Arkansas River Corridor Projects Summary of Fluvial Geomorphic Issues and Identification of Data Gaps

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Introduction

Tulsa County, as part of a master plan for the Arkansas River corridor (Carter & Burgess, 2004; C. H. Guernsey and Company et al., 2005), is undertaking an improvement project on the Arkansas River. The primary goals of the overall project are to improve least tern habitat, improve fish habitat and fish passage, improve the function of the river system itself, enhance economic development, increase recreational opportunities, and increase connectivity between the river and surrounding communities. The conceptual project components are described in detail in the Technical Memorandum (TM) entitled Baseline Project Summary for the Arkansas River Corridor Project (CH2M HILL, 2009a). Key components include:

- Design of habitat improvements along the corridor
- Design of bank stabilization in select areas
- Design of a new Sand Springs low-head dam, pedestrian bridge, and amenities
- Design of modifications to Zink Dam and lake with whitewater features
- Design of a new South Tulsa/Jenks low-head dam, pedestrian bridge, and amenities

This TM provides a summary and general assessment of available data and information on fluvial geomorphic issues related to elements of the proposed project. Fluvial geomorphology is the study of landform evolution related to rivers and includes sediment transport and hydraulic processes. The major elements of the proposed project (i.e. instream habitat improvement, bank stabilization, dam construction, and dam modification) all have the potential to influence sediment transport dynamics and hydraulics, and therefore could influence fluvial geomorphic processes and the long-term evolution of channel morphology in the project area (Figure 1). In addition, the success of ecosystem restoration and instream habitat improvements will depend on the fluvial geomorphic conditions after completion of the project. The project area extends from the upstream extent of Keystone Lake (river mile [RM] 562.5) downstream to the Tulsa-Wagoner County boundary (RM 495.6), about 66.9 river miles. The project area will likely change as the project alternatives and their effects are better understood.

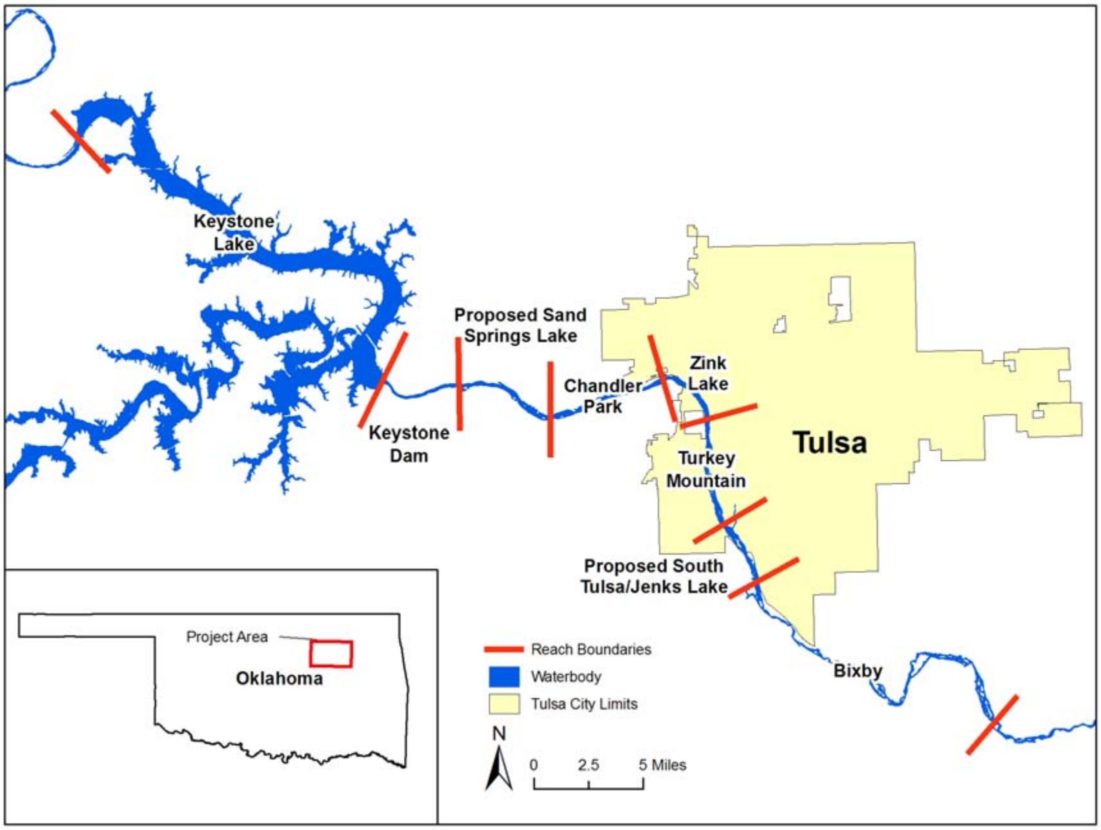

FIGURE 1
Arkansas River Project Area and Geomorphic Sub-reaches Extend from Upstream Extent of Keystone Lake (RM 562.5) to Tulsa-Wagoner County Boundary (RM 495.6). Sub-reaches are labeled between the red sub-reach boundary lines.

Summary

This TM summarizes the available data and information on fluvial geomorphic processes related to the proposed project and identifies data gaps that should be filled to further the understanding of fluvial geomorphic processes impacting the Arkansas River in the project area. Fluvial geomorphic conditions will be critical to the success of ecosystem restoration and habitat improvement elements of the proposed project, as well as to proposed dams and dam retrofit elements. No comprehensive study on the fluvial geomorphology of the Arkansas River in the project area has been conducted to date, but numerous studies and planning documents contain information that allows for a preliminary assessment of the fluvial geomorphic issues in the project area.

The Arkansas River is a typical low gradient river that contains many braided channels. The river has been significantly altered by construction and operation of Keystone Dam. Sediment continuity from the upstream reach has been interrupted by the dam and the flow regime has been modified. To generate hydroelectricity, water is released from Keystone Lake. The rapid increase and decrease in discharge at the beginning and end of a hydroelectric generation flow release (i.e.. a hydroelectric “peaking” release) from Keystone Lake during low water periods rapidly increases and decreases the wetted area of the channel, impacting nesting habitat for least terns and aquatic habitat for fish. Keystone Lake reduces small to moderate floods, but does not regulate extreme discharge events. The channel downstream of Keystone Dam has experienced incision and bank erosion as it has been scoured of sediment to regain the sediment load of the river that is trapped upstream in Keystone Lake. The sediment transport dynamics of the current system require a more comprehensive understanding, including development of a sediment budget, to ensure that the designs of project components properly account for short- and long-term scour and deposition of sediment. It is clear from available data that the Arkansas River is responding to changes in sediment load in the project area, and without a more thorough understanding of the sediment transport dynamics governing this response, future infrastructure and development along the channel banks could be compromised due to accelerated bank erosion or excessive sediment deposition, or other unforeseen impacts of sediment transport imbalances. Further, sediment transport dynamics should be understood to properly plan for sediment-related maintenance that will be required to meet the project objectives.

Data gaps were identified in each of the major topics in the field of fluvial geomorphology: channel morphology, sediment budget, hydrology, geology, and hydraulics. The data gaps identified in each section are summarized and assigned a priority at the end of this TM in Table 3. Table A1 in Appendix A summarizes the data sources reviewed for this analysis.

Channel Morphology

“Channel morphology” refers to the dimension (i.e., cross-sectional geometry), longitudinal profile, and alignment of the channel. River channels tend to establish equilibrium between the discharge and sediment load and the channel shape and alignment. Alteration of the discharge or sediment load of a river results in changes to the channel shape or alignment or both. The Arkansas River in the project area has been altered by Keystone Dam. Operation of the dam has reduced flood flows and reduced the sediment load of the Arkansas River downstream of the dam. As a result, the channel shape has been altered as the channel establishes a new equilibrium. Understanding the historical channel change may allow predictions regarding future channel response to proposed actions that must be recognized and addressed during planning and design of new channel infrastructure and habitat enhancement islands.

The Arkansas River corridor is characterized by a wide channel with large meanders and point bars and braided channels through most of the study area, except for the pool behind Zink Dam. The active channel is wide and flat-bottomed with a representative channel width of 1,500 feet and representative depth of 20 feet. The slope of the channel in the study reach is 0.00033. Widespread bank erosion is evident from aerial photographs and is discussed in the river corridor planning documents. The project area was divided into sub-reaches (Table 1) based on the proposed project infrastructure.

