BUREAU OF RECLAMATION
TECHNICAL SERVICE CENTER
DENVER, COLORADO

ANALYSIS OF LITTLE COLORADO RIVER STABILITY BETWEEN HOLBROOK AND WINSLOW, ARIZONA

REPORT OF FINDINGS

LITTLE COLORADO RIVER SEDIMENT STUDY

US Department of the Interior
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WATER RESOURCES MANAGEMENT.....FOR THE FUTURE

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U.S. Department of the Interior Mission Statement

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian tribes and our commitments to island communities.

Mission of the Bureau of Reclamation

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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UNITED STATES DEPARTMENT OF INTERIOR
BUREAU OF RECLAMATION

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STUDY TEAM

The Bureau of Reclamation Phoenix Area Office assembled a study team with expertise in water resources management, fluvial geomorphology, paleohydrology, hydraulics, sedimentation, and photogrammetry. The principal scientists were fluvial geomorphologists and engineers of the Reclamation Fluvial Hydraulics & Geomorphology Team, from the Technical Service Center. In addition, team members included technical staff from the Navajo County Public Works Department.

The team members are:

- Mr. Kevin Black Sr., Program Specialist. (Study Manager)
- Mr. Tom Hieb, Hydrologist. (Navajo County Public Works Department)
- Dr. Daniel R. Levish, Fluvial Geomorphologist. (Paleohydrology, Fluvial Geomorphology)
- Dr. Rodney J. Wittler, Hydraulic Engineer. (Hydraulics, Water Resources Management)
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- Mr. Donald Reiff, Chief Surveyor. (Surveying)
- Mrs. Kim Dannemiller, Cartographer. (Photogrammetry)
- Mr. Dean Montgomery, Cartographic Technician. (Photogrammetry)

ACKNOWLEDGEMENTS

The Bureau of Reclamation Phoenix Area Office (PXAO) and Navajo County provided Funding and support for this study under Cost Share Agreement No. 00–GI–32–0070. Kevin Black of the Phoenix Area Office served as Study Manager and Tom Heib of the Navajo County Public Works Department served as Navajo County's technical representative. Rod Wittler and Dan Levish from the Bureau of Reclamation Technical Service Center (TSC) in Denver served as TSC Study Team Leaders. Robert Hilldale of the Sedimentation and River Hydraulics Group and Jeanne Klawon and Ralph Klinger of the Flood Hydrology Group at the TSC developed the results and conclusions presented in this report. The report was peer reviewed by Dan Levish of the TSC Flood Hydrology Group, and Blair Greimann and Christi Young of the TSC Sedimentation and River Hydraulics Group. Patricia Deschamps of J.E. Fuller Hydrology and Geomorphology, Inc. in Phoenix, Arizona, provided external peer review. Ron Miller and Jan Oliver of the TSC Remote Sensing and Geographic Information Group produced digital versions of the final geomorphic maps. Donald Reiff, Lolito Esperanza, Doug Bingham, Kim Dannemiller and Dean Montgomery of the PXAO acquired the survey control data and developed the photogrammetry used in the topographic maps for hydraulic modeling and geomorphic mapping. Pacific Western Technologies of Albuquerque, New Mexico, flew the aerial photography for this project.

A major part of this study included the collection and development of field data. These data included the collection of sediment samples to characterize the grain size distribution of bed and bank material, survey control for the development of the detailed topography used in the hydraulic modeling effort and the geomorphic mapping, and stratigraphic information to verify the geomorphic mapping and the chronology of the map units. This would not have been possible without the assistance of the Navajo County Public Works Department. Reclamation gratefully acknowledges the Arizona Public Service (APS), Burlington Northern Santa Fe Railroad, City of Winslow Department of Parks and Recreation, and J.R. DeSpain and his family for allowing access to their property to collect this field data.

ANALYSIS OF LITTLE COLORADO RIVER STABILITY BETWEEN HOLBROOK AND WINSLOW, ARIZONA

EXECUTIVE SUMMARY

This report documents the findings of a sedimentation and fluvial geomorphology study along the main stem of the Little Colorado River in the reach between Holbrook and Winslow, Arizona. The study utilizes both fluvial geomorphic and hydraulic engineering analyses. These analyses allow for the prediction of future conditions considering the nature of historical sedimentation processes in combination with a long–term perspective on the alluvial history of the Little Colorado River.

In March of 2000, Navajo County posed the following questions:

1. Is the Little Colorado River between Holbrook and Winslow Arizona aggrading either regionally or locally? Is the aggradation due to climate change or other large scale factors? Is aggradation due to changes in river hydraulics caused by levees, bridges, or other channel changes?
2. What is the magnitude of the aggradation? What are the future impacts of aggradation on levees and bridges?
3. What cost–effective measures will reduce or reverse the impacts of aggradation?

The purpose of this study is to answer these three questions. Major products of this analysis include results from a numerical sediment transport model, a fluvial geomorphic analysis of the study reach including geomorphic maps that depict the current state of the river, and a monitoring plan. This report does not address the viability of the Winslow or Holbrook levees or water surface elevations for the 100–year flood. The analysis of the cause and magnitude of aggradation in the Little Colorado River includes information from previous studies.

The four major terraces mapped along the Little Colorado River between Holbrook and Winslow, Arizona document episodes of aggradation and degradation during the past 3,000 years. The timing of this aggradation and degradation is similar in timing to the alluvial history reported in nearby areas on the Colorado Plateau. The favored theory for these episodes is the climate cycles driving periods of alluviation during dry cycles and periods of degradation during wet cycles. Based on present channel conditions and presence of bedrock in the channel at multiple locations, the Little Colorado River between Holbrook and Winslow appears to be in a stable or slightly degrading state. Conditions along upstream sections of the river and in the larger tributaries appear to be similar. Estimates of sediment availability show that the amount of available sediment is essentially unlimited. Thus, the Little Colorado River system is transport, not supply, limited.

Reclamation modeled sediment transport in the Little Colorado River from the confluence of the Puerco River upstream of Holbrook to downstream of the Winslow Levee. The modeling addresses sedimentation and potential impacts related to aggradation. For this analysis, reclamation modeled five hydrologic scenarios using GSTARS–2C. They include 1) a 10–year base hydrograph consisting of the five wettest and five driest years on record, placed in chronological order, at the Holbrook gage (USGS station No. 09397000); 2) a 10–year dry hydrograph; 3) the 10–year base hydrograph with a synthetic 50–year flood event occurring in the last year of the simulation; 4) a 50–year hydrograph that was developed by repeating the 25 years of record available at the Holbrook gage; and 5) a 60,000 ft^3/s hydrograph with a duration of 76 hours. All hydrographs include partial peak data to better simulate the natural flow of the river. All hydrographic simulations show consistent results over the reach. The GSTARS–2C sediment model evaluated three geometric scenarios. These include 1) the removal of Penzance Dam; 2) realigning the levee near Bushman Acres; and 3) channelizing a portion of the river downstream of Bushman Acres to straighten the channel and move it away from the levee.

It is the conclusion of the sediment modeling effort that from Holbrook through Winslow the river is stable and projected to remain so. The reach along the Winslow levee shows no widespread aggradation. Some specific locations indicate local aggradation, primarily near hydraulic controls. This aggradation is less than two feet over the 50–year projection. Along the levee in Holbrook, the GSTARS–2C sediment model results show aggradation over a 50–year projection beginning at the Apache Railroad bridge and progressing upstream to the confluence with the Puerco River. The aggradation in this reach is largely attributable to the railroad bridge in Holbrook, since its presence creates a hydraulic control. Constriction of the channel and flood plain in this reach due to bridge and levee construction also contributes to the aggradation. A large meander upstream of the Route 77 Bridge in Holbrook appears to contribute to the aggradation, although to a lesser degree.

Because the results of the sediment modeling show no severe or detrimental aggradation, there is no need to entertain plans for corrective measures. Although aggradation may occur between the confluence of the Puerco River and the Apache Railroad Bridge, the modeled aggradation does not warrant further investigation. The Holbrook levee design allows for as much as 4.5 feet of aggradation. GSTARS–2C model results show 4.3 feet of aggradation over a 50–year period. Results of the sediment model indicate that removal of Penzance Dam would degrade the river upstream to Leroux Wash. The channelization and levee realignment scenarios in Winslow do not indicate sedimentation effects upstream or downstream of the specific project. The latter two scenarios modeled the sediment transport following implementation of projects designed to lower the water surface elevation adjacent to levees during floods. Reclamation does not recommend any of the geometric scenarios for the sole purpose of decreasing aggradation in Holbrook or Winslow. Reclamation recommends a systematic monitoring program to track aggradation or degradation. Monitoring the river at selected cross sections provides an on–going database of information to determine future meaningful changes in the river. This database will also increase the future value of the sediment modeling by providing calibration information should the model require adjustment.

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INTRODUCTION

This report documents the findings of a sedimentation and geomorphology study along the main stem of the Little Colorado River in the reach between Holbrook and Winslow, Arizona. Figure 1 shows the study area. By utilizing both geomorphic and hydraulic engineering approaches, these analyses allow for the prediction of future conditions considering the nature of historical sedimentation processes in combination with a long–term perspective on the alluvial history of the Little Colorado River.

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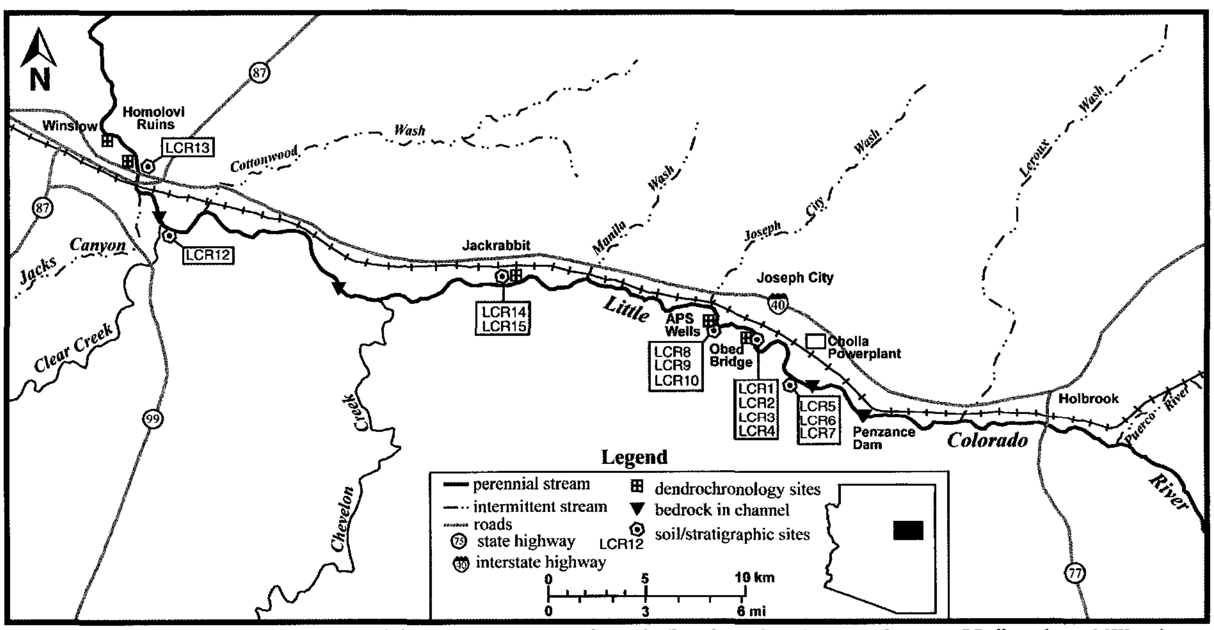


Figure 1. Map showing the location of detailed study sites along the Little Colorado River between Holbrook and Winslow.

PHYSIOGRAPHIC SETTING OF THE LITTLE COLORADO RIVER

The Little Colorado River is located in the Colorado Plateau physiographic province. This province is characterized by broad plateaus and mesas with deep canyons in relatively flat–lying Paleozoic and Mesozoic rocks. While the bedrock in Colorado Plateau province is relatively flat lying, in the Holbrook–Winslow area, the bedrock dips gently to the north–northeast. As a result, the younger Mesozoic rocks are found along the Little Colorado River and the plateau to the north and the older Paleozoic rocks are found on the highlands to the south. The Little Colorado River between Holbrook and Winslow flows primarily across the Moenkopi Formation (Wilson et. al., 1960), a poorly consolidated mudstone that contains thin beds of resistant sandstone. The Chinle Formation, also a poorly consolidated mudstone that contains thin beds of resistant sandstone, underlies the tributary basins of the Little Colorado River to the north and east (Wilson et. al., 1960). The Permian Coconino Sandstone and the Kaibab Limestone crop out in the headwaters of the Little Colorado River and its major tributaries to the south (Wilson et. al., 1960). Both formations are relatively resistant compared to the Moenkopi and Chinle Formations. Significantly younger Tertiary volcanic rocks form the San Francisco Peaks and White Mountains are found to the west and southeast, respectively, of the study area. Small exposures of volcanic rocks are found in the Leroux Wash drainage (Wilson et. al., 1960)

The Little Colorado River originates in the White Mountains of east–central Arizona and flows north to northwest through the towns of Holbrook, Winslow, and Cameron before it joins the Colorado River at the eastern end of the Grand Canyon. The Little Colorado River basin is a sub basin to the Colorado River basin and drains a large portion of the Colorado Plateau in northeastern Arizona. Tributaries in the upper headwaters to the south originate in the White Mountains while those to the north have their sources on the plateau. Although the study reach is predominantly alluvial, extensive narrow incised canyon reaches are present upstream of Holbrook, in the southern tributaries between Holbrook and Winslow, and downstream of Grand Falls.

