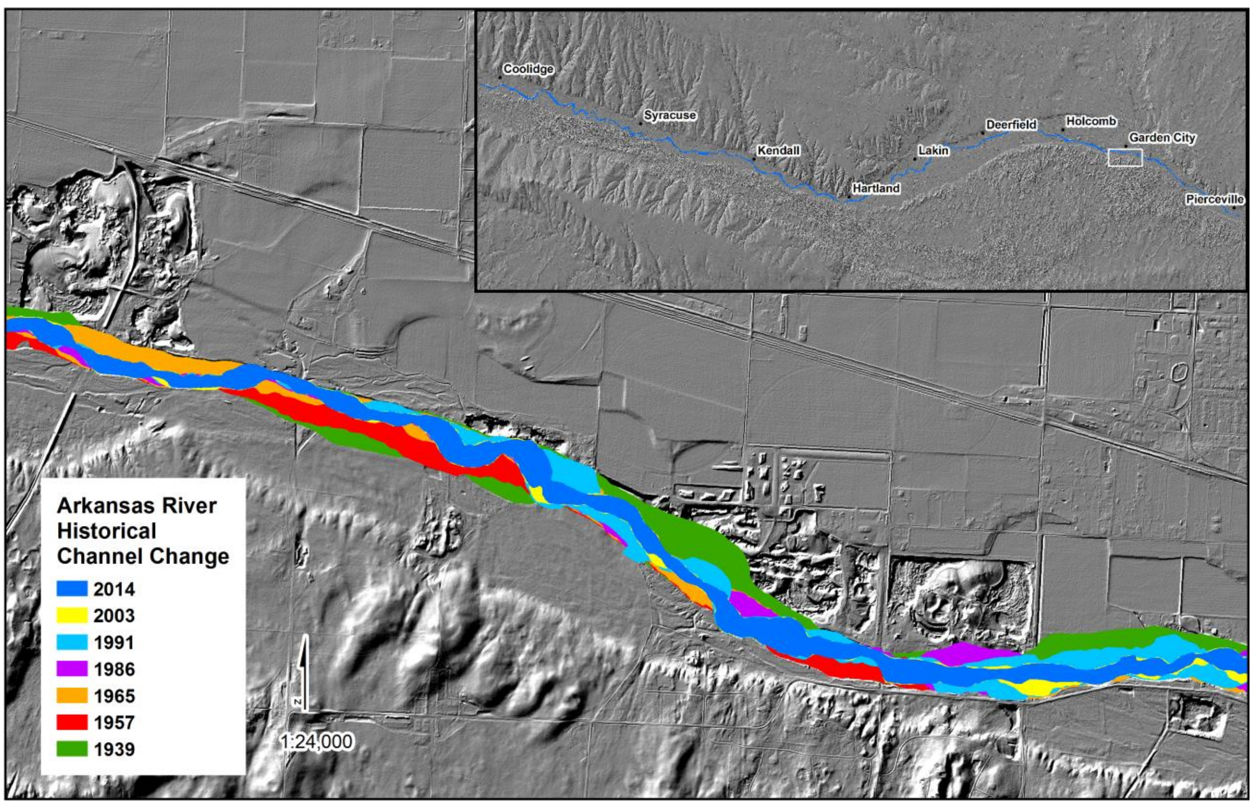

Figure 14: Reach of the Arkansas River exhibiting minor historical channel change (1939-2014) southwest of Garden City. Gravel pits, irrigation canals, and roads have stabilized channel segments by enhancing the channel banks with riprap, sediment, and Kellner jettyjack fields. Here gravel extraction activities have partially constrained channel position.