TABLE 1
Sub-reaches in Project Study Area

Sub-Reach Name	Description	Upstream Extent (RM)	Downstream Extent (RM)
Keystone Lake	Water storage reservoir upstream of Keystone Dam	562.5	538
Keystone Dam	Downstream of Keystone Dam	538	534.2
Proposed Sand Springs Lake	Impoundment behind proposed low-head dam	534.2	529.9
Chandler Park	Braided channel with sand bars	529.5	523.9
Zink Lake	Low-head dam impoundment	523.9	520.8
Turkey Mountain	Confined by bluffs	520.8	515.9
Proposed South Tulsa/Jenks Lake	Impoundment behind proposed low-head dam	515.9	512.8
Bixby Reach	Predominantly agricultural floodplain	512.8	495.6

Changes in channel morphology are common downstream of large dams. On the Arkansas River, the primary effect of the dam appears to be a reduction in the sediment supply that has resulted in channel incision and bank erosion as water released from Keystone Dam scours the channel bed and banks to re-establish equilibrium between flow and sediment transport. As a result, until equilibrium is reached, the channel cross section will likely continue to change until channel incision is arrested by bedrock or the banks of the channel are armored. Figure 2 shows the progression of bed incision during the period 1963 to 1988 from Keystone Dam to Zink Dam (West Consultants, 1990).

Channel storage (i.e., the volume of a given flow contained in the channel) has increased over the past 30 years as the Arkansas River has degraded vertically and eroded laterally. This likely means that hydraulic conditions have become more erosive as higher flows have been confined within the degrading channel. Depending upon how the proposed structures change existing hydraulic and sediment transport processes, chronic channel incision and bank erosion could undermine infrastructure constructed in the channel and threaten structures constructed on the floodplain. If widespread bank stabilization methods are employed without changes to hydraulics, channel incision could accelerate until bedrock is reached. Further incision of the channel could then undermine bank protection. As the bed elevation of the Arkansas River decreases due to incision, incision could migrate up tributaries as the tributaries adjust to the lower base level in the Arkansas River. Continued sand and gravel extraction from the Arkansas River could also continue to increase channel incision and bank erosion.

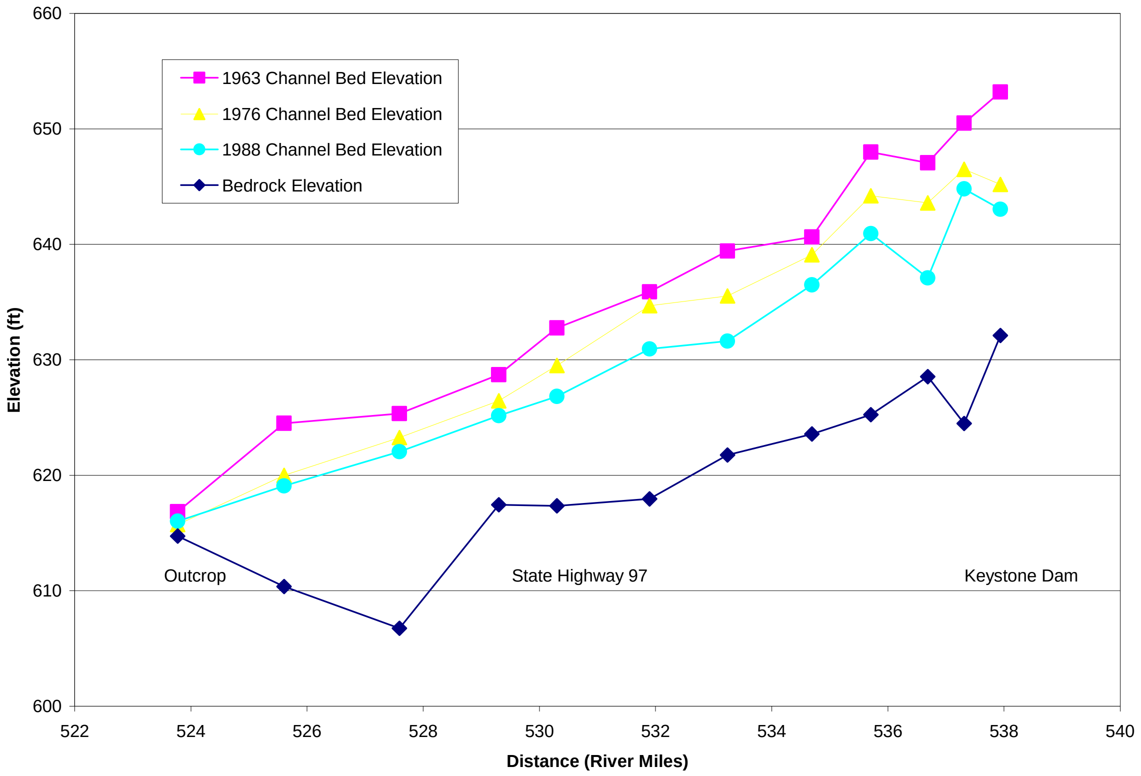

FIGURE 2
Arkansas River Channel Bed and Bedrock Elevation at 12 Locations between Keystone Dam and Zink Dam for Period 1963 to 1988 (figure reproduced from West Consultants, 1990).

Data Gaps: Further analysis is required to determine if the historical channel changes observed thus far (i.e., channel incision and bank erosion) are localized or widespread. Additionally, the spatial extent of bank erosion, channel bank armoring, and levees should be quantified. To quantify rates and estimate volumes of bank erosion, historical aerial photographs and maps should be rectified in the project Geographic Information System (GIS) so that the channel banks can be delineated. Ideally, one set of historical aerial photographs should be obtained for each decade, both pre- and post-dam construction. Historical aerial photographs from 1954, 1966, and 2008 have been obtained. Additional historical aerial photographs should be available from the Indian Nations Council of Governments (INCOG) for 1951, 1977, 1985, and 2001. Additional historical aerial photographs for other years can be purchased from the United States Geological Survey (USGS). Historical aerial photographs should also be compared to the 2009 Immersive Media aerial imagery of the Arkansas River Corridor. Maintenance records for bridges that cross the Arkansas River should be obtained from the Oklahoma Department of Transportation to determine if scour at bridge piers has been recorded. In addition, USGS field forms (9-207) can be analyzed to document bed stability at gage locations. A GIS layer should be created showing the extent of armored channel banks and the location of engineered levees. Cross sections from the 1977 HEC2 and 2002 HEC-RAS hydraulic models should be compared to determine the amount of channel widening and incision over the 25-year period.

Sediment Budget

A sediment budget quantifies sediment supply, storage, and transport in a fluvial system to describe the movement of sediment through a watershed. A sediment budget is a conceptual simplification of the processes that convey material down hillslopes, through channels, and out of a basin and is a quantitative summary of the rates of production, transport, and discharge for a basin (Dietrich et al., 1982). Specifically, a sediment budget will be essential in evaluating the influence of sediment transport dynamics on the maintenance of nesting habitat for the least tern, existing and proposed channel infrastructure, channel bank and bed stability, and sediment accumulation behind existing and proposed dams. Using a sediment budget framework, the following discussion of sediment in the Arkansas River is divided into sections on sediment supply (sources of sediment to the project area), sediment storage (the amount of sediment in the channel, banks, and floodplain), and sediment transport (the sediment load of the Arkansas River in the project area).

Sediment Supply

Sediment supply is the input of sediment particles to a reach of river channel from upstream transport, in-reach erosion, or other sediment-generating sources. Sediment supply is important to consider for this project because changes in sediment supply could directly impact structures built in the channel, including low-head dams, pedestrian bridges, whitewater features, and bank stabilization structures. Also, one of the major elements of the proposed project is creation and maintenance (self-sustaining vs. requiring augmentation) of islands to provide instream habitat for nesting least terns, and this depends upon sediment supply and transport.

Sediment supply to the project area from the Arkansas River and Cimarron River has been reduced by construction of Keystone Dam. Bedload (sediment transported along the bed of the channel) from upstream of Keystone Lake is deposited in Keystone Lake because the transport capacity of the Arkansas River decreases as it flows into Keystone Lake, facilitating deposition of bedload in a delta that fills the submerged river channel at the upstream end of the lake. Some suspended particles also settle out in Keystone Lake. During high flow events, unknown quantities of suspended sediment pass through Keystone Dam to the Arkansas River downstream. Water is released from the lower gates of Keystone Dam to improve water quality and an unknown amount of sediment may be sluiced through these lower gates.