The records of seven gaging stations comprise the hydrologic record of the Little Colorado River in the study area. There are four gages on the main stem and three gages on major tributaries (Table 1). When Sabol (Sabol, 1993) conducted the Little Colorado River Geomorphology and River Stability Study, six of these gages were in operation. The seventh gage, located at Winslow, was discontinued after recording data from 1954 to 1956 and reestablished in 2002. Data analysis by Sabol (Sabol, 1993) shows that annual unit peak discharges at Grand Falls are considerably larger on average than at Holbrook. This is due in part to contributions from Clear Creek and Chevelon Creek, major tributaries that drain the mountainous Mogollon Rim in the southern part of the basin. The combined flow from these two tributaries at times is greater than flow at Holbrook. The largest peak discharges at Holbrook have been largely a result of large flows on the Puerco River. The Puerco River drains the plateau region of the basin rather than the mountainous headwaters of the Little Colorado River.

The stream gaging data in the Little Colorado River basin is quite irregular. Of the seven gaging stations in study area, the gage at Woodruff (USGS station No. 09394500) on the Little Colorado River has the longest continuous record extending from 1929 to the current year. Records at the remainder of the gages are commonly less than 50 years. Discontinuous data within the basin extend back to the early 1900's, but the continuous record before 1925 is sparse. From the sparse records before 1925, data show large floods within parts of the basin in November 1905, January 1916, March 1918, December 1919, and September 1923. Flooding was widespread throughout the basin in 1929, but apparently resulted from two different storms. The first flood in early April appears larger at downstream sites; the second in July was larger in the upper basin site. A few large floods occurred during the late 1930's through the early 1950's. The frequency of large floods increased again beginning in the late 1960's. The largest floods in recent decades that appear to have impacted the study area were in December 1978 and January 1993.

Table 1. Stream gaging stations in the Little Colorado River basin.

USGS Station No.	Station Name	Period of Record	Maximum Peak Discharge (ft^3/s)	Drainage Area (mi^2)
09394500	Little Colorado River at Woodruff	1905–1919; 1929–1933; 1935–current	25,000 (12/05/1919)	7,775
09396500	Puerco River near Adamana	1940–1949	30,000 (8/12/1946)	2,604
09397000	Little Colorado River at Holbrook	1905–1907; 1949–1973	60,000 (9/19/1923)	11,115
09397300	Little Colorado River near Joseph City	1970–current	25,400 (12/19/1978)	12,045
09398000	Chevelon Creek near Winslow	1905–1906; 1915–1919; 1929–1972	33,600 (12/18/1978)	781
09399000	Clear Creek near Winslow	1906; 1929–1982	50,000 (4/04/1929)	621
09400000 09400350	Little Colorado River near Winslow	1954–1956; 2002		16,100
09401000	Little Colorado River at Grand Falls	1925–1960; 1989–1994	120,000 (9/19/1923)	20,700

The patterns of flooding are paralleled by comparative increases or decreases in mean annual discharges and precipitation. Sellers (Sellers, 1960) and Johnson (Johnson, 1976) noted negative (decreasing) trends in average annual precipitation since 1905. The cause for this trend was attributed to a decrease in winter precipitation. Notable departures from these average conditions include unusually wet periods from 1916 to 1925 and extended drought during the 1940's and 1950's. Graf (Graf et. al., 1991) note decreasing trends from 1940 to 1980 and increasing trends since 1980. Sabol (Sabol, 1993) and Hereford (Hereford et. al., 2002) describe the trends in precipitation data for the region and report similar trends. The hydrology has been linked to geomorphic processes along the Little Colorado River by several researchers (Hereford, 1984; Hereford and Webb, 1992; Graf , 1987) and is a topic that will be discussed in examining the causes for aggradation and degradation in the Little Colorado River system.

PREVIOUS STUDIES

The purpose of this literature review is to briefly summarize a number of previous studies of the Little Colorado River and the region. Selected studies pertain to the Quaternary alluvial stratigraphy, geomorphology, and sediment transport in the study area with application to this study. However, the limits of the review are studies that have direct relevance to recent history of the river (<10,000 years) or that deal with issues of aggradation and degradation in close proximity to the study area.

GEOMORPHOLOGY

Studies that document the Quaternary geology and alluvial history along drainages in the Black Mesa region and on the Colorado Plateau can be used to place the geomorphology along the Little Colorado River into a regional context. In many cases, the findings of these studies record geomorphic characteristics that are similar to those described in this study. Early studies were mainly prompted by archaeological discoveries and questions on how prehistoric peoples interacted with their environment. Historical arroyo cutting and its impacts on human interests have been the major drivers in generating the voluminous body of literature that documents the alluvial history on the Colorado Plateau and proposes differing theories on the cause(s) of entrenchment. Of these studies, several have direct relevance to this study.

Hack's (Hack, 1942) publication on "The Changing Physical Environment of the Hopi Indians of Arizona" is one of the first studies of the alluvial history in the region. As part of his research, Hack investigated erosion and sedimentation in major drainages in western Navajo County. Hack's classification of Quaternary stratigraphy is the earliest research on this subject in the area and has been retained by later workers. Major subdivisions defined by Hack include the Jeddito (10000–6000 B.C.), Tsegi (3,000 B.C.–1200 A.D.), and Naha (1300–1700 A.D.) formations. Periods of erosion occurred between the depositional periods represented by each formation. However, the formations are not simply vertically accreted deposits, as they record relatively minor episodes of erosion and deposition (cut and fill sequences). Hack does not describe the alluvial history or units younger than the Naha Formation, either because it was not directly related to the objectives of his research or there was no recognition of historical aggradation. Hack summarizes the history of erosion and deposition and postulates corresponding climatic conditions for each episode and the effects on prehistoric agricultural communities.

Later studies (Cooley, 1962; Cooley and Akers, 1961) document at least five cycles of aggradation and degradation drainages on the Colorado Plateau in Arizona, New Mexico, Utah, and Colorado. Historical documents and unconformities in the alluvial stratigraphy on the Colorado Plateau indicate two prominent and two secondary episodes of erosion in the late 19th and early 20th centuries. The description of units and timing for these cycles appear to be similar to Hack's alluvial history in northern Arizona.

Building on this previous work, chronostratigraphic data on the alluvial history in the Black Mesa region was later developed (Karlstrom, 1988; Karlstrom and Karlstrom, 1986). Using dendrochronology, radiocarbon, and archaeological correlation, the age of unconformities and buried soils in the depositional record was established. Karlstrom (Karlstrom, 1988) documents five major episodes of erosion and soil formation that center around AD 1900, 1450, 850, 350, and 250 BC. According to Karlstrom, these episodes would correspond with drought conditions with secondary episodes centered on AD 1700, 1150, 600 and 50. Drought conditions would correspond with stream entrenchment, reduced sediment yield, relative slope stability, narrow channels with confined flooding, and inferred lower water tables. Conversely, wetter conditions would correspond with periods of aggradation in overbank depositional settings, wider channels, increased sediment yield from more unstable slopes, and inferred higher water tables. Based on his study of alluvial stratigraphy, Karlstrom proposes a model of "broadly synchronous and cyclic patterns of hydroclimatic change" (Karlstrom, 1988; p. 71).

Kolbe (Kolbe, 1991) examined the alluvial history in relation to the settlement and abandonment of the Homolovi III Pueblo near Winslow. The alluvium that Kolbe mapped is very similar to those units described by Hereford (Hereford, 1984; Hereford, 1987 a,b) and later by Huckleberry (Huckleberry, 1996) including a terrace that was abandoned during the historical arroyo–cutting phase (post–1880) on the Little Colorado River and a terrace that aggraded between the 1930's and 1970's. The age for each of the terraces was based on germination dates of Cottonwood and Tamarisk trees on its surface. Kolbe (Kolbe, 1991) indicates that the post–1880 entrenchment coincided with a period of channel widening, decreased sinuosity, and increased sediment transport and eolian activity. Aggradation beginning in the 1930's coincided with channel narrowing, increased sinuosity, and flood plain development and stabilization. Kolbe proposed that perhaps the settlement patterns associated with the Homolovi III Pueblo are linked to the hydroclimatic and alluvial record such that settlement took place during periods of drought while abandonment was associated with periods of above average discharge and aggradation. While this may seem counterintuitive, the idea is that during periods of drought, settlement was concentrated nearer the river and a source of water. During wetter periods, more of the landscape became available for exploitation, so settlement moved away from the river.

The most comprehensive studies of the Little Colorado River were conducted by Hereford (Hereford, 1979; Hereford, 1984; Hereford, 1987 a,b) on the reach between Winslow and Cameron and included some tributaries as well as other regional drainages. Hereford's studies focused on the historical depositional and erosional history of the Little Colorado River and the processes or factors likely to be causing these changes. By mapping the surficial geology and examining the alluvial stratigraphy, Hereford constructed an alluvial history that spans the last century. Findings of his study indicate that a period of stream entrenchment commenced in this area of the Colorado Plateau around 1880. This period of degradation was followed by a period of aggradation and channel narrowing from 1940–1980. During this time frame, there were few extreme discharges in the hydrologic record. Hereford estimates that roughly six to ten feet of sediment was deposited during this time interval. Since 1980, flood plain incision has been the dominant process. Hereford found that he could correlate deposits over a 100 mile–long reach and that these deposits were not time–transgressive, but were deposited over the same time interval. Based on this synchronicity and regional observations that record similar stratigraphy and depositional history, Hereford concluded that the cause for stream behavior must be regional. He favored both hydrology and climate as causative mechanisms for aggradation/degradation cycles.

The most recent work in the area was undertaken by Huckleberry (Huckleberry, 1996; Huckleberry, 1998) who mapped surficial deposits and estimated the magnitude of sediment deposition in the Winslow area in response to questions regarding the impact of aggradation on channel conveyance and the levee breach during the 1993 flood. Utilizing the germination dates of Tamarisk trees, Huckleberry indicates that up to 3 feet of sediment was deposited on the lowest two terraces while <8 to 24 inches was deposited on the higher terraces during the 1970's to 1990's. The thickness of sediment deposited decreased with distance from the main channel. Huckleberry stressed that while there has been aggradation within the levees in the last two decades, it has been highly variable relative to the age and topographic position of the alluvial surface and its distance from the main channel.

SEDIMENTATION

In 1940 the United States Army Corps of Engineers (USACE, 1940) completed a report titled "Report on Survey, Flood Control, Little Colorado River and its Tributaries Upstream from the Boundary of the Navajo Indian Reservation in Arizona". This report led to the construction of the levee in Holbrook in 1948. A subsequent report by the United States Army Corps of Engineers titled "Definite Project Report on Colorado River Basin, Little Colorado River levee, Holbrook, AZ" was completed in 1946 detailing the design of the levee. Beginning in 1974, the United States Army Corps of Engineers performed a preliminary sediment study. This was subsequently published in 1980 as "Review Report for Flood Control and Recreational Development for the Little Colorado River at Holbrook, AZ." This report investigated the 1948 levee in Holbrook and its ability to provide flood control. The report also reviewed related water resource problems. The report recommended reconstruction of the levee (constructed in 1948). Regulations were prescribed to prevent encroachment on improved channels, levees and other areas that might reduce the capacity of the Little Colorado River.

In 1990 (revised in April, 1991) the United States Army Corps of Engineers published the General Design Memorandum, Project Design (USACE, 1991) for the Holbrook levees. This report presents a flood control plan that provides the city of Holbrook with necessary protection from floods on the Little Colorado River. Recommendations were that the city of Holbrook operate and maintain the newly constructed levees through an organization headed by an official (superintendent) appointed by the city.

The Bureau of Reclamation (Reclamation, 1944) produced a report in 1944 on the Little Colorado River Basin investigating potential reservoir sites for irrigation and power development. Water quality was also investigated for irrigation and municipal consumption. The report considers flood control a minor issue, citing sparse population and a lack of improvement. One exception is in Holbrook due to floods that might originate on the Puerco River. The Bureau of Reclamation concurred with the findings of the United States Army Corps of Engineers regarding the need for a levee in Holbrook.