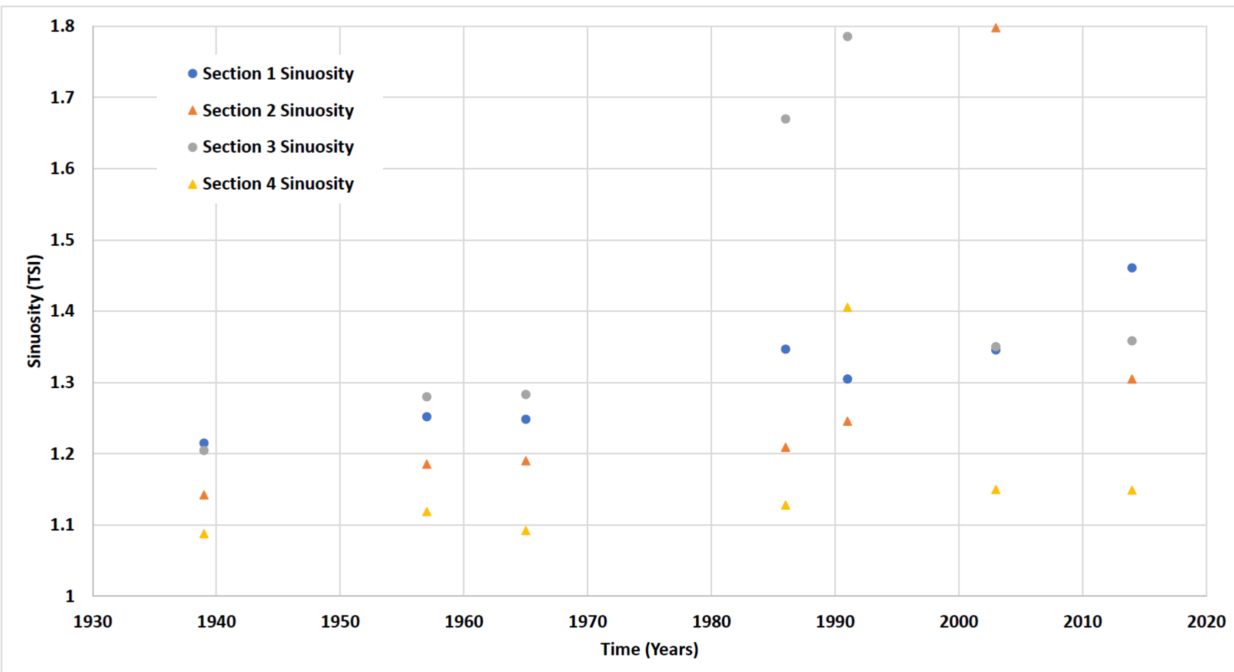

Figure 15: The study reach classified into four sections based on valley width. Sections 1 and 3 have wide valleys (circles) and sections 2 and 4 (triangles) have narrow valleys.