Sediment supply downstream of Keystone Dam is limited to three primary sources: the channel bed, channel banks, and tributary inputs (Figure 3). Channel incision has been documented (West Consultants, 1990) by comparing depth to bedrock measurements taken at 12 locations by the United States Army Corps of Engineers (USACE) in the channel in 1963, 1976, and 1988. The surveys showed that the channel bed incised from 5 to 10 feet between 1963 and 1988 over the study reach from Keystone Dam to Zink Dam. Wide-scale bank erosion downstream of Keystone Dam has also been documented in numerous planning studies of the Arkansas River; however, no comprehensive study has been undertaken to quantify the volume of material eroded. Sand and gravel extraction in the channel and on the floodplain has further reduced the sediment supply downstream of

Keystone Dam; however, extraction volumes have not yet been acquired from mine operators.

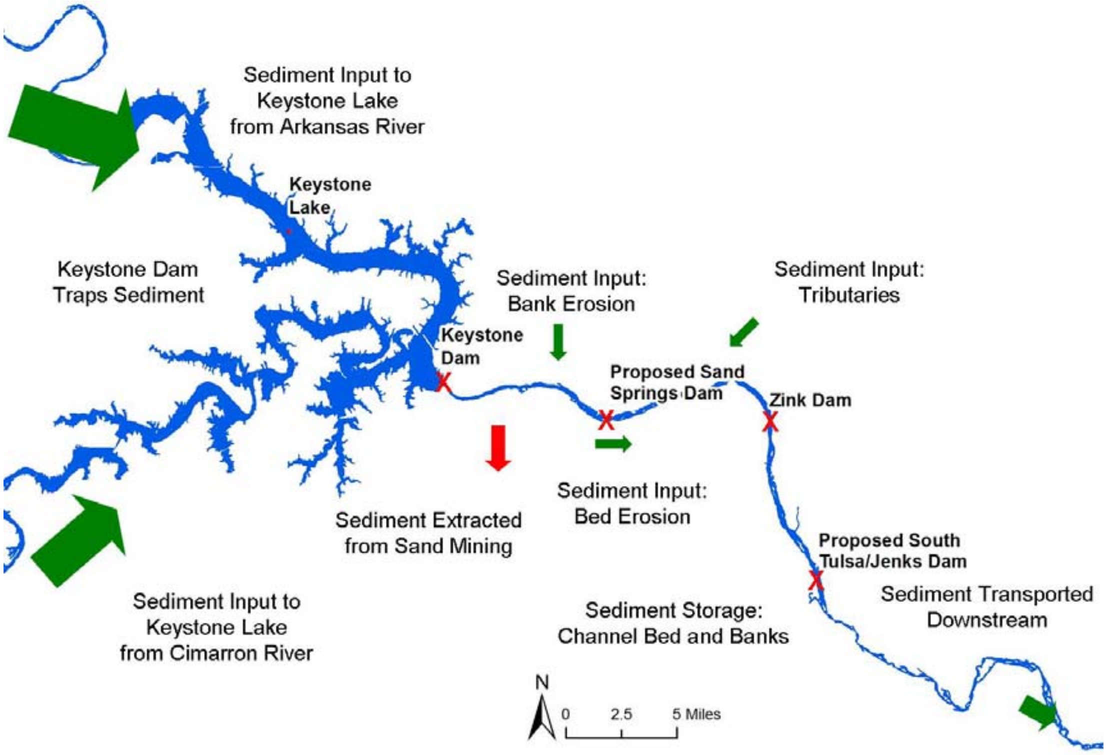

FIGURE 3
Conceptual Model of Sediment Supply to Arkansas River in Project Study Area (Arrows not to scale).

Data Gaps: Sediment supply is not quantified or not adequately understood in the project study area. The rate of sediment supply from bank erosion should be estimated and the trap efficiency of Keystone Dam calculated. Tributary sediment inputs and the extraction rate of sediment from sand and gravel mining operations should be quantified. The channel surveys conducted by USACE in 1963, 1976, and 1988 should be repeated to determine if the channel has continued to incise or if it has reached equilibrium. A systematic assessment of bank erosion using historical aerial photographs and historical cross sections should be conducted to estimate the rate of sediment supply from bank erosion.

Another data gap is the trap efficiency of Keystone Dam. The trap efficiency of Keystone Dam likely was determined during design. Therefore, Keystone Dam design documents and operations manuals should be acquired and reviewed for trap efficiency information as an initial estimate of the amount of suspended sediment that is transported through Keystone Lake. The sediment supplied from tributaries should be estimated from USGS gage records (if available), by measurement of sediment deltas at the confluence of tributaries with the main-stem, or through direct measurement of sediment transport and development of representative sediment transport rating curves. The permit history for sand and gravel mines should also be reviewed to determine the volume of sand and gravel extracted from the channel and floodplain. The downstream movement of sand and gravel mining operations from near Keystone Dam to the current location near Jenks will likely provide additional data on the distribution of sediment deposits in the channel and the overall sediment continuity in the entire 42-mile project reach.

Sediment Storage

Sediment storage is the temporary residence of sediment particles in a river channel or on its floodplain. A thorough understanding of sediment storage is important for the project because the proposed new dams and dam modifications will alter existing sediment storage characteristics in the project area. Least tern habitat is created by sediment storage in the project area and therefore successful enhancement of this habitat will require a detailed understanding of this process.

Studies conducted in the project area have documented that, in general, sediment storage in the channel has been reduced. This is due, at least in part, to the reduction of sediment supply from upstream of Keystone Dam combined with the alterations to the hydrology of the river. The ongoing channel incision and erosion reflect sediment transport capacity that is higher than sediment supply in the project area. Localized sediment storage still occurs in areas such as tributary confluences, expansion zones, and dam backwaters where hydraulic conditions are conducive to deposition. However, in general, the river has been degrading since the construction of Keystone Dam. In addition, the material stored on the river bed has generally coarsened (from approximately 2 millimeters [mm] to approximately 4 mm) (West Consultants, 1990). Average annual deposition rates to in the Zink Dam pool were estimated at 195.1 acre-feet (ac-ft) by West Consultants (1990) for the period from 1963 to 1987 and deposition rates varied from 17.9 ac-ft to 666.6 ac-ft. The current level of sediment storage in the channel from Keystone Dam to Zink Dam has reduced available least tern habitat as the channel has incised (CH2M HILL, 2009b).

Data Gaps: While useful data on deposition rates do exist (from 1963 to 1986 from Keystone Dam to Zink Dam), additional work is required to assess sediment storage in the project area. This additional work should include mapping of the sediment size classes on the channel bed and quantification of stored sediment, size and lithological characterization of stored sediment, and analysis of required hydraulic conditions to induce and maintain storage.

Sediment Transport

Sediment transport is the movement of sediment particles through a river system by the force of flowing water. There are two primary components of sediment transport with respect to fluvial geomorphology: competence (i.e., the ability of flows to mobilize sediment) and capacity (i.e., the amount of sediment that flows are capable of transporting). A thorough understanding of the magnitude, frequency, duration, and timing of sediment transport into, through, and out of the Arkansas River project area is important because they will ultimately play a major role in operation and maintenance of the dams and lakes in the project area, as well as being major factors in the development of sustainable bank stabilization designs and ecologically viable habitat improvements.

The construction of Keystone Dam fundamentally altered sediment transport dynamics in the project area. Studies of portions of the project area (West Consultants, 1990) documented reductions in suspended sediment transport after dam construction, especially for flows greater than 10,000 cubic feet per second (cfs). The sediment deficit caused by Keystone Dam initiated increased transport of channel bed and bank sediments in the project area (as evidenced by 5 to 10 feet of channel bed degradation and widespread bank erosion). Comparing suspended sediment transport rates at the USGS Tulsa gage pre- and post-Keystone Dam construction shows a reduction of 55 percent to 97 percent at flows of 120 cfs to 80,000 cfs, respectively, in the suspended sediment load downstream of the dam (Figure 4).