In March, 1969, as reported by the Unites States Army Corps of Engineers (USACE, 1991), the NRCS (formerly SCS) reported on the sediment accumulation in the Holbrook area. The report identifies three contributing factors; deposition of sediment from Leroux Wash, Joseph City (Penzance) diversion dam, and uncontrolled growth of phreatophytes. The report recommended excavation of sand bars and river deposits and modification of Penzance Dam to include a collapsible section. The city of Holbrook began dredging the Little Colorado River from the mouth of the Puerco River to Penzance Dam following a flood in 1971. The channel was roughly 5 feet deep and 300 feet wide. This channel was periodically maintained through 1986.

George V. Sabol Consulting Engineers, Inc. published the "Little Colorado River Geomorphology and River Stability Study" in 1993 (Sabol, 1993). This study was requested by the Department of Public Works, Navajo County, ARIZONA so that the results could be used to assess the viability of flood control projects for the Little Colorado River. The report is a summary of water discharge, sediment and precipitation data for the basin. Information was collected and summarized using previous reports by the United States Army Corps of Engineers, Bureau of Reclamation, Natural Resources Conservation Service, Arizona Department of Water Resources and the Arizona Department of Transportation. Recommendations and conclusions are included in an Engineering Report published in the same year. The report concludes that; the Little Colorado River (and other rivers in the Colorado Plateau) have undergone periods of aggradation and degradation, with a period of degradation on the Little Colorado River commencing in the early 1980's; the periods of aggradation and degradation are climatically controlled; there is a discrepancy in the 100–year flood in Holbrook; and the Puerco River is the largest sediment producer in the Little Colorado River basin. Some recommendations of this report are to perform a feasibility study for lowering bedrock controls in the Winslow to Luepp reach of the river and to investigate sediment dam(s) on the Puerco River. A data collection plan was also recommended for long–term management of the river.

Another report by Sabol published in 1997 (Sabol, 1997) details data collection and analysis, and includes aerial surveys of 46 cross sections beginning at Grand Falls and extending through Holbrook. These surveys were compared to the topographic map used in the current study. Because both cross section data sets were aerial surveys the comparison was inconclusive for determination of aggradation between the surveys. Some of the cross section comparisons are contained in the current study.

A report released in September 1995 by Daniel B Stephens and Associates evaluates watershed and stream flow characteristics in the Little Colorado Basin. This report was performed as part of a cooperative agreement between the Hopi Tribe and the Bureau of Reclamation and was intended to quantify the sediment input to the main stem of the Colorado River. A spreadsheet based stream flow model was developed to estimate average adjusted monthly flows for input to the sediment model. The ARMSED model was used to evaluate sediment volumes in the Little Colorado River beginning at Hunt, Arizona. Tributaries included in this model were the Puerco River beginning at Chambers, Silver Creek near Snowflake, ARIZONA and Moenkopi Wash near Moenkopi. The sediment model used in this report evaluates sediment concentrations to obtain volumes of sediment derived from the watershed. That is a different purpose compared to the GSTARS-2C sediment model used in this study. Although the GSTARS-2C sediment model evaluates sediment volumes, the intent of the current study was to evaluate sediment aggradation and degradation along the Little Colorado River using a dynamic analysis.

PART I – GEOMORPHIC METHODOLOGY AND ANALYSIS

A geomorphic analysis was conducted along the Little Colorado River between Holbrook and Winslow. A major benefit of conducting a geomorphic analysis is to provide a broad perspective on the long–term behavior of the Little Colorado River between Holbrook and Winslow, particularly in regards to the extent of aggradation and/or degradation in this reach. Mapping the geomorphology along the river provides the means to answering the questions 1) Is the river acting differently now than it has in the past and where is the river aggrading or degrading?; 2) Is the aggradation due to climate change or other large scale factors?; and 3) Is the river aggrading either regionally or locally? In combination with hydraulic and sediment transport modeling results, the map can answer these questions in both levied and in less modified reaches, and help to identify important controls on river behavior. These controls include physical characteristics of the river system such as the location of bedrock, sources of readily available or easily eroded sediment, the age and position of this sediment on the landscape, the relative stability or instability of particular river–related features, and long term trends in specific river behavior indicated by meandering, entrenchment, and deposition.

An additional benefit of the geomorphic analysis is identifying the spatial relationship between the various alluvial units. This relationship helps document changes in river form and position over the age span of the alluvial deposits. In this particular study, that age span covers the last several 10's to many 1,000's of years. This information is important for assessing how and where the river has shifted its position, the extent of aggradation or degradation, where sediment is being stored in the river system, and how much sediment is available for erosion and transport.

This geomorphic analysis was facilitated by the development of a detailed topographic map compiled from 1:10,000 scale aerial photography. A geomorphic map was produced by combining an aerial photo interpretation of the fluvial geomorphology with field observations of the alluvial stratigraphy and chronology based on tree–ring studies and radiocarbon analysis of detrital charcoal (see Plates; Sheets 1–18, Table 2, and Table 3). Geomorphic map units were delineated on the basis of differences in their surface characteristics and topographic position. These properties are the direct result of the process of emplacement and their relative age. Along the Little Colorado River, both fluvial and eolian processes are important. Geomorphic units were mapped based on the interpreted dominant process responsible for their formation (e.g., eolian processes are dominant on units labeled Qe and fluvial processes dominant on alluvial units labeled Qa). It should be noted that an eolian component is present on practically all the alluvial units in the study area.

The physical characteristics of the ground surface of geomorphic units (alluvial fans, flood plains, stream terraces) may be used to differentiate their associated deposits by age. Large–scale depositional processes shape initial surface features of alluvial landforms. When surfaces are abandoned or otherwise removed from positions of deposition or reworking by large streams, they stabilize or are gradually modified by other processes. These processes operate very slowly and on a smaller scale. Modifying processes include (1) small–scale erosion and deposition that tends to smooth the original surface topography; (2) bioturbation, the churning of sediments by organisms that obliterates depositional structures; (3) development of soils, primarily through the weathering of surface sediments and the accumulation and translocation of silt, clay and calcium carbonate; and (4) entrenchment of stream networks below original depositional surfaces and subsequent dissection of these surfaces. Alluvial surfaces of similar age have a characteristic appearance because they have undergone similar post–depositional modifications, and are distinctly different from both younger and older surfaces based on differences in the characteristics noted above. Field checking the aerial photo interpretation verifies that these characteristics are viable for defining geomorphic map units. Problematic areas were given the most consideration during field checking. Features that are difficult to map from aerial photography such as bedrock in the channel and man–made structures along the river were also documented.

Soil and sedimentologic characteristics of the alluvial stratigraphy were described following USDA guidelines and standard sedimentary terminology (Tucker, 1981; Soil Survey Staff, 1993; Birkeland, 1999). Data collected at a total of 20 sites provide subsurface information (up to 10 feet) for each of the major geomorphic units. Figure 1 shows the locations of the sites and Appendix A contains the stratigraphic descriptions. Eleven of the sites were described at natural bank exposures and nine in excavated soil pits. Samples were collected from both exposures and soil pits in order to develop age control for the mapped alluvial units. Two techniques were used to estimate the age of geomorphic surfaces in the study area. Radiocarbon analysis relies on the decay rate of radioactive carbon that was incorporated in the tissue of a once living organism (Trumbore, 2000). There are numerous problems associated with ages derived using this methodology, but there are precautions that when followed can provide accurate age estimates for the sediments that comprise the terrace (see Appendix B). The most common materials found in fluvial sediments that are collected for radiocarbon analysis are charcoal and gastropod shell. Both types of materials are identified to the species level if possible prior to radiocarbon analysis in order to minimize some of the potential problems.

Dendrochronology, the study of the annual rings of trees to determine the dates and chronology of past events, was also used to provide age control on Little Colorado River alluvial deposits. Tamarisk and Cottonwood trees were sectioned or cored in order to determine germination dates for the vegetation rooted on various geomorphic surfaces. These data provide a minimum age for the deposition of the terrace because the trees normally root on the surface after it has been abandoned and stabilizes. In some cases, burial of vegetation by younger flood sediment can be used to bracket the age of the surface deposits. Both Cottonwood and Tamarisk appear to be viable species for tree ring dating. According to Fritts (Fritts, 1976), Cottonwoods produce annual rings. Although Tamarisk is not mentioned by Fritts, observations by Hereford (Hereford, 1984) suggest that this species also produces annual rings in this region.

To assess the volume of stored and easily erodible sediment and the potential for aggradation on a regional scale, an inventory of stored sediment was measured in cross sections on the main stem of the Little Colorado River upstream of the study reach and in major tributaries. The cross sections were either surveyed directly using a laser range finder or developed from the geomorphic maps (see Plates; Sheet 18). The error associated with the surveyed measurement is ±0.5 feet. This error is greater than using traditional surveying techniques; however, based on the gross nature of the estimate of available sediment, it was determined to be a reasonable and cost–effective approach for regional reconnaissance. On the tributaries where cross sections were obtained from the detailed topographic maps developed for this study, the error is half the contour interval or ±1.0 feet.

OBSERVATIONS AND RESULTS

ALLUVIAL MAP UNITS OF THE LITTLE COLORADO RIVER

The alluvial units mapped along the Little Colorado River are primarily delineated on the basis of their geomorphic characteristics. These characteristics include the elevation and relative position of each unit to the active channel (Qac) and adjacent map units, surface morphology, and the dominant type and relative coverage of vegetation on the surface. These types of indicators are widely used and provide reliable evidence for the relative age of each map unit (Hereford, 1984; 2002; Huckleberry, 1996). The nomenclature used for the map units in this study is similar to that used by Hereford (Hereford, 1984), and Huckleberry (Huckleberry, 1996) and follows similar criteria. The formation of each of these units can be related directly to river processes of the Little Colorado River and its tributaries. Deposits associated with each of these map units include eolian and alluvial sediments, and the soils formed on them. For the purposes of mapping, the terms "flood plain" and "terrace" are used interchangeably in this study; no distinction is made between these terms other than simply the relative age of the last significant inundation or abandonment. The terraces mapped as part of this study were deposited in the late Holocene (<3,000 years) and may have been deposited historically (post–1880). The units shown on the geomorphic maps (see Plates) are described in the following paragraphs.

Unit Qac – active channel – primarily silty sand alluvium with clay–rich alluvium in meander bends and backwater channels. Figure 2 illustrates these channel conditions near Holbrook. This unit includes the active channel deposits on both the main stem and major tributaries to the Little Colorado River. This unit may also incorporate small outcrops of bedrock exposed at low flow in the channel bed.

Figure 2. Looking downstream at the active channel (Qac) of the Little Colorado River near Holbrook. The channel forms a single thread with point bars visible during periods of low flow. The active channel is virtually free of vegetation when compared to the adjacent terraces. Photographed May 10, 2000.

Unit Qa1 – Desert Broom terrace – sandy alluvium that forms low point bars and flood plains immediately adjacent to the active channel with either no vegetation or sparse young Tamarisk and Desert Broom. Figure 3 shows an example of this terrace. This unit is inundated regularly except in the driest years and is roughly 1–2 feet above the active channel. Low dunes may be present in places on unit Qa1 but are localized features. Where unit Qa1 can be differentiated, two members are mapped. Qa1a, the younger member, has smaller and fewer Tamarisk and Desert Broom saplings while Qa1b is slightly higher and crosscut by Qa1a. Its vegetation is denser and larger with an increase in the presence of Desert Broom.

Figure 3. Morphological characteristics of the Desert Broom alluvium (Qa1). The Desert Broom alluvium is vegetated with Tamarisk and Desert Broom saplings and can be relatively planar (this photo) or channelized by recent fluvial activity. (March, 2002)

Unit Qa2 – Tamarisk terrace – silty sand alluvium covered by thick vegetation, primarily Tamarisk. The surface is composed of fine–to medium–grained eolian sand that variably forms thin sheets, low coppice dunes, and high sand dunes. Figure 4 shows an example of this terrace. Where continuity and extent is adequate, sand dunes are mapped separately from Unit Qa2 as Unit Qe. Despite the fact that the eolian component of Qa2 overlies the fluvial component in most places, both deposits are considered to be equivalent in age because in exposure they are commonly found inter–bedded. Large portions of the Tamarisk terrace exhibit vegetation lineations on aerial photography that mark historical flow patterns on the Qa2 surface. Many of these deposits have been inundated historically. Unit Qa2 is roughly 2–5 feet above the modern channel.

Unit Qa2 is comprised of three nearly equivalent aged members that are differentiated based on crosscutting relationships in plan view and height above the active channel. These units are labeled Qa2a, Qa2b, and Qa2c in order of increasing age. Units are mapped based on the local geomorphology and are not necessarily correlative with the same unit at other points along the river.

Figure 4. Morphological characteristics of the Tamarisk alluvium (Qa2) near Winslow. The surface is vegetated with densely populated mature Tamarisk and some Cottonwood and may have somewhat irregular topography that is created by dunes on its surface. (September 19, 2000)

Unit Qa3 – Cottonwood terrace – sandy alluvium that forms terraces marked by mature, widely spaced Cottonwood and Tamarisk trees. Figure 5 shows an example of this type of terrace. Thin sand beds and low coppice dunes may overlie the surface of the Cottonwood terrace. Unit Qe forms in association with Unit Qa3 in many places along the length of the mapped reach. Unit Qa3 is roughly 5–10 feet above the active channel. Where Unit Qa3 can be differentiated, it is composed of three members, Qa3a, Qa3b, and Qa3c, in order of increasing age. These members are defined based on differences in height and position relative to the main channel. These members seem to be present in areas with sufficient space to allow for multiple generations of closely aged surfaces to form, while in more narrow areas along the channel only Unit Qa3 is present. Members may not correlate in age along the length of the reach but should all fall within the age range of Unit Qa3.