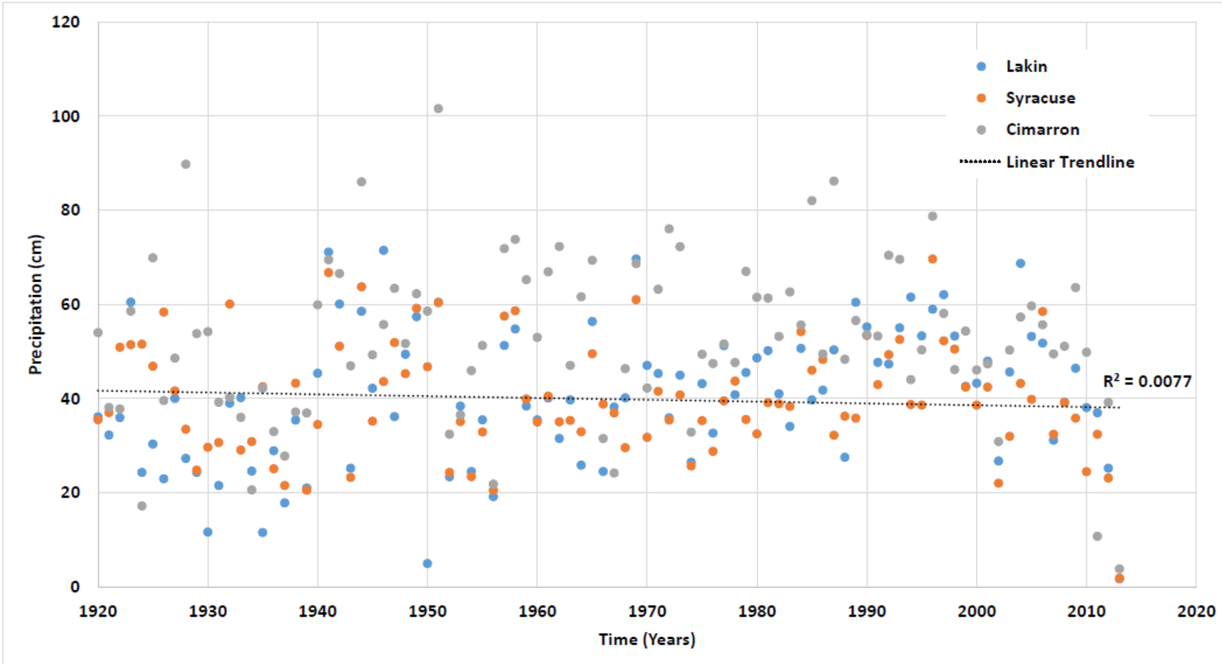

Figure 16: Annual precipitation recorded at Syracuse, Lakin, and Cimarron beginning in 1920. (High Plains Regional Climate Center: http://www.hprcc.unl.edu/data/historical/)

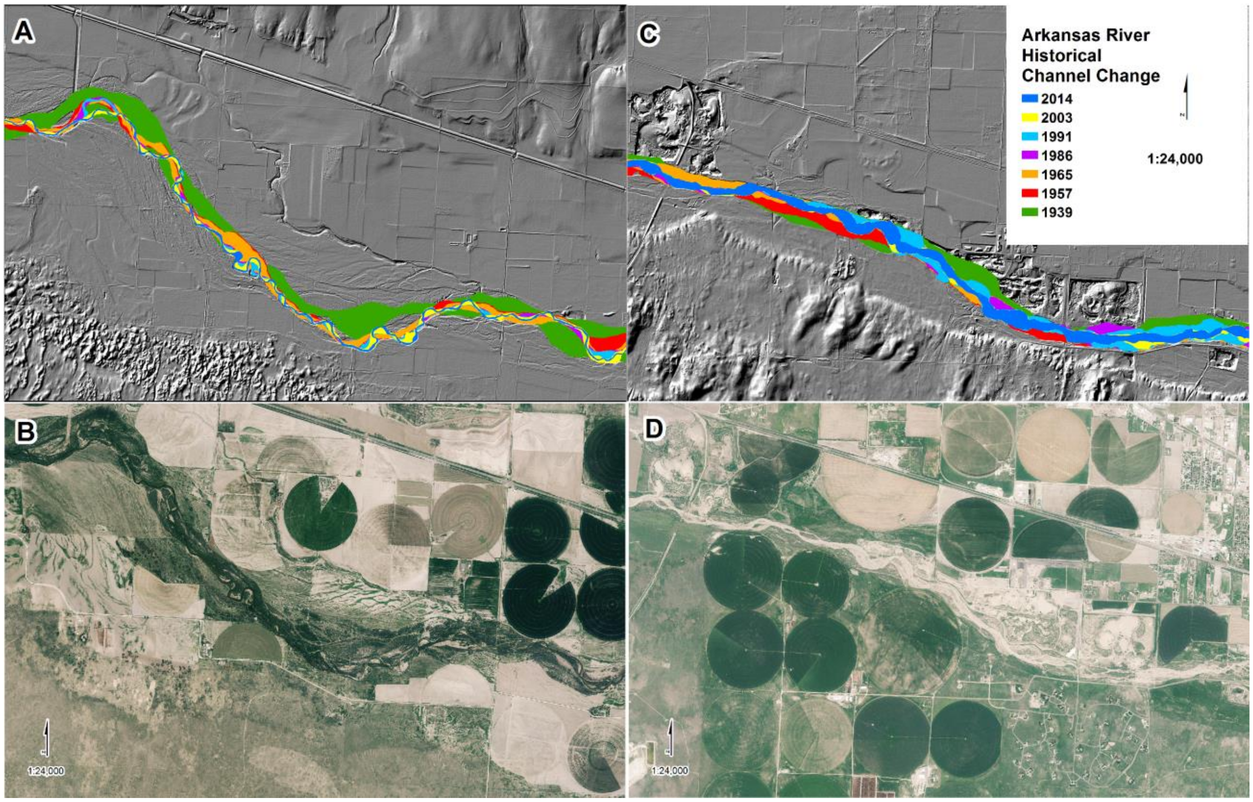

Figure 17: LiDAR-derived hillshade digital elevation models (top) and image pairs exemplifying the effect of riparian vegetation on channel sinuosity (bottom). A) Reach of major change showing high sinuosity southeast of Syracuse in Hamilton County. B) 2014 NAIP image of area in A, depicting dense riparian vegetation. C) Reach of minor change showing low sinuosity southwest of Garden City in Finney County. D) 2014 NAIP image of area in C, illustrating minimal riparian vegetation.