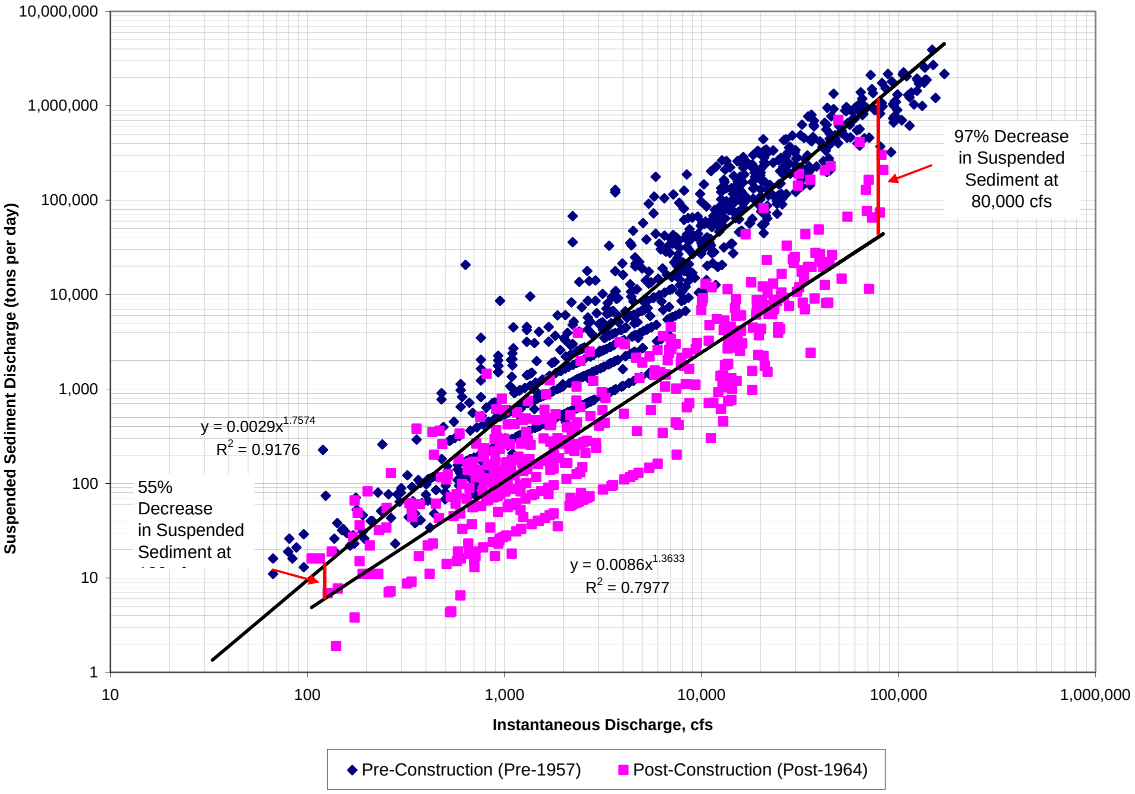

FIGURE 4
Observed Suspended Sediment Transport Rates at USGS Arkansas River at Tulsa Stream Gage (07164500). Note the reduced sediment transport rates post-dam construction.

Data Gaps: First, and perhaps most importantly, an order-of-magnitude sediment budget has not been developed for the project area. Such a budget could be used to address project design questions related to sediment transport. An order–of-magnitude sediment budget could be developed using existing data on sediment supply, storage, and transport combined with new data collected to fill the data gaps identified for each of these areas using a method similar to that of Reid and Dunne (1996) or Dietrich et al. (1982). Several sediment transport data gaps exist that could impair project development. In addition, flow thresholds required to mobilize and transport channel bed and bank sediments have not been determined. Basic incipient motion equations could be applied using hydraulic and sediment size distribution data to estimate these thresholds. Finally, a detailed sediment transport model has not been developed for the entire project area. Such a model could be developed using existing channel topography data and available hydrology data for the project area.

Hydrology

"Hydrology," for the purpose of this study, relates to the discharge of the Arkansas River and tributaries. Understanding hydrology is important to understanding fluvial geomorphology, as discharge is a dominant landscape forming process. Discharge-dependent channel shaping processes include scour of the channel bed and banks, deposition of sediment, and sediment transport. Hydrology and its interaction with river channel forms will also significantly influence the success of ecosystem restoration and habitat improvements included in this project.

The Arkansas River is the fourth longest river in the United States and flows from the headwaters near Leadville, Colorado, to the confluence with the Mississippi River near Rosedale, Mississippi. The river flows 1,450 miles through Colorado, Kansas, Oklahoma, and Arkansas. The Arkansas River has a watershed area of almost 195,000 square miles (mi^2) at the confluence with the Mississippi River (McCord, 2007 cited in Cherokee CRC, 2009) and a watershed area of 74,615 mi^2 at the USGS Tulsa gage. Regional discharge gages maintained by the USGS are listed in Table 2. The USGS gage at Tulsa provides a long-term historical record of the daily average and annual peak discharges.

TABLE 2
Summary of Available USGS Streamflow Gage Data on the Arkansas River

USGS Gage Number	Gage Name	River Mile	Drainage Area (mi^2)	Annual/ Daily Counts	Period of Record	Available Data
07152500	Arkansas River at Ralston, OK[a]	499	54,465	84 / 30,524	10/1/1925 to current	Real Time, Instantaneous Peak, Mean Daily Discharge, Gage Height, Suspended Sediment
07164500	Arkansas River at Tulsa, OK	553	74,615	84 / 30,524	10/1/1925 to current	Real Time, Instantaneous, Mean Daily Discharge, Gage Height, Suspended Sediment
07165570	Arkansas River near Haskell, OK[b]	608	75,473	37 / 13,476	6/1/1972 to current	Real Time, Instantaneous, Mean Daily Discharge, Gage Height, Suspended Sediment
07160000	Cimarron River near Guthrie, OK	Keystone Lake	16,893	72 / 23,818	10/1/1937 to current	Real Time, Instantaneous Peak, Mean Daily Discharge, Gage Height, Suspended Sediment
07161450	Cimarron River near Ripley, OK	Keystone Lake	17,979	22 / 7,879	10/1/1987 to current	Real Time, Instantaneous Peak, Mean Daily Discharge, Gage Height

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07165570	Arkansas River near Haskell, OK[b]	608	75,473	37 / 13,476	6/1/1972 to current	Real Time, Instantaneous, Mean Daily Discharge, Gage Height, Suspended Sediment
07164600	Joe Creek at 61st St at Tulsa, OK[c]	560	12.2	21 / 7,718	03/11/1988 to current	Real Time, Instantaneous Peak, Mean Daily Discharge
07165562	Haikey Creek at 101st St South at Tulsa, OK[c]	575	17.8	20 / 7,766	01/20/1988 to current	Real Time, Instantaneous, Mean Daily Discharge
07165565	Little Haikey Creek at 101st St South at Tulsa, OK	Tributary to Haikey Creek	5.5	22 / 7,899	10/01/1987 to current	Real Time, Instantaneous, Mean Daily Discharge, Gage Height

[a] Gage at Ralston, OK is upstream of Keystone Dam

[b] Gage at Haskell, OK is downstream of Tulsa – Wagoner County Line

[c] River mile (RM) at tributary confluence with Arkansas River

Regulation at Keystone Dam and other upstream reservoirs has altered the flow regime of the Arkansas River. Keystone Dam was authorized by the Flood Control Act of 1950 to provide flood control, water supply, hydroelectric power, sediment retention and water quality control, recreation, and fish and wildlife enhancement. USACE began construction in 1957 and the dam was completed and placed into operation in 1964. The storage capacity of Keystone Lake is 1,167,232 ac-ft. Power production at Keystone Dam began in 1968 (USACE, 2005). Comparing the pre- and post-dam discharge records at the USGS gage at Tulsa (gage # 7164500) shows that the pre-dam average annual peak discharge has decreased by nearly 40 percent from 96,000 cfs to 57,000 cfs despite a flow of more than 300,000 cfs following dam construction (Figure 5). However, Keystone Dam does not have the capacity to regulate extreme discharge events. The 1986 flood of record had a peak inflow to Keystone Lake of 344,000 cfs, and the peak discharge at the USGS Tulsa gage was 301,800 cfs. The 100-year flood was re-evaluated and increased from 170,000 to 205,000 cfs (C.H. Guernsey and Company et al., 2005). The flood conveyance capacity of the Arkansas River in the reaches protected by levees is 350,000 cfs, which is greater than the currently estimated 100-year discharge (Guernsey and Company et al., 2005). The channel capacity is less than 350,000 cfs in reaches without levees. In addition, the frequent and extreme changes in stream flow caused by operation of Keystone Dam and reservoir have altered the natural hydrograph (i.e., the magnitude, frequency, duration, and timing of flows) of the Arkansas River in the project area.