Unit Qa4 – Moenkopi terrace – dark red, clay and silt–rich alluvium that forms the highest terrace associated with the Little Colorado River. Figure 6 shows an example of the Moenkopi terrace. The character of deposits on the terrace is similar in appearance to weathered Moenkopi Formation; its thickness varies based on its position on the landscape and decreases with proximity to exposed bedrock. The unit is delineated on the basis of the light tone on aerial photographs imparted by salt crust formed on the surface and sparse vegetation dominated by sagebrush and is roughly 15–20 feet above the active channel. The terrace surface commonly exhibits abandoned meander scars, shown in Figure 7, that are clearly associated with fluvial processes and are exposed along riverbanks as cut and fill sequences.

Figure 5. Morphological characteristics of the Cottonwood alluvium (Qa3) near Obed Bridge. The surface includes mature stands of Cottonwood, Tamarisk, and other shrubs and grasses. The surface is irregular due to the presence of partially vegetated dunes. (March, 2002)

Figure 6. Morphological characteristics of the Moenkopi alluvium (Qa4) near Jackrabbit. The Moenkopi alluvium exhibits planar morphology and sparse shrub vegetation including sagebrush, camelthorn, and grasses. The surface of the unit appears similar to weathered Moenkopi Formation and may exhibit light–colored patches that have greater concentrations of precipitated salts (See Figure 7). (March, 2002)

Figure 7. Aerial photograph of the Little Colorado River upstream of the confluence with Clear Creek showing meander scars on the Moenkopi alluvium (example indicated by the arrow). Note the paleochannels and meanders occur on the younger alluvium on the north side of the river.

Unit Qau – Undifferentiated alluvium – includes alluvium that cannot be specifically identified with one of the four major terraces, or, due to its particular location, may include alluvium of multiple ages that cannot be shown at the scale of the map. This unit also includes tributary alluvium and alluvial fans derived from adjacent mountain fronts.

Unit Qe – Dunes – fine to medium–grained eolian sand. Although dunes overlie many of the units described previously, this unit is mapped separately where the dunes are continuous and extensive enough to map as a distinct unit. This unit includes deposits spanning a broad age range; the age of the deposit in any particular area is best estimated based on its relationship to adjacent or surrounding deposits. It is likely that the dunes are formed during several distinct periods based on differences in vegetation maturity and soil formation. The thickest eolian deposits are commonly found downwind of the active channel (Qac) along the northern side of the river.

Unit Qpc – undifferentiated paleochannels – numerous meander scars and recently abandoned channels. Paleochannels are mapped in areas where they are either continuous or extensive enough to identify and map as a distinct unit. In many cases, the age of abandonment can be estimated by comparison to older topographic maps or by the position of the paleochannel relative to the adjacent mapped units, as shown in Figure 7. Paleochannels are more sinuous on the Unit Qa4 surface than the active channel, while younger paleochannels appear to have sinuosity similar to the active channel. The height above the active channel varies based on the associated geomorphic surface.

BEDROCK MAP UNITS

The bedrock exposed in the study area include the Early Permian Coconino Sandstone, the Early Triassic Moenkopi Formation, and the Middle Triassic Shinarump Conglomerate. For the geomorphic map, the bedrock was grouped into a single unit. The following descriptions are based on field observations of bedrock exposed in the map area and descriptions included in Wilson (Wilson et. al., 1960), Beus and Morales (Beus & Morales, 1990), and Stewart (Stewart et. al., 1972a, 1972b).

Unit R – Bedrock – All of the consolidated or semi–consolidated rock units considered to be in situ and not transported or redeposited by the Little Colorado River. This unit also includes colluvium deposited locally on bedrock slopes.

Early Permian Coconino Sandstone (roughly 280 million years old) – fine to medium–grained, well sorted, rounded, moderately cemented quartz arenite. The Coconino Sandstone outcrops in the channel of the Little Colorado River near Penzance Dam and forms the canyon walls immediately upstream of Clear Creek Dam. On aerial photography, the Coconino Sandstone exhibits distinct joint patterns with very light surface tone, that directly relates to its white quartz arenite composition.

Early Triassic Moenkopi Formation (roughly 225 million years old) – The Moenkopi Formation is described as a pale, reddish–brown siltstone and sandstone with inter–bedded and crosscutting gypsiferous beds. The Moenkopi Formation unconformably overlies the Coconino sandstone in the map area. Near the base of the formation, a distinctive, thin sandstone bed forms a prominent ledge in the map area and outcrops in the Little Colorado River channel in places. Near the top of the formation, a 10–20 foot thick conglomerate bed of siltstone and limestone cobbles occurs locally. On aerial photography, the Moenkopi Formation has a dark gray surface tone.

Middle Triassic Shinarump Conglomerate (roughly 210 million years old) – present along the Little Colorado River as a thin veneer of sandy gravel comprised primarily of rounded to well–rounded coarse pebbles to large cobbles of chert with minor sandstone and petrified wood. The Shinarump Conglomerate along the Little Colorado River is found unconformably overlying both the Moenkopi Formation and Coconino Sandstone. Thicker deposits form isolated low hills adjacent to the river. Gravel mining activities in the area are often associated with the thicker deposits (e.g., near Clear Creek Dam). On aerial photography, the Shinarump Conglomerate forms low, rounded hills with slighter darker surface tone than adjacent bed rock or alluvial surfaces. This darker tone is due to the desert varnish that is formed on the gravel.

Unit Rs – Strath terrace – fluvial terrace formed on bedrock. Unit Rs is rare in the study area. This unit has only been identified near Penzance Dam on the right bank and may in fact be related to this structure. At this location the terrace is an equivalent height to Unit Qa3 and is formed in Coconino Sandstone adjacent to the diversion structure.

MISCELLANEOUS MAP UNIT(S)

Unit m – Modified terrain – terrain that has been modified by artificial means, such as scraping or piling of sediment in a particular area, so that the present landscape is not representative of a naturally formed surface; includes levees and embankments built along the river to prevent the river from flooding a particular area.

ALLUVIAL CHRONOLOGY

The alluvial chronology developed for the Little Colorado River is based on 14 radiocarbon ages from charcoal samples listed in Table 2 and ring counts from 42 tree cores or sections listed in Table 3.

Table 2. Radiocarbon ages.

Sample No. (Lab No.)	Type of Material	Sample Weight (g)	Age (^{14}C yrs. B.P.[1])	Calibrated Age (cal yrs. B.P.[2])
PR1–1JU (Beta–158226)	Juniperius charcoal	0.015	460 ± 40	550 – 440 350 – 330
PR1–1QU (Beta–158227)	Quercus charcoal	0.132	50 ± 30	260 – 220 140 – 30 10 – 0
LCR1–1JU (Beta–169016)	Juniperius charcoal	0.003	3,120 ± 40	3,450 – 3,210
LCR1–2AT (Beta–169017)	Atriplex charcoal	0.015	3,030 ± 40	3,350 – 3,070
LCR1–6JU (Beta–169019)	Juniperius leaf	0.004	106.6 ± 0.5 pMC[3]	N/A
LCR2–2CO (Beta–169020)	Conifer charcoal	0.005	4,340 ± 40	5,040 – 5,010 4,980 – 4,830
LCR3C–2AT (Beta–169021)	Atriplex charcoal	0.007	3,160 ± 40	3,470 – 3,320 3,290 – 3,260
LCR3E–2PI (Beta–169022)	Pinus charcoal	0.011	840 ± 50	910 – 660
LCR8–1PI (Beta–169023)	Pinus charcoal	0.004	1,060 ± 40	1,060 – 920
LCR8–2PI (Beta–169024)	Pinus charcoal	0.004	350 ± 40	500 – 310
LCR8–2PI–2 (Beta–170174)	Pinus charcoal	0.005	260 ± 40	460 – 270 190 – 140 20 – 0
LCR14–1AR (Beta–169025)	Artemisia charcoal	0.003	930 ± 40	930 – 740
LCR14–1AT (Beta–169026)	Atriplex charcoal	0.005	1,330 ± 40	1,310 – 1,170
LCR14–1FR (Beta–169027)	Fraxinus charcoal	0.011	9,190 ± 40	10,480 – 10,230

Table 3. Tree ring samples and ring counts.

Surface	Site	Sample no.	UTM Coordinates	Species	Tree Ring Count	Germination date
Cottonwood Terrace	APS Well Field	LCR32	0559791 3867099	Cottonwood Core	77	1925
		LCR33	0559814 3867125	Cottonwood	81	1921
		LCR34	0559814 3867125	Cottonwood Core	78	1924
		LCR35	0559746 3867046	Cottonwood Section (dead)	39(?)	1963

[1] Conventional radiocarbon age in years before present with present being 1950 A.D.

[2] Calibrated radiocarbon age in years before present derived from computer calibration program Oxcal v. 3.5 (Bronk, 1995).

[3] Percent of Modern Carbon

Surface	Site	Sample no.	UTM Coordinates	Species	Tree Ring Count	Germination date
		LCR36	0559713 3866994	Cottonwood Section (dead)	43(?)	1959
		LCR37 LIMB	0559967 3866644	Tamarisk	45	1957
		LCR37 MAIN	0559967 3866644	Tamarisk	51	1951
	Winslow	LCR48	0530461 3875649	Cottonwood Core	82+	pre–1920
		LCR49	0530461 3875649	Cottonwood Core	99+	pre–1903
Tamarisk Terrace	Obed Bridge	LCR16	0562096 3866581	Tamarisk	23	1979
		LCR17	0562096 3866581	Tamarisk	36	1966
		LCR18	0562096 3866581	Tamarisk	39	1963
		LCR19	0562096 3866581	Tamarisk	16	1986
		LCR20	0562094 3366278	Tamarisk	36	1966
		LCR25	0562107 3866266	Tamarisk	39	1963
		LCR26	0562106 3866266	Tamarisk	42	1960
		LCR27	0562090 3866250	Cottonwood Core	63	1939
		LCR28	0562156 3866375	Tamarisk	33	1969
		LCR29	0562036 3866400	Tamarisk	28	1974
		LCR30	0562025 3866379	Tamarisk	30	1972
		LCR31	0562022 3866397	Tamarisk	26	1976
	Jackrabbit	LCR24	0551389 3869078	Tamarisk	41	1961
		LCR24 CH	0551389 3869078	Tamarisk	42	1960
		LCR38 MAIN	0551427 3869082	Tamarisk	45	1957
		LCR38 LIMB	0551427 3869082	Tamarisk	38	1964
		LCR39	0551426 3869051	Tamarisk	44	1958
		LCR44		Cottonwood Core	31(?)	1971
	Winslow	LCR45	0531529 3874378	Tamarisk	52	1950

Surface	Site	Sample no.	UTM Coordinates	Species	Tree Ring Count	Germination date
		LCR46 MAIN	0531558 3874440	Tamarisk	50	1952
		LCR46 LIMB	0531558 3874440	Tamarisk	43	1959
		LCR47	0531293 3874436	Tamarisk	58	1944
		LCR47	0531293 3874436	Tamarisk	58	1944
		LCR47	0531293 3874436	Tamarisk	52	1950
		LCR47	0531293 3874436	Tamarisk	36	1966
Desert Broom Terrace	Obed Bridge	LCR21A	0562138 3866496	Tamarisk	9	1993
		LCR21B	0562138 3866496	Tamarisk	9	1993
		LCR22	0562138 3866496	Tamarisk	9	1993
		LCR23	0562154 3866511	Tamarisk	12	1990
	Jackrabbit	LCR40	0551417 3868949	Tamarisk	9	1993
		LCR41	0551417 3868949	Tamarisk	9	1993
		LCR42	0551417 3868949	Tamarisk	8	1994
		LCR43	0551417 3868949	Tamarisk	8	1994

The Desert Broom alluvium (units Qa1, Qa1a, Qa1b) exhibits little soil development and is a predominantly sandy deposit with inter–bedded clay and silt lenses. The oldest Tamarisk saplings sampled from this surface have germination dates of 1990–1993 and indicate that this surface was formed during the last decade. These ages suggest that the extreme flooding on the Little Colorado River associated with the 1993 flood significantly modified the surface of these deposits.

The Tamarisk alluvium (units Qa2, Qa2a, Qa2b, Qa2c) is composed of a fine–medium sand with abundant tabular cross–bedding and laminated bedding. Soil development in the sediments of the Tamarisk terrace is weak with little structure or pedogenic development of color. Sandy beds are inter–bedded with very thinly laminated clay and silt rich beds. In places, bands of fine–grained rip–up clasts may be found at the basal contact of sandy units when they overlay clay or silt–rich beds. The thin clay and silt beds were most likely deposited during low velocity or waning flows; portions of these beds were later eroded to form the rip–up clasts found in the overlying sandy units. In the sandy beds, laminated bedding was most likely formed during the plane bed phase of upper–flow regime transport. In contrast, tabular cross–bedding is typically deposited by migration of large scale current ripples under lower flow regime conditions. Each of these sedimentary structures is indicative of formation during different phases of large floods.