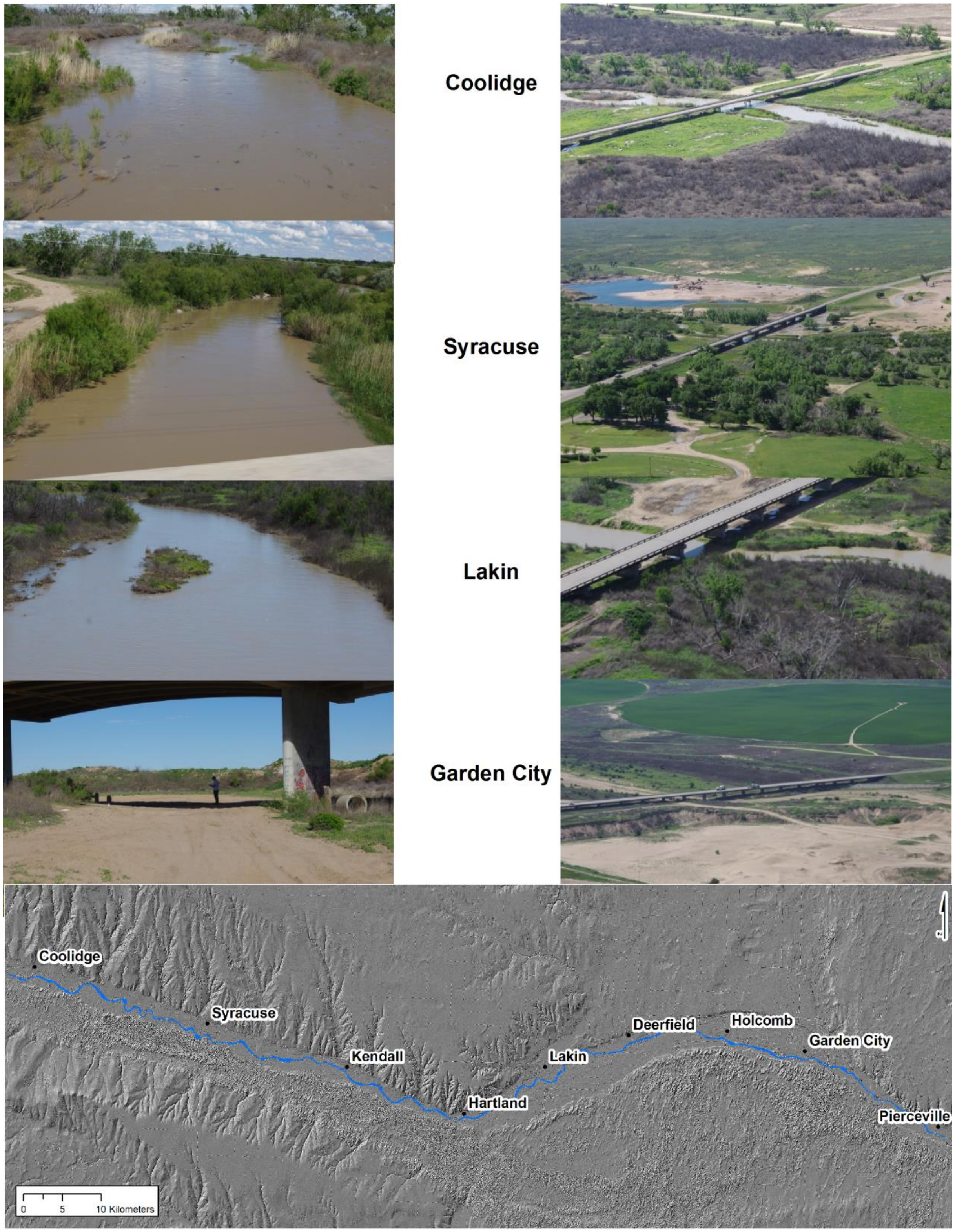

Figure 18: Town Bridge crossings (left to right) going downstream of the Kansas High Plains. Left images are ground views captured from bridges and right images are oblique aerial photos of the associate bridge. Riparian vegetation decreases and channel width increases in the downstream direction (to the right on the map).