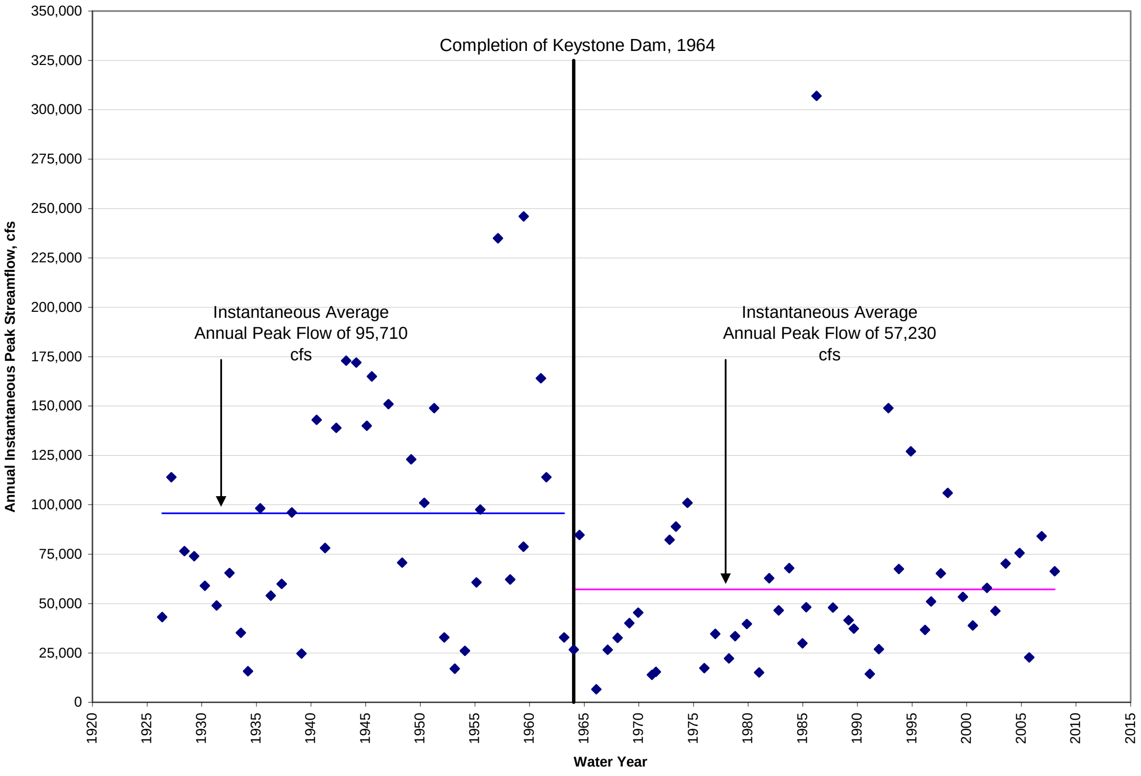

FIGURE 5
Annual Peak Flows as Measured at USGS Arkansas River at Tulsa Stream Gage (07164500). Note reduction in peak flows after construction of Keystone Dam.

Management of Keystone Dam for hydropower production results in hydropower peaking releases of up to 12,000 cfs. Hydropower releases typically last for a few hours once in the morning and once in the evening. During low flow conditions, hydropower peaking operations rapidly increase and decrease the amount of water in the channel, which inundates and then re-exposes large portions of the wide and shallow channel.

Data Gaps: Hydrology data gaps include hourly discharge data from hydropower releases prior to1987. Releases from Keystone Dam for hydropower production increase the discharge in the channel by 12,000 cfs for a few hours twice a day. These hydropower flows during low flow conditions inundate the wide and flat channel, impacting habitat for least terns and fish. Hourly discharge records were obtained for the USGS Arkansas River at Tulsa gage (7164500) and a flow-duration analysis conducted by Meshek & Associates (2009) to quantify the change in discharge caused by daily hydropower releases from Keystone Dam. Hourly discharge data from 1968 to 1987 should be obtained and added to the existing data set. Future hydrology analyses of the Arkansas River should recognize the fluctuation of the river stage due to hydropower discharges from Keystone Dam. Discharge records for tributaries to the Arkansas River in the project area should also be obtained, if available, from local agencies. The USGS maintains discharge gages on two tributaries to the Arkansas River in the project area, but additional gages may be maintained by local agencies. Meshek & Associates (2009) compiled results from existing hydrology models for tributaries to the Arkansas River and developed hydrology models for 10 additional tributaries. The discharge records and modeling results from tributaries can be useful in determining sediment transport dynamics in tributaries.

Geology

"Geology," in the context of fluvial geomorphology, refers to the history of the landforms and the parent material that compose a watershed. The sediment eroded from the watershed and the sediment load in the Arkansas River are derived from the rocks or parent material that make up the watershed. Through the project area, the location and depth of bedrock also provide geologic control for the Arkansas River. Channel migration and bed incision are limited by bedrock outcrops. In addition, the characteristics of rock formations in the project area are important for designing the footings for the proposed low-head dams and other in-channel construction-related activities.

The regional geology provides context for the past and current geomorphic processes that shape the Arkansas River and floodplain. Rocks in the project area were formed from ancient river and sea deposits. Rock outcrops in the hills adjacent to the Arkansas River in the project area are of Pennsylvanian age, and rocks in the upper portion of the project area consist of Dewey Limestone and Nellie Bly Formation. The rocks in the lower portion of the study area are older and include the Coffeyville, Checkerboard Limestone, Seminole, Holdenville, and Nowata Shale. The broad Arkansas River floodplain is composed of Quaternary alluvium, and the river floodplain is composed of Holocene alluvium deposited over older Pleistocene terrace deposits. The alluvium consists of unconsolidated gravels, sands, silts, and clays (Bennison et al., 1972; Marcher and Bingham, 1988 cited in Cherokee CRC, 2009; Heran et al., 2003).

Other key information sources related to geology are the depth to bedrock measurements conducted by USACE (West Consultants, 1990) and the recent geotechnical report for the Sand Springs and Jenks areas (Stantec, 2008). The depth of sediment to bedrock in the Arkansas River in 1988 from RM 524 to 538 ranges from 0 feet at a bedrock outcrop to 10 to 20 feet for the majority of the reach. Depth to bedrock data were collected in 1963, 1976, and 1988 by USACE at 12 locations and show a trend of decreasing sediment depth through time from Keystone Dam to Zink Dam (West Consultants, 1990). Stantec drilled eight borings across the width of the Arkansas River in 2008: five at the approximate location of the proposed South Tulsa/Jenks Dam and three at the proposed location of the Sand Springs Dam. The depth to bedrock at the proposed Jenks site ranged from 21 to 27.5 feet on the floodplain and from 3.8 feet to 8.0 feet in the channel. At the proposed Sand Springs site, the floodplain depth to bedrock ranged from 18.3 feet to 34.8 feet. The only channel boring at the proposed Sand Springs site was drilled on a bar in the channel and the depth to bedrock was 10.0 feet.

Data Gaps: The last depth to bedrock measurements were conducted in 1988 (West Consultants, 1990) and current measurements are required to determine if the trend of channel incision has continued or stabilized. The 12 USACE depth to bedrock sites should be re-measured to determine if the trend of decreasing depth to bedrock has continued or if the channel has established an equilibrium invert elevation since 1988. Additional borings should also be drilled throughout the project reach to provide similar information for the entire project area. Borings should be drilled at all proposed infrastructure locations and at locations where the depth to bedrock has been reported. Potential locations include bridge crossings where as-built construction drawings may show the depth to bedrock. Extending the comparison of historical to current depth to bedrock data can provide information on the extent of channel incision.

Hydraulics

Sediment transport is influenced by hydraulics. Therefore, hydraulic forces are extremely important in the evolution of channel form. A thorough understanding of current and potential hydraulics will be critical for the Arkansas River Corridor Projects because the proposed new dams and dam modifications will have the potential to modify and partially control hydraulic conditions in the project area. The design of the two proposed dams and their operation will influence hydraulics and sediment transport directly and channel bank stability and instream habitat development and maintenance indirectly. In addition, hydraulic conditions will be critical to the long-term success of ecosystem restoration and habitat improvement elements of this project.

Data Gaps: Hydraulic modeling analyses have been reviewed, compiled, and conducted for this project by Meshek & Associates (2009). That July 2009 document presents water surface elevations for a range of steady and unsteady state flow scenarios. These hydraulic model results should be evaluated further for predictions of velocities and shear stresses associated with flows near and above the expected threshold of channel bed and bank mobility. Depending on the complexity of site-specific river conditions or design elements, multi-dimensional hydraulic modeling could be used to address design questions.