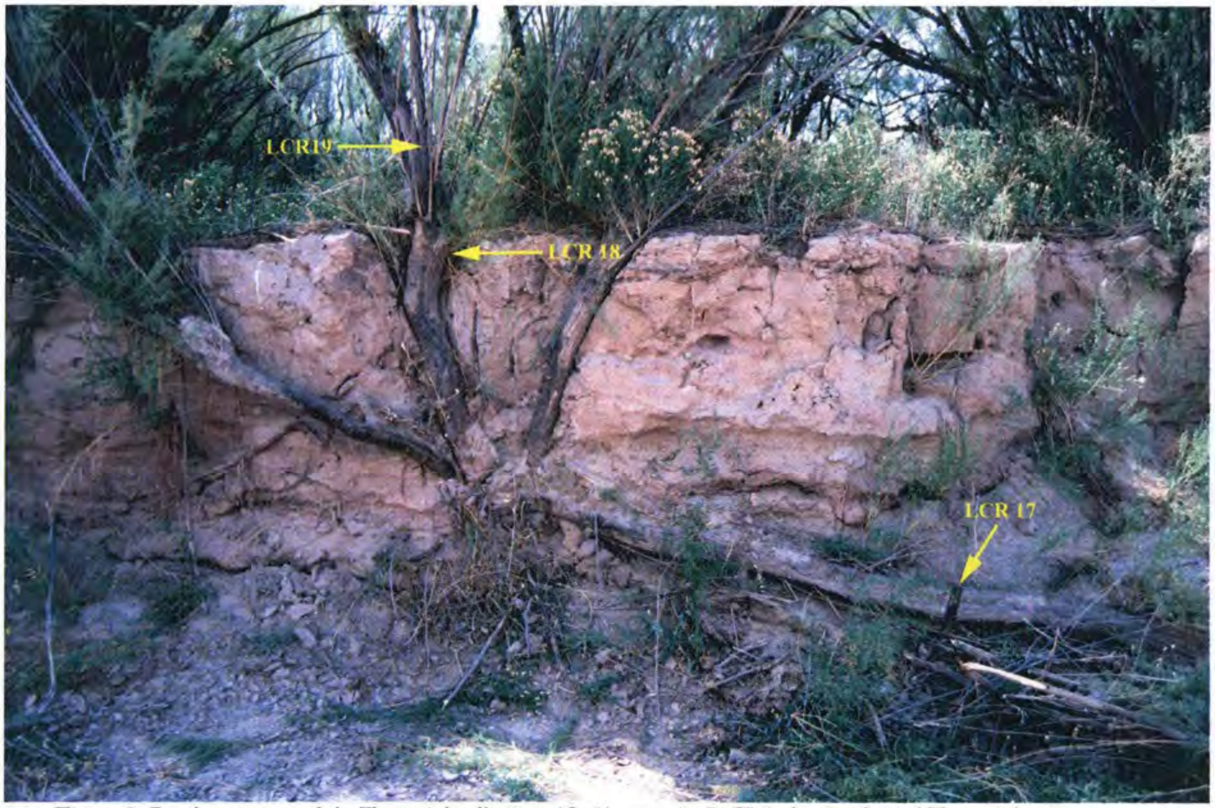
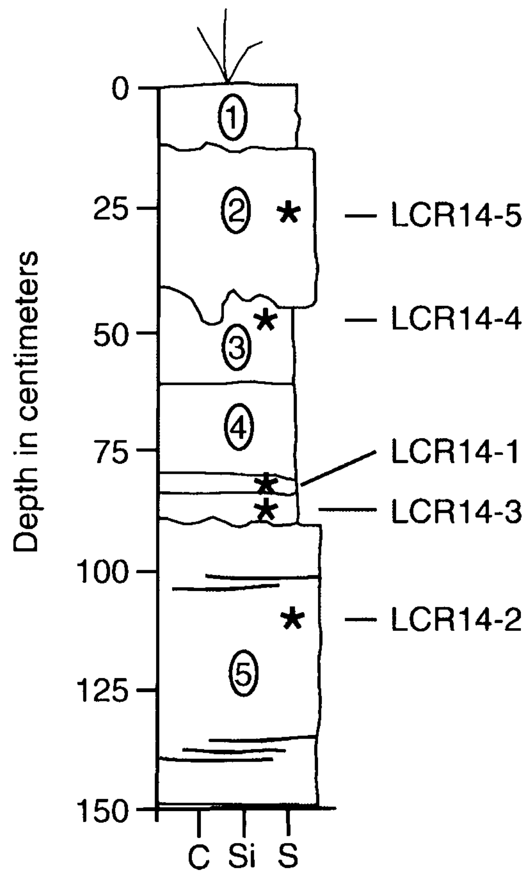


Figure 8. Bank exposure of the Tamarisk alluvium (Qa2) near site LCR4 showing buried Tamarisk. Arrows indicate locations of tree ring samples listed in Table 3 that were collected to provide age control.

Dendrochronologic data indicate that the Tamarisk alluvium is a complex of surfaces that were deposited from the 1940's to the 1970's. This range is reflected in the ring counts, listed in Table 3, of vegetation at several sites through the study reach. At Obed Bridge, germination dates range from 1939 to 1976 for trees rooted on the surface. Near site LCR4. Figure 8 shows a buried Tamarisk with a germination date of 1963 is buried by roughly 3 feet of alluvium. The majority of deposition at this site appears to have occurred prior to 1986, the germination date of a limb (sample LCR19) that sprouted at the present surface of the deposit. At Jackrabbit, a site downstream of the Obed Bridge, the germination dates for Tamarisk range from the late 1950's to the early 1960's. A core extracted from a Cottonwood on the eroding edge of the terrace upstream from the Tamarisk samples has a younger germination date of 1971. The oldest sample collected from the Tamarisk terrace was at Winslow with germination dates ranging from the 1940's to the 1960's. Radiocarbon ages obtained from site LCR14 proved inconclusive as they encompass a range that spans the entire Holocene, as illustrated in Figure 9. Based on soil development, position in the landscape, dendrochronology, and the alluvial chronology developed for this unit at other sites as well as two other ages from the same bed, it appears that the oldest radiocarbon age at this site should be disregarded. In addition, radiocarbon analysis of *Juniperus* charcoal recovered from beneath the sand dunes on Unit Qa2 along the Puerco River yielded an age of 460±40 (540–470 calibrated years B.P.). That is correlative with the other two radiocarbon ages at site LCR14 (Table 2).

LCR14 (Unit Qa2)

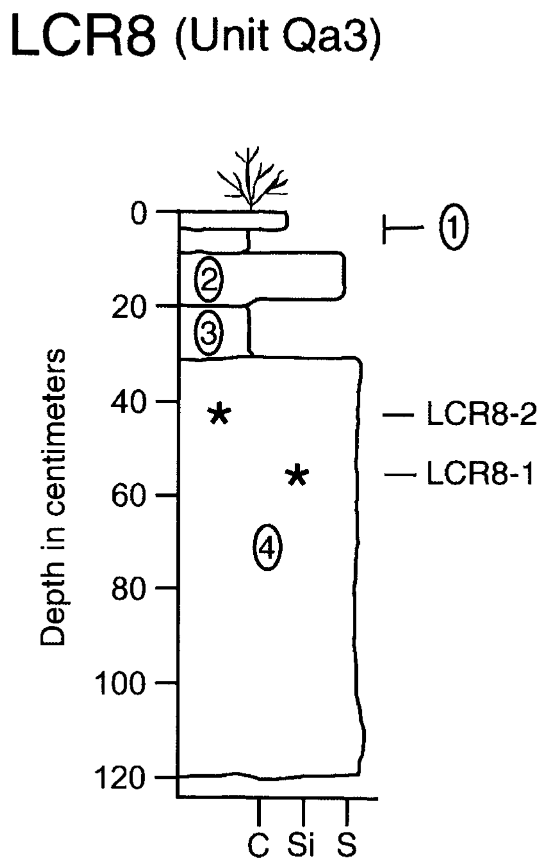


* Radiocarbon sample site

Radiocarbon Ages:
LCR14-1AR (930 - 750 cal yrs B.P.)
LCR14-1AT (1300 - 1180 cal yrs B.P.)
LCR14-1FR (10480 - 10230 cal yrs B.P.)

Beds:
1 - Fine eolian sand
2 - Red fine to medium sand
3 - Fine sand
4 - Fine sand with clay rip up clats
5 - Fine to medium sand with thin beds of coal

Figure 9. Stratigraphic section of Tamarisk alluvium (Qa2) described at site LCR14. Sample numbers indicate material that was collected and submitted for radiocarbon analysis. Material is described in Appendix B.



★ Radiocarbon sample site

Radiocarbon Ages:

LCR8-1PI (1060 - 920 cal yrs B.P.)
LCR8-2PI (510 - 300 cal yrs B.P.)

Beds:

1 - A/2Bk soil horizons
2 - 3Bk soil horizon
3 - 4Bk soil horizon
4 - Ck soil horizon

Figure 10. Stratigraphic section of Cottonwood alluvium (Qa3) described at site LCR8. Sample numbers indicate material that was collected and submitted for radiocarbon analysis. Material is described in Appendix B.

The Cottonwood alluvium (units Qa3, Qa3a, Qa3b, Qa3c) was described at four localities, LCR2, LCR7, LCR8, and LCR9, shown in Figure 1. Each site exhibited a weak to moderately developed sandy soil (see Appendix A). A typical soil profile consists a of a 0.5–3 inch (1–8 cm) thick reddish brown A–horizon with weak to moderate granular to platy structure and silt loam to sandy loam texture. The B–horizon is roughly 10–11 inches (25–30 cm) thick with predominantly reddish brown sandy beds and thin clay loam and silt loam beds. The reaction of the horizon to hydrochloric acid is effervescent to strongly effervescent; the field calcium carbonate morphology is Stage I to I–. Structure is weak to moderate, medium to coarse sub angular blocky. Sedimentary structures were obscured in this horizon by soil development. The underlying C–horizon is composed of cross bedded and laminated sandy sediments with occasional pebble lenses and clay lenses. The sedimentology of the Cottonwood terrace suggests fluvial deposition of sediments during predominantly lower flow regime conditions.

The age of the Cottonwood alluvium was estimated from two cores extracted from Cottonwood trees near Winslow, and seven samples recovered from Cottonwood and Tamarisk trees near Joseph City. The oldest Cottonwood trees that were cored on this surface have germination dates in the early 1900's, while younger Cottonwoods date from the 1920's (Table 3). The age of two Tamarisk trees that were sectioned on the Cottonwood terrace have germination dates in the 1950's. Three radiocarbon ages from site LCR8 recovered from a depth of 16–24 inches (40–60 cm) range from 270 to roughly 1060 calibrated years B.P. One of the samples, LCR8–2PI–2, listed in Table 2, intercepts the radiocarbon calibration curve with an age range of 270 to 460 calibrated years B.P., but has a small probability of having a modern age, as listed in Table 2 and shown in Figure 10. Based on the overlap in the ages with a sub sample from the same location in the section, the age for this part of the section appears to be between 270 and 500 calibrated years B.P. The age of the third sample collected roughly 5–6 inches (13–15 cm) below the above samples ranges from 920–1,000 calibrated years B.P. Based on these radiocarbon ages and the extent of soil development, an age of several hundred to perhaps 1,000 years for the Cottonwood alluvium is supported. The Cottonwood terrace has certainly been inundated and had minor amounts of sediment deposited on the surface in the last several hundred years. The stratigraphy at site LCR8 suggests that during this period, roughly 4–5 inches (10 cm) of fine–grained sediment has been deposited on the surface each time the terrace has been inundated, as illustrated in Figure 10. Two primary soil characteristics, the structure in the A–horizon and the accumulation of calcium carbonate in the lower part of the profiles, are both properties that can exhibit weak development within 100 years in arid environments. Based on weak development of these properties on the Cottonwood alluvium and the age of the Cottonwood trees on the terrace surface, it appears that the Cottonwood terrace has been relatively stable for the past 100 years.

The Moenkopi alluvium (unit Qa4) was described at nine sites, LCR1, LCR3, LCR5, LCR6, LCR10–13, and LCR15, site locations shown in Figure 1, and represents the oldest alluvial unit described in the Holbrook to Winslow reach. Based on the character of the unit and numerous unconformities observed in bank exposures, it is apparent that the Moenkopi alluvium is a complex fill sequence, as illustrated in Figure 11. Multiple meander scars present on the Moenkopi surface and observed on aerial photography support this interpretation. The most extensive exposure of the Moenkopi alluvium was observed upstream of Obed bridge at sites LCR3 and LCR1 upstream of Obed Bridge, shown in Figure 12 and Figure 13 respectively. Sedimentary structures in channel fills include both tabular and trough cross bedding, suggesting both upper and lower–flow regime conditions are responsible for deposition of the unit.