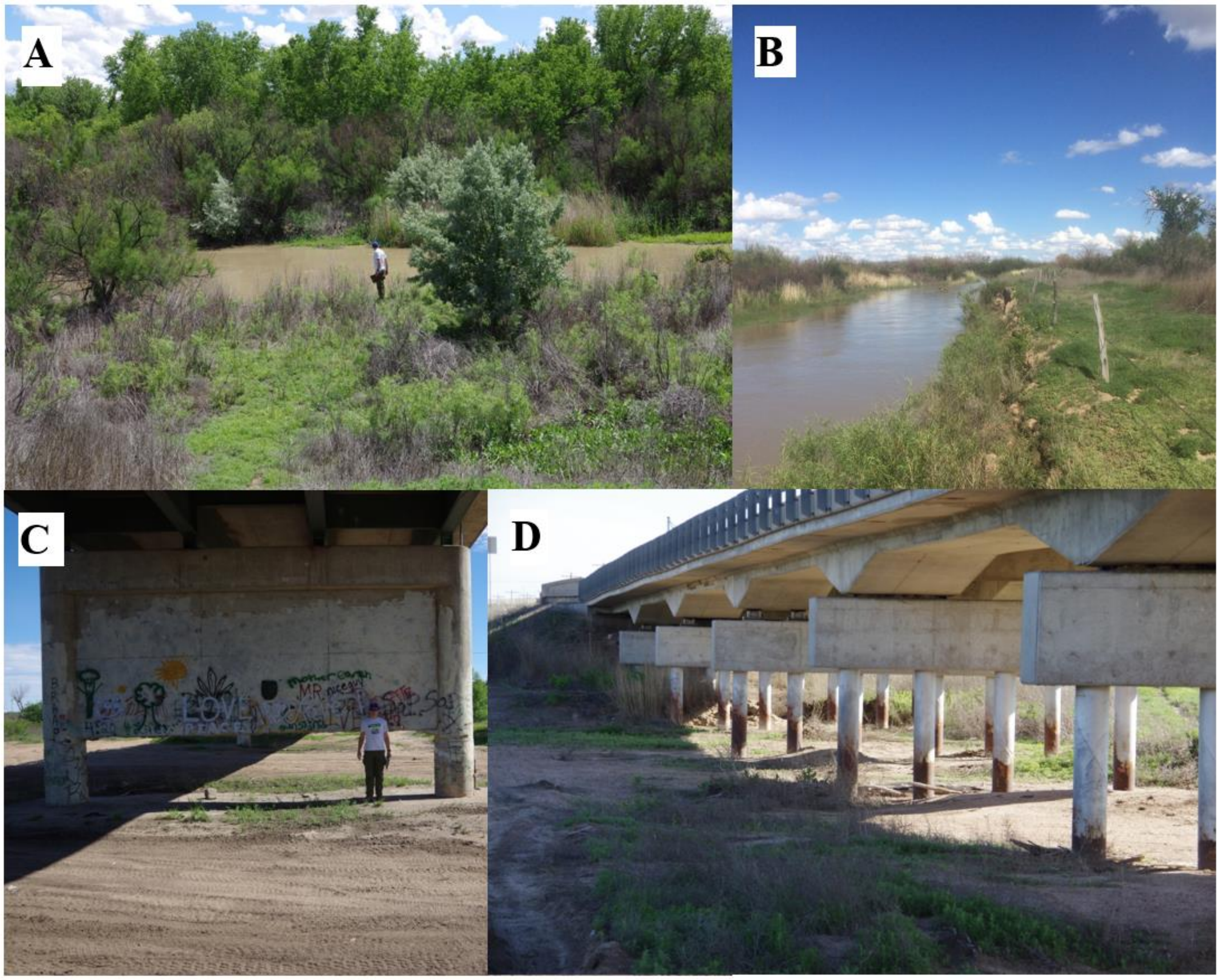

Figure 19: Examples of evidence for channel entrenchment at four locations within the study area reach: A) author standing on the former braided channel bed, B) the change in elevation of the river flowing east near Kendall, C) author standing on the present-day channel bed (dry); when the Garden City West Bridge pilings were emplaced in 1957 the channel bed was at the base of the cross panel between the support columns (entrenchment of about 1.5 m), and D) Pierceville Bridge with similar conditions to that of C.