Conclusion

This TM summarizes the available data and information on fluvial geomorphologic processes and identifies data gaps for further understanding of fluvial geomorphology on the Arkansas River. Fluvial geomorphic conditions will be critical to the success of ecosystem restoration and habitat improvement elements of the proposed project, as well as to proposed dam and dam retrofit elements. The Arkansas River has been significantly altered from its natural state by construction and operation of Keystone Dam. Sediment continuity from the upstream reach has been interrupted by the dam and the flow regime has been modified. The rapid increase and decrease in discharge during and after releases from Keystone Dam for hydropower production during low water periods rapidly increase and decrease the wetted area of the channel, impacting nesting habitat for least terns and fish habitat. The channel downstream of Keystone Dam has experienced incision and bank erosion as it has been scoured of sediment to regain the sediment load of the river. Further planning or design of proposed project elements should be informed by a more thorough understanding of the sediment transport dynamics of the current system, which can be developed by filling the data gaps identified in this TM. Based on the preliminary analyses summarized in this TM, the Arkansas River channel is responding to changes in sediment transport dynamics in the project area. Therefore, without a more complete understanding of the sediment transport dynamics in the project area, future infrastructure and development along the channel banks could be compromised due to future changes in channel conditions associated with ongoing channel adjustment or new adjustments in response to elements of the proposed project. These adjustments could include accelerated bank erosion, localized deposition and flow redirection, and increased channel bed scour, all of which could pose significant challenges for the sustainable design of new infrastructure to be located in or near the river channel. In addition, a better understanding of sediment transport dynamics should be developed to adequately plan for sediment-related maintenance that will be required to meet the project objectives.

Data gaps were identified in each of the sections above and are summarized and assigned a priority in Table 3.

TABLE 3
Summary and Prioritization of Data Gaps Identified

Fluvial Geomorphology Topic	Description of Data Gap	Methods to Fill Data Gap	Priority of Addressing Data Gap
Channel Morphology			
	Adequate understanding of historical channel change (bank erosion and migration) to predict potential future channel adjustments.	Obtain and rectify historical aerial photographs and maps, delineate the channel banks, and calculate channel migration rates.	High
	Extent of bed scour at bridge piers.	Obtain maintenance records for bridges that cross the Arkansas River and extract scour depth data.	Low
	Extent of bank armoring and levees in the project area.	Create a GIS layer showing the extent of armored channel banks and the location of engineered levees from aerial photographs, field work, and topographic maps.	High
	Adequate understanding of channel widening and incision over the 25-year period from 1977 to 2002.	Compare cross sections from the 1977 HEC-2 and 2002 HEC-RAS hydraulic models.	High
Sediment Budget			
	Adequate understanding of sediment dynamics (storage, production, and transport) in the Arkansas River in the project area.	Develop order-of-magnitude level sediment budget.	High
Sediment Supply			
	Recent change in channel geometry relative to historical change.	Repeat channel surveys conducted by USACE in 1963, 1976, and 1988.	High

TABLE 3
Summary and Prioritization of Data Gaps Identified

Fluvial Geomorphology Topic	Description of Data Gap	Methods to Fill Data Gap	Priority of Addressing Data Gap
	Rate of sediment supply from eroding banks.	Conduct a systematic assessment of bank erosion using historical aerial photographs and historical cross sections.	High
	Quantity of suspended sediment that is transported through Keystone Lake.	Calculate the trap efficiency of Keystone Dam.	Low
	Quantity of sediment supplied from tributaries.	Use USGS gages (if available) or measurement of sediment deltas at the confluence of tributaries with the main-stem.	Medium
	Volume of sand and gravel extracted from the channel and floodplain.	Review permit history for sand and gravel mines and calculate extraction volumes.	Medium
Sediment Storage			
	Size classes of sediment stored in the channel bed.	Conduct facies mapping.	Low
	Current depth of erodible sediment between channel invert and underlying bedrock.	Drill borings to measure depth to bedrock and sediment composition.	High
	Size and lithology of channel bed sediment.	Collect bulk samples and have a geotechnical laboratory analyze the samples.	High
	Hydraulic influences on sediment storage.	Conduct hydraulic modeling.	High
Sediment Transport			
	Sediment transport rates throughout the project area.	Develop a detailed sediment transport model for the entire project area.	High
	Flow thresholds required to mobilize and transport channel bed and bank sediments.	Conduct incipient motion analysis.	High
	Adequate understanding of sediment transport in the Arkansas River in the project area.	Develop an order-of-magnitude sediment budget.	High

TABLE 3
Summary and Prioritization of Data Gaps Identified

Fluvial Geomorphology Topic	Description of Data Gap	Methods to Fill Data Gap	Priority of Addressing Data Gap
Hydrology			
	Adequate understanding of the change in discharge during daily peaking from Keystone Dam.	Obtain hourly discharge records pre-1987 and conduct a flow-duration analysis.	Low
	Hydrologic characteristics of tributaries to the Arkansas River.	Obtain discharge records or hydrology model results for tributaries to the Arkansas River in the project area from local agencies. The discharge records and modeling results from tributaries can be useful when trying to determine the sediment input from tributaries.	Low
Geology			
	Adequate understanding of channel invert elevation condition/trajectory/equilibrium to guide project design.	Re-survey 12 USACE depth to bedrock sites.	High
	Adequate understanding of the amount and composition of alluvial sediments and parent material throughout the study area to guide project design.	Drill systematic geotechnical borings in the project area.	Medium
Hydraulics			
	Thresholds for channel bed mobility and bank erosion.	Review hydraulic modeling and analyses conducted by Meshek & Associates (2009) of water surface elevations, velocities, and shear stresses for flows near and above the threshold of channel bed and bank mobility.	High
	Spatial extent of scour, deposition, and storage of sediment related to design of in-channel structures.	Conduct multi-dimensional hydraulic modeling.	Medium

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Appendix A

TABLE A1

Summary of Geomorphic Information Complied from Project Documents

Major Fluvial Geomorphic Topic	Data Source (Title)	Data Source (Author)	Data Source (Month and Year)	Relevant Information
Channel Morphology				
	Water Management Analysis Report Flood of September - October 1986	U.S. Army Corps of Engineers, Southwestern Division, Tulsa District	August 1987	The Arkansas River Basin in Oklahoma and Kansas is a transition between the Great Plains on the west and the Ozark Mountains and Central Lowlands on the east. The basin is approximately 160,000 mi^2. The Arkansas River is approximately 342 mi from Oklahoma-Kansas state line to Oklahoma-Arkansas state line. It is characterized by a broad, sandy bed, with long, easy bends and has an average fall (in this reach) of 1.9 feet per mile. Banks are well defined and range in height between 10 and 30 feet. Channel width varies from 600 to 3,000 ft. Much of the Arkansas River channel has been straightened from the mouth of Verdigris River to the Mississippi River to shorten the overall length and create the McClellan-Kerr Arkansas River Navigation channel (MKARNS). The banks have been stabilized to aid in the maintenance of depth and horizontal alignment.
	Arkansas River Corridor Master Plan Phase II Master Plan and Pre-Reconnaissance Study Volume 1, Part I	C.H. Guernsey and Company	October 2005	The Arkansas River has been degrading and eroding over the past 25 years, leading to increased channel storage, which has allowed the river to handle larger flows without noticeable increase in Water Surface Elevations (WSE).

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Summary of Geomorphic Information Complied from Project Documents

Major Fluvial Geomorphic Topic	Data Source (Title)	Data Source (Author)	Data Source (Month and Year)	Relevant Information
	Arkansas River Corridor Master Plan Phase II Master Plan and Pre-Reconnaissance Study Volume 1, Part II	C.H. Guernsey and Company	October 2005	The proposed location of the Sand Springs Dam is downstream of SH97 Bridge. Sand Springs Gravel/Mohawk Materials Sand and Gravel operation is on the upstream side of bridge. The available volume of sand and gravel is diminishing in the reach. The river is horizontally controlled by a levee, SH64, and Wekiwa Road, SH51, SH97 bridge. The proposed location of the Creek Turnpike Dam is downstream of Creek Turnpike Bridge and 96th St Bridge and upstream of Polecat Creek. The river is horizontally controlled by Riverside Dr (west bank) and railway (east bank). A sand and gravel operation is located downstream. Controls such as development, the Zink Lake Pedestrian Bridge, 21st St Bridge, a concrete plant, railway, and levee are within the proposed location of the Zink Lake Riverfront area. The west floodplain of the Crow Creek Planning Area appears to consist mainly of industrial land use and is controlled by Riverside Drive on the east bank. A natural terrace, Turkey Mountain, limits lateral movement of the river in the 71st Street Riverfront Planning Area and is also controlled by Riverside Drive on the east bank. The South Tulsa/Jenks Planning Area is controlled by Riverside Drive, Delaware Ave, the 96th St Bridge and Creek Turnpike. A large gravel point bar is located in the Bixby Riverfront Planning Area. Sand and gravel operations exist on both sides of Memorial Drive in addition to sod farms and concrete plants.
	Final Environmental Impact Statement Arkansas River Navigation Study	U.S. Army Corps of Engineers, Little Rock District and Tulsa District	August 2005	The Arkansas River was once a meandering and unpredictable river, which had a wide floodplain in many areas. Large sections of the Arkansas River were often not navigable by boat due to shallow water depths. In 1946, after many years of study and debate, Congress authorized USACE to begin constructing locks and dams. The MKARNS has been channelized and stabilized with