The age of the Moenkopi alluvium is estimated from four radiocarbon ages collected from two different sites (Table 2). The oldest sections of the Moenkopi fill sequence are comprised of vertically accreted clay–rich sediments that have associated ages of roughly 3,000 to 3,500 calibrated years B.P. shown in Figure 12 and Figure 14. These clay–rich sediments are unconformably overlain by a series of silt and sand channel fill sequences. Based on a single radiocarbon age (LCR3E–2PI; 910–670 calibrated years B.P.), these sequences appear to have been deposited within the last 1,000 years, shown in Figure 14. This age is in agreement with the interpreted age for the onset of deposition of the younger Cottonwood alluvium at roughly 920–1,000 calibrated years B.P. Based on these radiocarbon ages and the extent of soil development on the Moenkopi alluvium, it appears that the surface of the Moenkopi terrace has been stable for at least 1,000 years. Based on the complex cut–and–fill history exhibited within the unit, it is apparent that the Moenkopi alluvium represents a time–transgressive deposit. Therefore, older parts of the deposit may have been stable for many thousands of years (>3,500 years).

A fifth sample collected from site LCR1 and submitted for radiocarbon analysis yielded a modern age. This age may be viewed as being problematic to the age estimate of 1,000–3,000 years for the Moenkopi alluvium. This sample (LCR1–6JU; Table 2) was collected from a depth of roughly 14.4 feet (440 cm), and should have yielded a much older age based on its stratigraphic position as illustrated in Figure 12. Despite precautions to eliminate modern material from the analyses, it is apparent that submitting the

Juniperus leaf that was recovered yielded erroneous results. Based on the results of more than 500 radiocarbon analyses on materials recovered from Holocene fluvial deposits by Reclamation in the western United States, materials that include leaves, seeds, flowers, and grass more commonly yield modern ages than wood charcoal. In many cases, these type of materials have been carried deep into a profile by burrowing animals where they are utilized as foodstuffs and bedding. In this particular case, it is believed that this material got deep into the subsurface by moving down large cracks that commonly form in the alluvium along the high banks. Due to the clay–rich nature of the alluvium at this site, large irreversible cracks have formed along the margin of the terrace. These large cracks act to increase infiltration of organic material into the subsurface. It is believed that the *Juniperus* leaf that the yielded modern age was deposited in the section at LCR1 via this process. This interpretation is supported by the presence of other historical debris found in open cracks at depth in this and other profiles in the area.

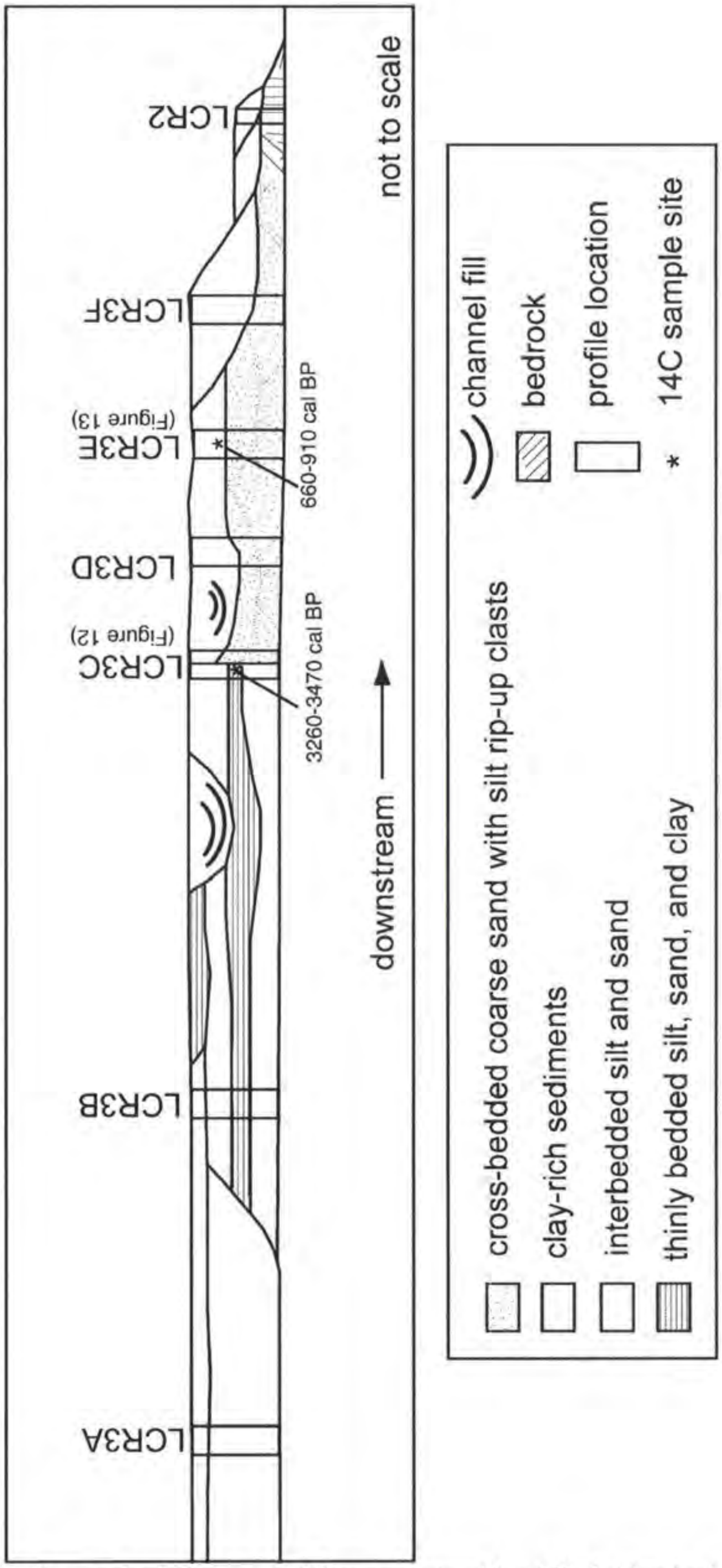


Figure 11. Schematic diagram showing the cut and fill sequence exposed in a 660–foot long bank exposure of the Moenkopi alluvium at site LCR3 near Obed Bridge. Two profiles are depicted as Figure 12 and Figure 13 in the text showing the oldest alluvium I the profile (LCR3C) and a younger channel fill sequence (LCR3E). All profile descriptions can be found in Appendix A.

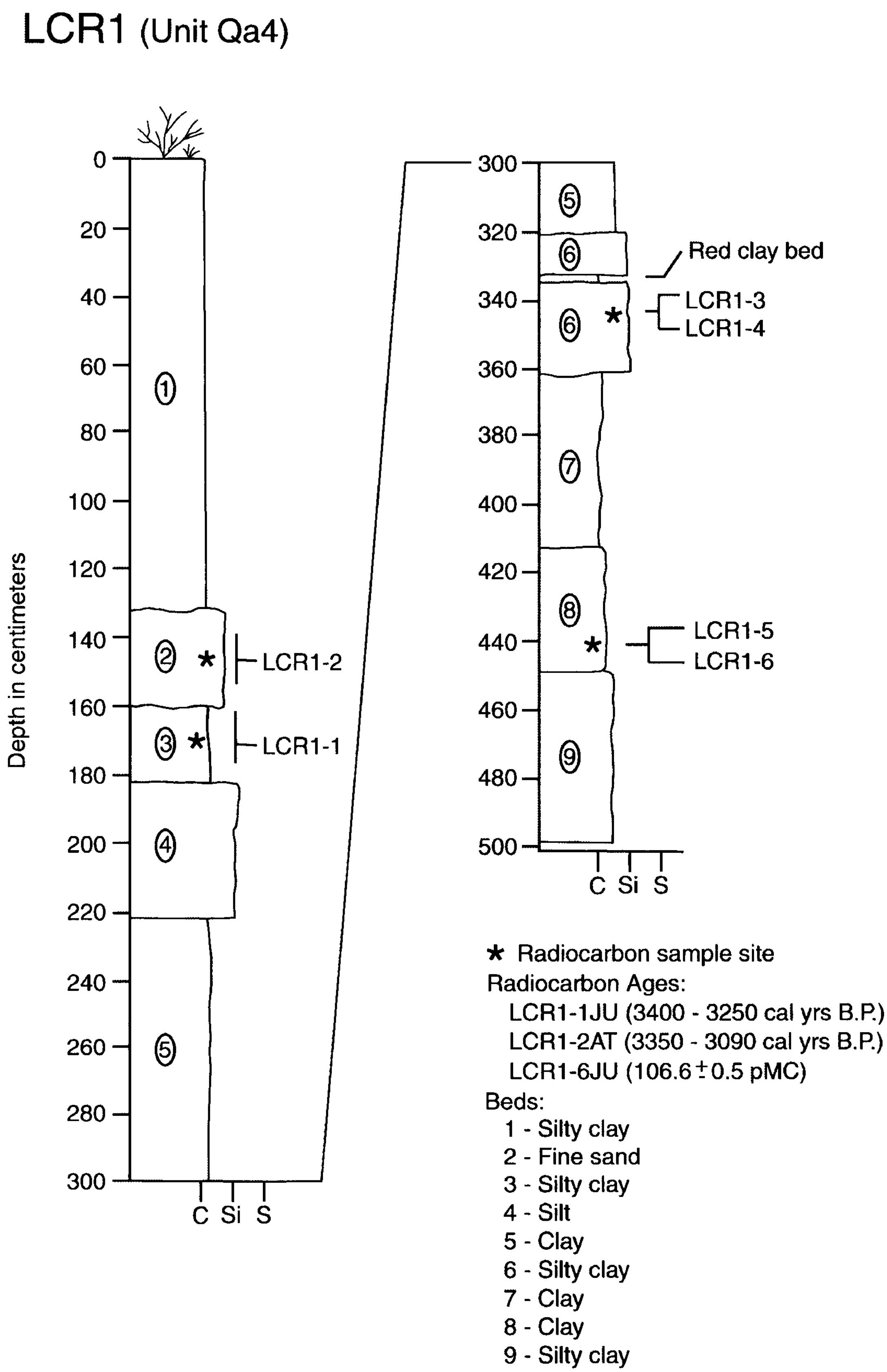


Figure 12. Stratigraphic section of Moenkopi alluvium (Qa4) described at site LCR1. Sample numbers indicate material that was collected and submitted for radiocarbon analysis. Material collected is described in Appendix B.

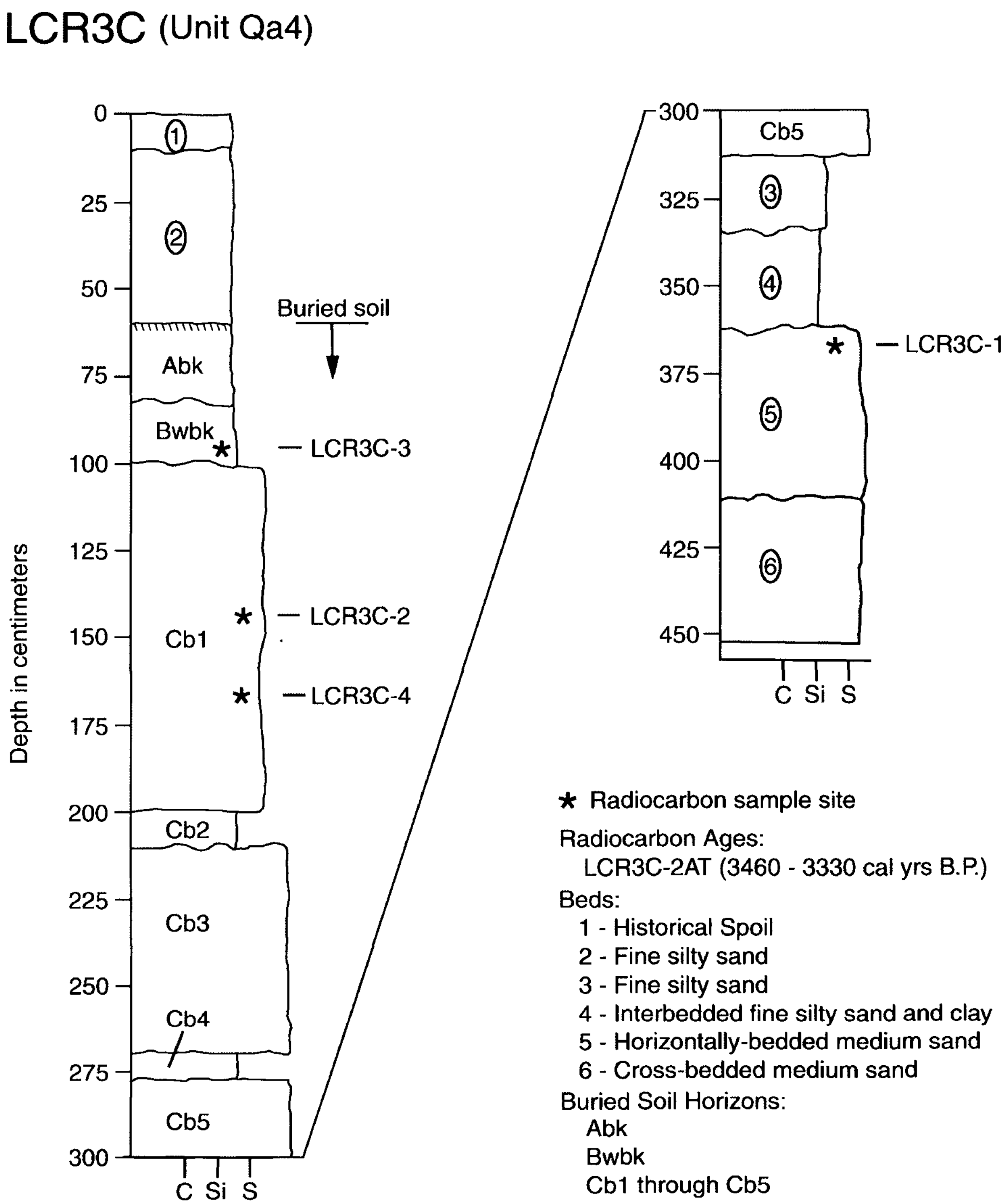


Figure 13. Stratigraphic section of Moenkopi alluvium (Qa4) described at site LCR3C. Sample numbers indicate material that was collected and submitted for radiocarbon analysis. Material collected is described in Appendix B; the location of this site is illustrated in Figure 11.