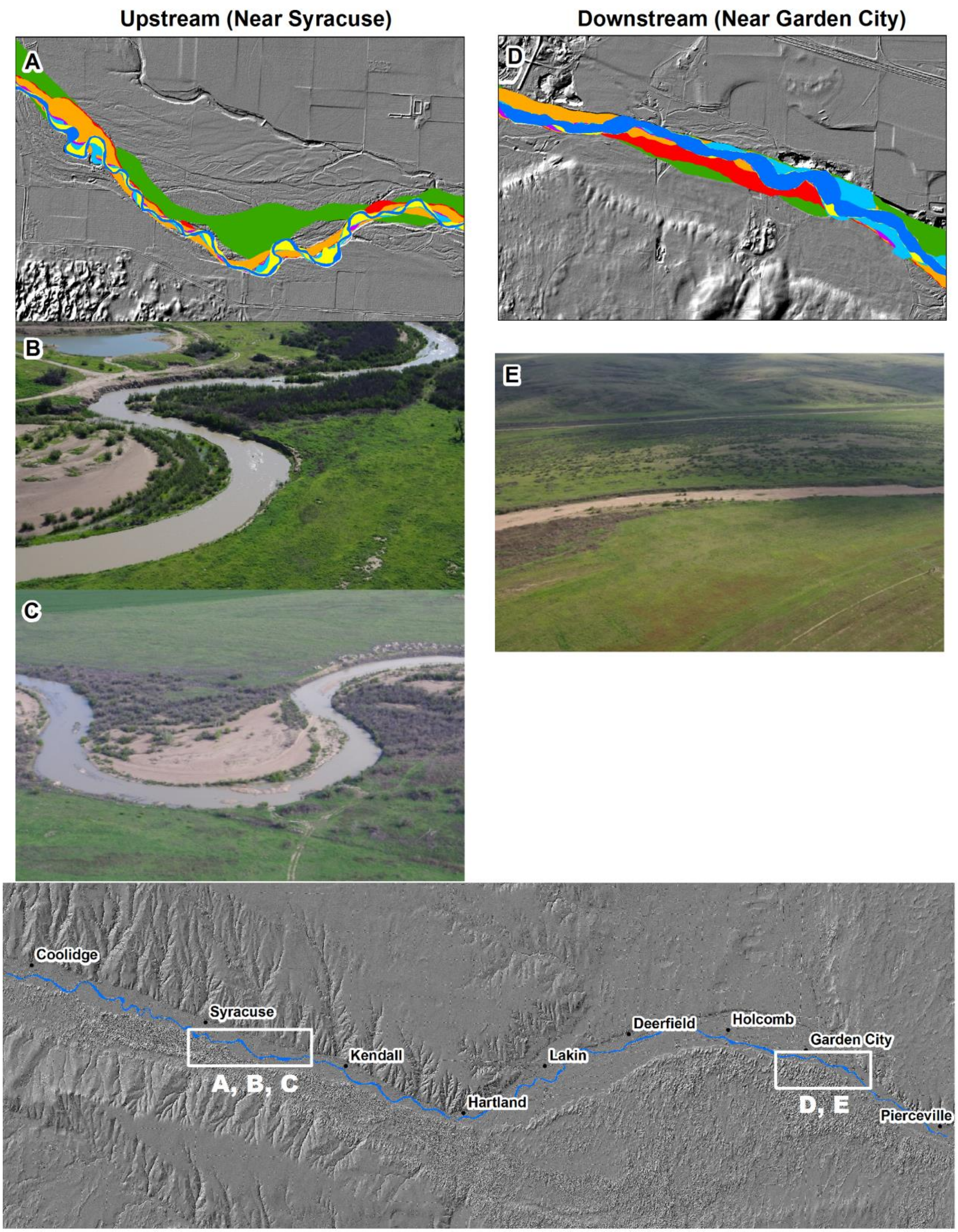

Figure 20: Differences in sinuosity from upstream and downstream reaches within the Kansas High Plains reach: A) Map illustrating reach of major channel change near Syracuse, B and C) Well-defined cutbank and pointbar sequences upstream, D) Map illustrating reach of minor channel change near Garden City, E) Channel reach downstream exhibiting low sinuosity.