TABLE A1

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Major Fluvial Geomorphic Topic	Data Source (Title)	Data Source (Author)	Data Source (Month and Year)	Relevant Information
				dikes and revetments to improve navigation, which has reduced the historical floodplain. Flood control levees also constrict the historic floodplain.
	Vision for the Arkansas River Corridor at Tulsa	Tennessee Valley Authority	March 2008	The river bed drops approx 35 feet between the proposed Sand Springs and South Tulsa/Jenks Dam locations.
	Faunal & Floral Inventory Draft Report Task 1 Environmental Data for the Arkansas River Corridor Project, Tulsa, Oklahoma, W912BV-06-P-0303	Cherokee CRC, LLC	June 2008	Geomorphic features identified in Tulsa County include the Eastern Sandstone Cuesta Plain (ESCP) and the Claremore Cuesta Plain (CCP). The ESCP forms rugged hills with one steep face. The CCP has less pronounced and frequent hills composed of sandstone and limestone on top of broad shale plains. These hills form the topographic highs, while the Arkansas River forms the topographic lows. Both lows and highs define the watersheds and drainage basin boundaries. Relief ranges from 180 to 300 feet for cuestas (ridges with a steep face on one side and a gentle slope on the other) close to the river and 20 to 60 feet at floodplains.
	Aquatic Macroinvertebrates Structure and Composition Inventory Draft Report Task III Environmental Data for the Arkansas River Corridor Project, Tulsa, Oklahoma	Eagle Environmental Consulting, Inc.	November 2008	The Arkansas River throughout Oklahoma is considered to be a mature, late stage river classified as a large sixth to seventh order stream. A late stage river is characterized by the formation of a broad floodplain with large meanders, natural levees, oxbow lakes, point bars, back swamp areas, and some tributary streams that run parallel to the main-stem and eventually join the main-stem. The river's drainage system is identified by a dendritic pattern formed on flat laying homogeneous sedimentary rocks. In planview, a dendritic pattern has v-shaped junctions that usually flow on gentle slopes. The Arkansas River has characteristics of a braided stream throughout the study area with the exception of the Zink

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Major Fluvial Geomorphic Topic	Data Source (Title)	Data Source (Author)	Data Source (Month and Year)	Relevant Information
				Lake area. A braided stream is characterized by multiple interconnecting channels within the confines of the river bank. The braids are subject to widely fluctuating discharge and intermittent, abundant sediment supply due to alternating scouring and subsequent filling of the channels.
Sediment Supply	Vision 2025, Arkansas River Corridor, Ecosystem Restoration Plan, In Conjunction With Proposed Low Water Dams	U.S. Army Corps of Engineers, Tulsa County, & Tennessee Valley Authority	February 2009	Changes to geomorphology have resulted in streambank erosion problems and destruction of wetlands and oxbow habitat, which have led to the decline of species diversity and overall productivity.
	Anchor Stone Jenks Sand Plant Specific Use Permit #JZ-375-SUP-55	Cinnabar Environmental Services	October 2002	Aerial photos from 1951, 1966, 1977, 1985, 2001 were evaluated to determine the location and changes to the west bank between 71st Street and 131st Street (about 7 river miles). The report conclusions include: USACE has documented erosion along banks of Arkansas River since the 1940s, evaluation of aerial photos indicated that erosion along west bank near Jenks most prominent between 1951 and 1966, and no significant change in bank alignment between 1966 and 2001.
	Final Arkansas River Corridor Master Plan Phase I Vision Plan	Carter & Burgess	August 2004	The use of sand mining operations to assist in sand management is critical for continued viability. Studies of this scope, given the size of the study, can be very involved and consequently costly; however, the downside of not designing channel improvements correctly would

TABLE A1

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Major Fluvial Geomorphic Topic	Data Source (Title)	Data Source (Author)	Data Source (Month and Year)	Relevant Information
				be more costly.
	Final Environmental Impact Statement Arkansas River Navigation Study	U.S. Army Corps of Engineers, Little Rock District and Tulsa District	August 2005	During high river flows, silt and sand are carried in suspension. As flows decrease, heavier suspended materials are dropped and shoals develop in eddies and slow moving water. These shoals are typically removed by cutter head suction dredges to maintain the channel. The material from the Arkansas River is sand and is not suitable for planting. Dredged material is most likely to be free of contaminants it is composed primarily of sand, gravel, or similar material found in areas of high current or wave action.
	Arkansas River Corridor Master Plan Phase II Master Plan and Pre-Reconnaissance Study Volume 1, Part II	C.H. Guernsey and Company	October 2005	Severe streambank erosion is prevalent throughout the river corridor.
	Aquatic Macroinvertebrates Structure and Composition Inventory Draft Report Task III Environmental Data for the Arkansas River Corridor Project, Tulsa, Oklahoma	Eagle Environmental Consulting, Inc.	November 2008	The elevation of the Arkansas River is 670 feet at Keystone Dam and 577 at the Tulsa/Wagoner County line. The stream slope is 2.21 feet per mile (42-mile long study reach). Keystone Dam dramatically influences the volume of flow and sediment supply downstream. For the last 10 years, the average annual discharge rate at the Tulsa gage has been 9,892 cfs. Over the past 25 years, the Arkansas River has eroded, which has increased channel storage and capacity for Base Flood Flow to 205,000 cfs. Prior to construction of the dam in 1964, the average annual sediment load passing the Tulsa, OK gage was approx 22,100,000 tons according to a 1972

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Major Fluvial Geomorphic Topic	Data Source (Title)	Data Source (Author)	Data Source (Month and Year)	Relevant Information
				study by Bennison et al. There have not been any recent sediment loading studies for the Tulsa vicinity.
	Vision 2025, Arkansas River Corridor, Ecosystem Restoration Plan, In Conjunction With Proposed Low Water Dams	U.S. Army Corps of Engineers, Tulsa County, & Tennessee Valley Authority	February 2009	Twenty-foot high cut bank of Prattville Creek could compromise the proposed dam location at Sand Springs. Tennessee Valley Authority (TVA) recommends moving the dam on south bank upstream (150 feet).
Sediment Storage				
	Zink Dam Sedimentation Study, Final report	West Consultants, Inc.	February 1990	Annual depositional rates to the Zink Dam pool were estimated: average 195.1 ac-ft and vary from 666.6 ac-ft to 17.9 ac-ft from 1963 to 1987.
	Annual Report 2006 and 2007	Oklahoma Mining Commission Department of Mines	August 2008	2.9 million tons of sand and 2.4 million tons of gravel were extracted from rivers and floodplains in Tulsa County in 2006 and 2007.
Sediment Transport				
	Zink Dam Sedimentation Study, Final report	West Consultants, Inc.	February 1990	Suspended sediment rating curves were developed for time periods 1961-1964, 1965-1969, 1970-1974, 1975-1980, and 1981-1988 at the 11th Street bridge (upstream of Zink Dam). Suspended sediment yield and transport have decreased since construction of Keystone Dam. Bed elevation changes (between Keystone Dam and Zink Dam) were documented in the report. Cross section

TABLE A1

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Major Fluvial Geomorphic Topic	Data Source (Title)	Data Source (Author)	Data Source (Month and Year)	Relevant Information
				surveys in 1963, 1976, and 1988 were conducted at 12 locations. The results show that the channel bed is degrading at a constant rate. Streambank depletion occurred, especially during the 1986 flood. Although upstream sediment sources have diminished, there are sufficient sources to maintain a constant yield to Zink Dam for the next 15-20 years.
	Final Arkansas River Corridor Master Plan Phase I Vision Plan	Carter & Burgess	August 2004	The low-head dams must be designed for fish passage and sediment transport. A sediment transport study should be undertaken to accurately assess the amount of sediment that passes through the system. Zink Lake shows that improvements within the river channel banks cannot be undertaken without consideration for transporting sediment through the system. The long-term presence of sand mining operations indicates that large amounts of sediment can move through the system; use of impounded lakes is not an ideal solution to sedimentation. Anecdotal information has been collected on sediment transport. The following observations were compiled during several public meetings: (1) the sand operations in the more northern locations periodically run out of sand, (2) the bridge piers at old 96th Street bridge at Jenks were formerly buried and have now been uncovered, (3) the character and quality of the sand are changing, and (4) sand plants have never and will never run out of sand.
	Arkansas River Corridor Master Plan Phase II Master Plan and Pre-Reconnaissance Study Volume 1, Part II	C.H. Guernsey and Company	October 2005	Changes have occurred to the natural flow regime due to land use changes. Frequent and extreme river fluctuations are a result of hydropower operations.