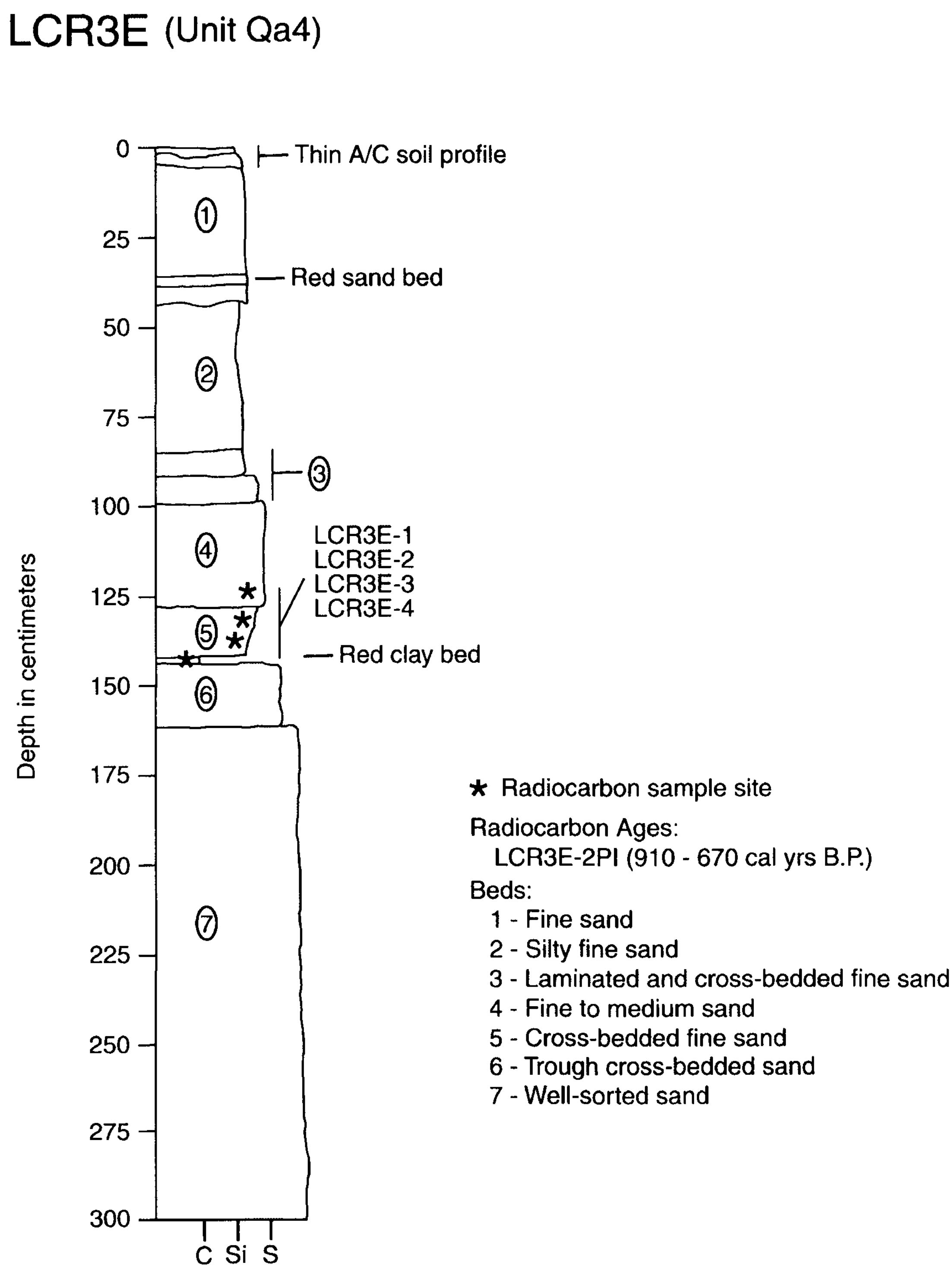


Figure 14. Stratigraphic section of Moenkopi alluvium (Qa4) described at site LCR3E. Sample numbers indicate material that was collected and submitted for radiocarbon analysis. Material collected is described in Appendix B; the location of this site is illustrated in Figure 11.

Figure 15. Portion of the geomorphic map at Holbrook showing the distribution of map units (see plates; Sheets 16 and 17). Map units located in this reach were deposited or modified historically with the exception of unit Qa3. The surface of this unit was abandoned early in the 20th century, but the deposits under the surface may be as old as 1,000 years. Flow is from right to left in the photograph.

GEOMORPHOLOGY AT SELECTED SITES

The geomorphology along the Little Colorado River was examined in detail at three sites where it appeared that the presence of levees, bridges, or other structures might have some influence on river behavior. These sites were compared qualitatively to two other sites where the influence of these man–made controls was considered to be minimal or non–existent in order to evaluate the relative impact of the man–made controls on the river historically. Of the three impacted sites, two of the sites were located within levied reaches of the river at Holbrook and Winslow. Both of these reaches also contain several bridges that cross the river. An additional site at Penzance Dam, a low head diversion dam located between Holbrook and Joseph City was examined. Two unaffected sites were examined near Obed Bridge. Figure 1 shows the location of Obed bridge crossing the Little Colorado River between the Cholla power plant and Jackrabbit. These sites exhibit the four major alluvial units present and exposed along stream banks in this reach.

HOLBROOK

No detailed studies of the alluvial stratigraphy or geomorphology were undertaken in the Holbrook reach. However, some conclusions can be drawn from an analysis of the aerial photography and observations made while field checking the geomorphic mapping. In this reach, shown in Figure 15, the Little Colorado River is bounded by bedrock on the south and levees or modified terrain on the north as it flows through Holbrook. Levees built on both sides of the river between the Arizona Route 77 bridge and the Apache Railroad bridge have produced changes in the morphological characteristics of the river that are markedly different than characteristics both upstream and downstream of the bridges. The flood plain width is much narrower in the reach between bridges due to levees on both sides of the river. Only narrow bands of the Desert Broom terrace are present in this reach. Narrow remnants of the Tamarisk and Cottonwood terraces are present in this reach, but have been isolated from the river by a low levee on the south side of the river. In adjacent reaches upstream and downstream of the bridges, these terraces are more extensive and allow for lateral movement of the channel and large areas of flood plain are available for ineffective flow and storage during higher flows. While the channel has been dredged and straightened through this entire reach, much of the channel has migrated from the artificially straightened channel to a more sinuous channel pattern seen upstream of the bridges. The natural tendency of the river at this location will be continued lateral migration and deposition. A projection of the extent of deposition is addressed by the sediment transport modeling.

Figure 16. Photograph of Penzance Dam and the Coconino Sandstone in the channel bed that provides natural grade control on the river at this location.

PENZANCE DAM

Penzance Dam is located on the Little Colorado River roughly 5.25 miles downstream of the Route 77 bridge in Holbrook. The dam, shown in Figure 16, is between 10–12 feet high, and was constructed on the Coconino Sandstone where it crops out in the channel. The Coconino Sandstone at this location formed a natural grade control on the Little Colorado River prior to the construction of the dam. The river in this reach forms a single thread and is flanked on the right bank at the dam by a stripped bedrock strath terrace. Based on the geomorphology of the terraces in the area of the dam, it appears that the strath terrace was previously buried by Cottonwood alluvium. Due to the presence of the dam at this site, the stage of the river during large floods has been elevated. Flow across this terrace during flood stage appears to have eroded the alluvium and exposed the bedrock at this location.

The most notable geomorphic feature along this reach of the river is a paleochannel that directed flow in the Little Colorado River around the current site of Penzance Dam (see Plates, Sheets 14 and 15). Overall, the position and geometry of the river channel through this reach is controlled by rock. The sinuosity of the river upstream of Penzance Dam is relatively low, but the geomorphology of the alluvium indicates that the channel meandered widely across its flood plain during the last several thousand years. Downstream of Penzance Dam, the river currently flows through several meanders whose position similarly appears to be largely controlled by bedrock. A resistant sandstone bed within the Moenkopi Formation crops out in the channel roughly 2 miles downstream of Penzance Dam.

OBED BRIDGE

The Little Colorado River forms a single thread through the Obed Bridge reach with secondary channels along the back edge of the Desert Broom (Qa1) terrace, shown in Figure 17. The Moenkopi (Qa4) alluvium dominates the fluvial deposits in this reach; but lateral erosion and incision of the Little Colorado River has formed three younger and lower terraces that are inset into the Moenkopi alluvium. In those areas where the river flows against the Moenkopi alluvium, high vertical banks have formed. Dunes are present on the Cottonwood (Qa3) and Tamarisk (Qa2) terraces and to a lesser extent on the Desert Broom and Moenkopi terraces. The dunes along the Little Colorado River are larger and more extensive north and northeast (downwind) of the active channel. However, in this reach the dunes are more extensive south of the active channel. This apparently is the result of the river formerly occupying a position south of its present position, as illustrated in Figure 17.

The most notable feature of the fluvial geomorphology in this reach is the evidence for lateral migration of the channel. The active channel (Qac) upstream of Obed bridge is relatively sinuous. The form of the Desert Broom and Tamarisk surfaces (Qa1 and Qa2), as well as meander scars on the Moenkopi alluvium, indicate that the channel of the Little Colorado River has migrated laterally. This lateral erosion appears to be largely controlled by the presence of bedrock in the channel at site LCR2, shown in Figure 17. Bedrock is also present in the channel upstream of this reach at a diversion near the Cholla Power Plant (see Plates; Sheet 14). Based on the alluvial chronology, it appears that the Little Colorado River incised the Moenkopi alluvium at this site 1,000 years ago and has migrated laterally historically further widening the flood plain.

JACKRABBIT

Just south of Jackrabbit, the Little Colorado River makes two large bends, shown in Figure 18. The four major terraces mapped in this study along the Little Colorado River are present in this reach, illustrated in Figure 18. Paleochannels (Qpc), indicating the location of former channels of the Little Colorado River, are present on the Desert Broom, Tamarisk, and Moenkopi (Qa4) terraces. Dunes (Unit Qe) are prevalent in this reach and form coppice dunes on the Tamarisk and Cottonwood terraces, and cover large areas of the Tamarisk terrace. Vegetation density on the Desert Broom (Qa1a; Qa1b) and Tamarisk (Qa2; Qa2a; Qa2b) terraces highlights the complex of surfaces that have been formed at various times.