TABLE A1

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Major Fluvial Geomorphic Topic	**Data Source (Title)**	**Data Source (Author)**	**Data Source (Month and Year)**	**Relevant Information**
Hydrology				
	Water Management Analysis Report Flood of September - October 1986	U.S. Army Corps of Engineers, Southwestern Division, Tulsa District	August 1987	Average annual precipitation is 39 inches, with an average annual snowfall of 10 inches. Storms are generally of long duration, with large total rainfall amounts and large spatial extents. Average annual rainfall for region ranges from 32 inches at Wichita, KS and Oklahoma City, OK to 44 inches near Oklahoma-Arkansas line. The Arkansas River system has very limited flood control storage and can only partially control larger floods. Eleven lakes have primary control of flows on the main-stem Arkansas River downstream from Keystone Dam accounting for approx 75% of the total flood control storage available in the basin. The Tulsa District operates 35 lakes in the Arkansas River Basin for multiple uses such as flood control, hydropower, navigation, water supply, water quality, recreation, irrigation, and fish and wildlife management.
	Final Environmental Impact Statement Arkansas River Navigation Study	U.S. Army Corps of Engineers, Little Rock District and Tulsa District	August 2005	Keystone Lake has two major arms, including the Cimarron River arm, which is characterized by gently rolling hills, and the Arkansas River arm, which is characterized by steep, broken hills to low rolling hills and many small valleys in its upper reaches. The lake was formed by the damming of the Arkansas River at river mile 538.8, approximately 15 miles east of Tulsa, in Tulsa County, Oklahoma. The lake shore includes sandy beaches as well as wooded shorelines and high bluffs. Topography surrounding Keystone Lake varies from rugged rocky terrain and forests near the dam, to gently rolling hills and grasslands in the upper reaches. The reservoir drains a 74,506- mi^2 area above the dam. The surface areas for the lake are 54,320 acres, 22,420 acres, and 12,430 acres for the top of the flood control, conservation pool, and inactive pool, respectively. The lake has approximately 330 miles of shoreline.

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Major Fluvial Geomorphic Topic	Data Source (Title)	Data Source (Author)	Data Source (Month and Year)	Relevant Information
				Approximately 251 miles of the shoreline is classified as protected lakeshore and 55 miles is designated for public recreation. The remaining shoreline includes 21 miles allocated for limited development and 3 miles allocated as prohibited access.
	Arkansas River Corridor Master Plan Phase II Master Plan and Pre-Reconnaissance Study Volume 1, Part I	C.H. Guernsey and Company	October 2005	The construction of Keystone Dam began in 1956 and the lake became operational in 1968. The maximum historical inflow to Keystone Lake was 344,000 cfs (Oct. 1986) and the max recorded flow at Tulsa was 301,800 cfs from the same flooding event.
	Arkansas River Corridor Master Plan Phase II Master Plan and Pre-Reconnaissance Study Volume 1, Part II	C.H. Guernsey and Company	October 2005	Keystone Dam was built for hydropower and flood control. Changes have occurred to the natural flow regime due to land use changes. Frequent and extreme river fluctuations are a result of hydropower operations.
	Vision 2025, Arkansas River Corridor, Ecosystem Restoration Plan, In Conjunction With Proposed Low Water Dams	U.S. Army Corps of Engineers, Tulsa County, & Tennessee Valley Authority	February 2009	Keystone Dam has altered the river corridor ecosystem. For example, Keystone Lake significantly reduces the amount of sediment that maintains downstream island habitat for terns. Frequent and extreme river fluctuations from hydropower operations (high flows followed by low flows) have a drying effect on aquatic habitat.

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Major Fluvial Geomorphic Topic	Data Source (Title)	Data Source (Author)	Data Source (Month and Year)	Relevant Information
Geology				
	Final Environmental Impact Statement Arkansas River Navigation Study	U.S. Army Corps of Engineers, Little Rock District and Tulsa District	August 2005	Rocks under the Oucahita and Ozark Provinces are Paleozoic in age. Ouachita bedrock is fractured, faulted, and folded shale, sandstone, limestone, and cherty-novaculite rocks. The Ozark Province consists of well consolidated, flat-laying to south dipping, fractured carbonate and clastic rocks underlain by dolomite and sandstone beds of Cambrian age formed at the basal part of the Paleozoic sequence. Deposition and down-cutting by major rivers and streams were extensive from the end of the Tertiary period to the Quaternary period. This pattern of erosion and deposition left a series of alluvial terraces which may be only a few feet above the current floodplain. Alluvium is the most recent depositional material within the confines of the current floodplain. In Oklahoma, alluvium and alluvial terraces of the main-stem of the Arkansas River average more than 5 miles in width and 45 feet in depth between the confluence of the Cimarron River and where the Arkansas River passes Tulsa. The deposits are predominantly sand and gravel and the water table is generally less than 20 feet below the soils. In the northwestern portion of Arkansas, where the Arkansas River enters the state, the valley is characterized by rolling flat-topped hills, long narrow ridges, and broad valleys. The hilltops and ridges are mostly underlain by shale.

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Major Fluvial Geomorphic Topic	Data Source (Title)	Data Source (Author)	Data Source (Month and Year)	Relevant Information
	Geotechnical Investigation and Testing, Arkansas River Corridor Project, Arkansas River Contract No. DACW912BV-07-D-1000, Sand Springs/Jenks, Oklahoma	Stantec Consulting Services Inc.	May 2008	Soils testing has been conducted in the vicinity of the proposed Sand Springs and South Tulsa/Jenks low-head dams. Analysis includes borings, coordinates of sample locations, strength test results, particle size distributions, and photographs. Eight borings were drilled across the width of the Arkansas River in 2008: five at the approximate location of the proposed South Tulsa/Jenks Dam and three at the proposed location of the Sand Springs Dam. The depth to bedrock at the proposed South Tulsa/Jenks site ranged from 21 to 27.5 feet on the floodplain and from 3.8 feet to 8.0 feet in the channel. At the proposed Sand Springs site, the floodplain depth to bedrock ranged from 18.3 feet to 34.8 feet. The only channel boring at the proposed Sand Springs site was drilled on a bar in the channel and the depth to bedrock was 10.0 feet.
	Faunal & Floral Inventory Draft Report Task 1 Environmental Data for the Arkansas River Corridor Project, Tulsa, Oklahoma, W912BV-06-P-0303	Cherokee CRC, LLC	June 2008	The geology of the Arkansas River Corridor study area is underlain by rocks of Pennsylvanian age. Hills in the upper reaches of the river are composed of Dewey Limestone and Nellie Bly Formation. Rock formations become progressively younger downstream and include Coffeyville, Checkerboard Limestone, Seminole, Holdenville, and Nowata Shale. These rocks formed in ancient river and sea deposits that include delta, prodelta, subtidal clastics and marine shell banks, shallow marine banks, platform shallow marine, and marine basinal shales. Quaternary river deposits overlie the younger Pennsylvanian formations on the broad floodplains along the river. The younger Holocene deposits represent modern floodplain alluvium that overlie older Pleistocene terrace deposits of unconsolidated gravels, sand, silts, and clays.

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Major Fluvial Geomorphic Topic	Data Source (Title)	Data Source (Author)	Data Source (Month and Year)	Relevant Information
Hydraulics				
	1980 HEC-2 Hydraulic Model	FEMA	1980	1980 HEC-2 Hydraulic Model developed to support the FEMA Tulsa County Flood Insurance Study. The cross sections for the model were taken from 5-foot contour interval mylar maps.
	2002 HEC-RAS Hydraulic Model	U.S. Army Corps of Engineers	2002	2002 HEC-RAS Hydraulic Model. The elevation data input into the model were collected using photogrammetric methods and channel was supplemented with ground surveys. The model geometry was extracted from the resulting surface with 2-foot contour intervals.