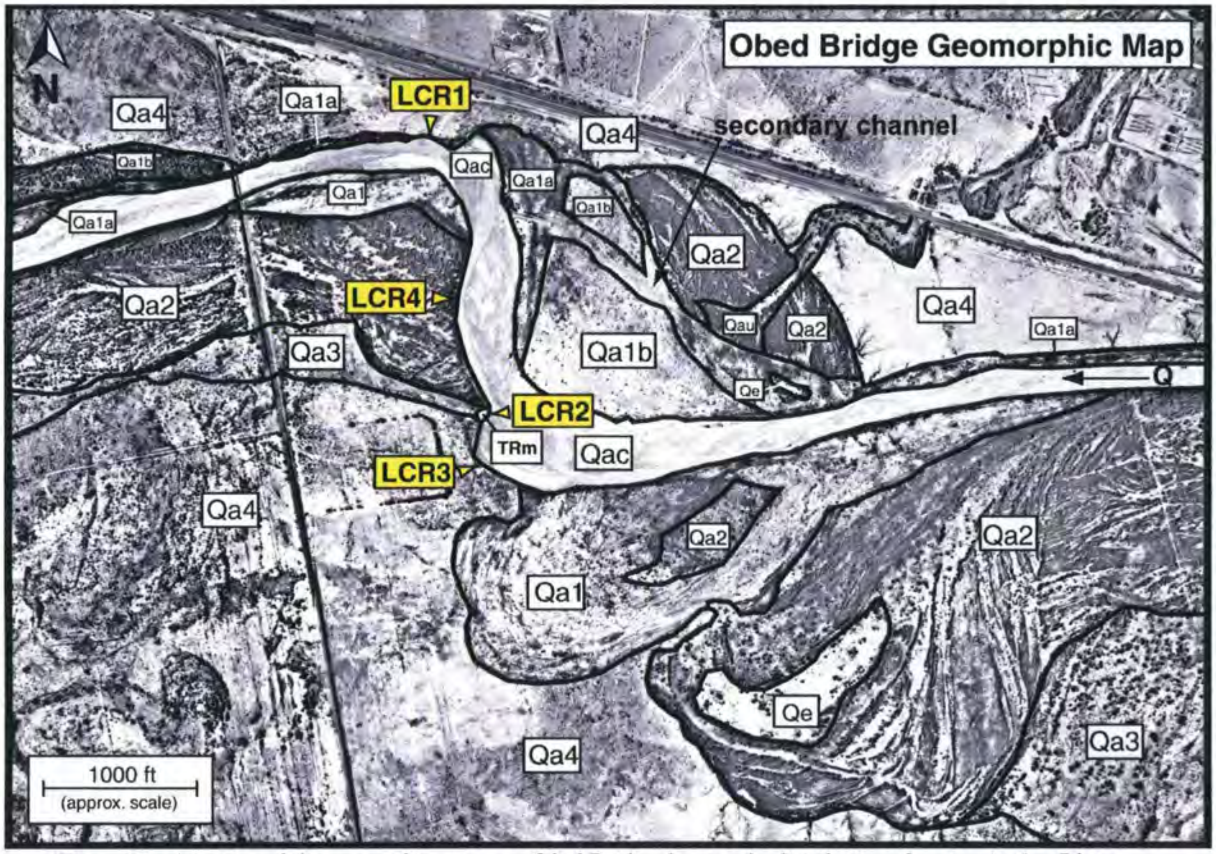


Figure 17. A portion of the geomorphic map near Obed Bridge showing the distribution of map units (see Plates; Sheet 12). Based on the age of units along the river, it appears that the Little Colorado River has occupied the area between deposits of the Moenkopi alluvium (Qa4) for the past 1,000 years and in places has migrated laterally over wide areas eroding the Moenkopi alluvium. Flow is from right to left in the photograph.

The older terraces are on the outside of bends and the younger terraces are on the inside bends. Along the inside of channel bends, the age of the alluvium and the terrace height increases with distance from the main channel. This suggests that the sinuosity of the channel has increased historically through this reach and that the river has been in an overall state of degradation since the abandonment of the Moenkopi alluvium. The reason for this migration is unclear, but based on the sinuosity of preserved paleochannels (Qpc) and meander scars on the surface of the Moenkopi terrace, it is apparent that this has been a regular process on the Little Colorado River in this reach.

WINSLOW

The geomorphology of the Little Colorado River in the Winslow area differs significantly compared to the Holbrook reach. In the Winslow reach, the width of the flood plain increases dramatically. It appears that this change in the flood plain width is related to the increase in basin area and hence a related increase in stream flow immediately downstream of the confluences of Chevelon Canyon, Clear Canyon, Cottonwood Creek, and Jacks Canyon with the Little Colorado River. Although the floodplain near Winslow is much wider than upstream reaches on the Little Colorado River, the Winslow levee cuts off the majority of additional flood plain.

Geomorphic mapping for this study was limited to the river and terraces within the levee. The Little Colorado River near the Homolovi Ruins is bounded on the right bank by bedrock and on the left bank by the Winslow levee , shown in Figure 20. The Moenkopi terrace is present along the right bank adjacent to bedrock, but not along the left bank within the levee. Terraces within the levee are limited to primarily the Tamarisk and Desert Broom alluvium. The Cottonwood terrace is outside the levee.

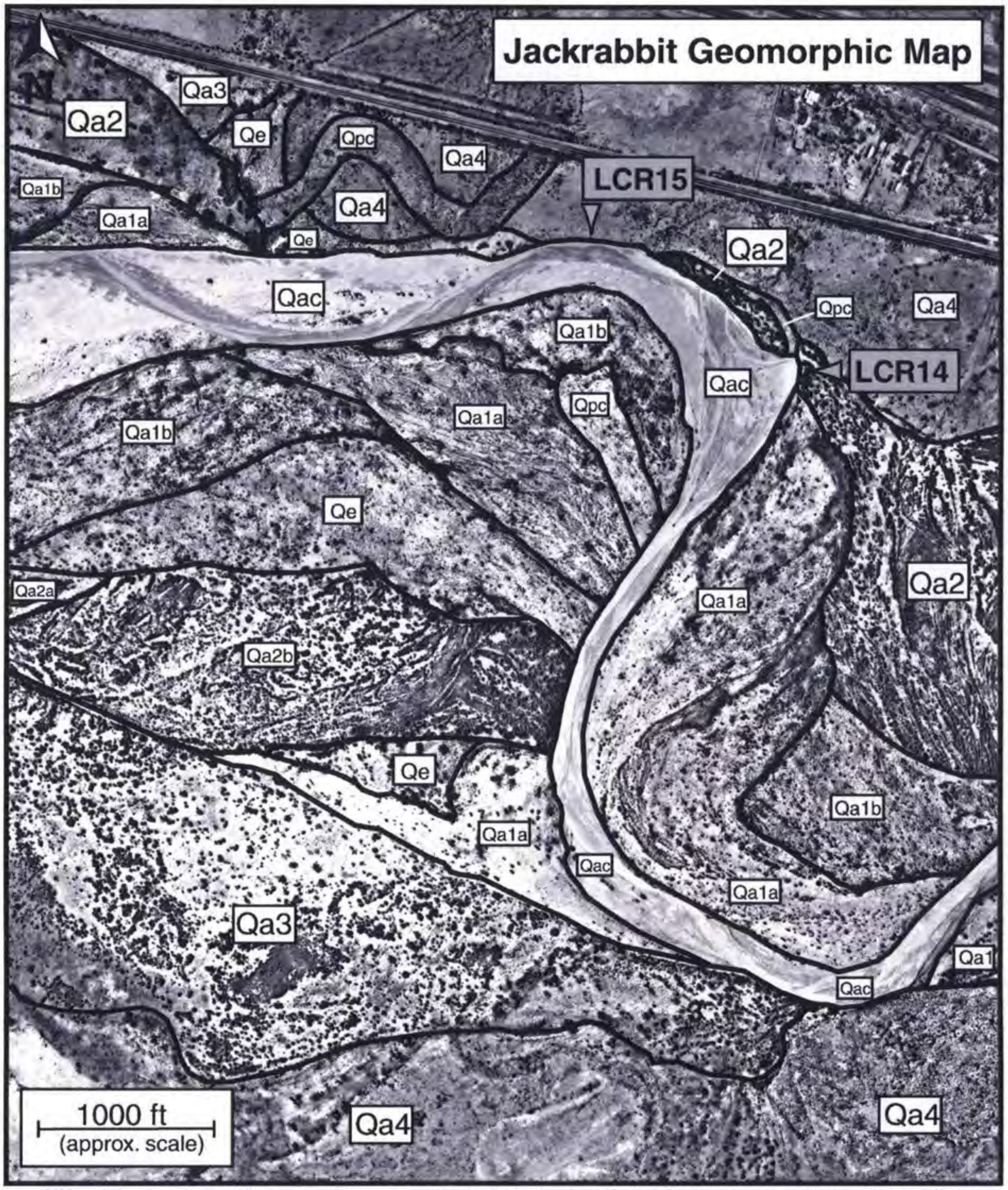


Figure 18. A portion of the geomorphic map near Jackrabbit showing the distribution of map units (see Plates; Sheet 9). The Little Colorado River has migrated across a wide zone at this location within the last 1,000 years. Flow is from bottom right to top left in the photograph.

Dunes (Qe) in the area are quite extensive and exist on both the east and west sides of the river. Mature Tamarisk or Cottonwood trees (50–100 years old) stabilize many of the dunes. Smaller dunes are also present on the younger the Desert Broom and Tamarisk terraces.

Near the Homolovi Ruins, channel dredging and channelization between 1984 and 1993 shifted the channel to the east from a position against the levee, indicated by the Qa1a channel shown in Figure 19.

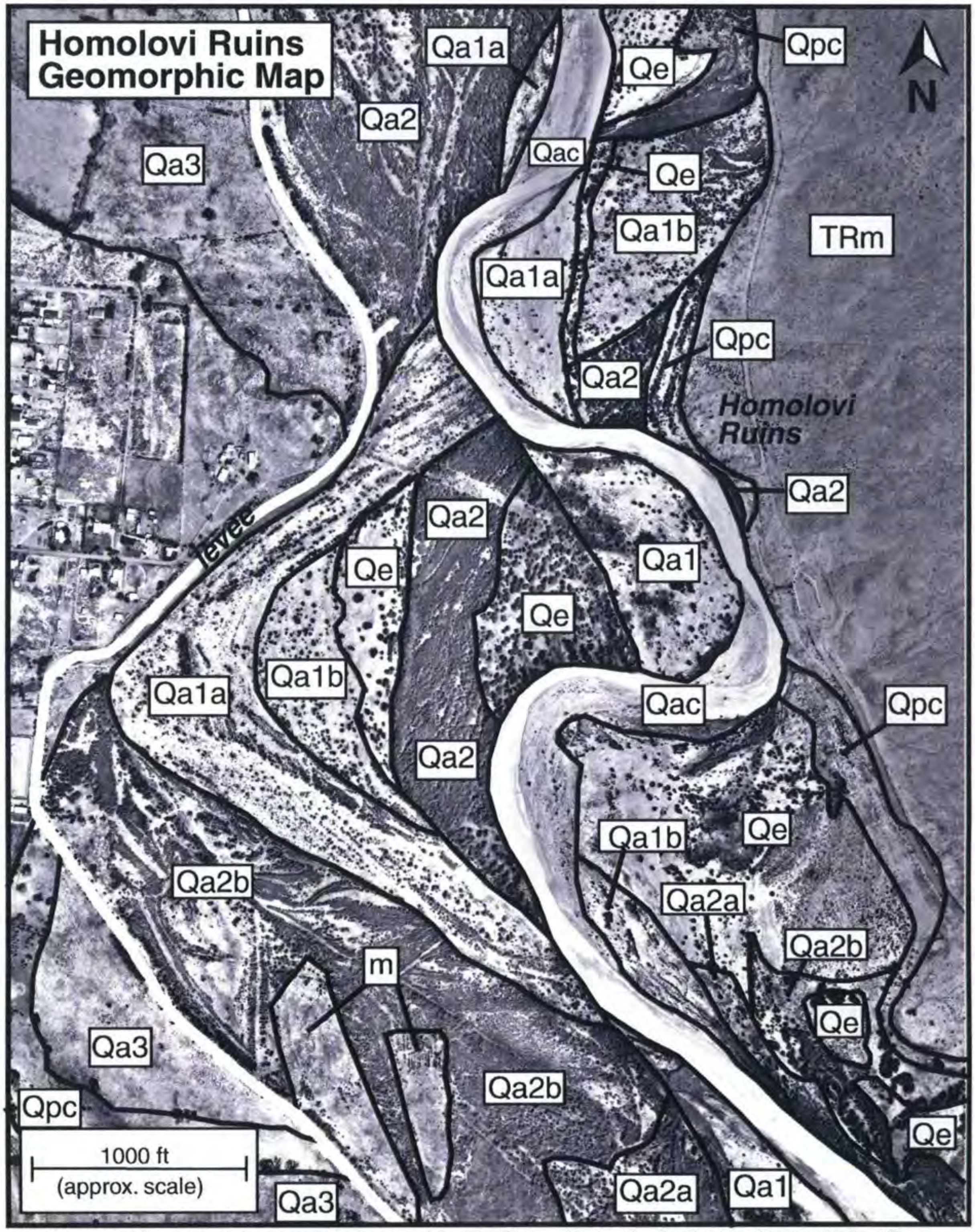


Figure 19. A portion of the geomorphic map near Homolovi Ruins showing the distribution of map units (see Plates; Sheet 2). All of the alluvial units mapped within this area formed historically (i.e., within the last 100 years) and indicate a high potential for lateral migration of the active channel. Flow is from bottom to top in the photograph.

The previous channel, unit Qa1a, is now only accessed during larger flows. Much of the active channel through this reach has formed meanders following dredging, and has migrated to its easternmost extent near Homolovi Ruins where it flows against bedrock. Large dune complexes prevalent along the east side of the river are sparsely vegetated, modified by high flows (unit Qa2b) on the Little Colorado River. Dunes on the west side of the river are more heavily vegetated with Tamarisk and Cottonwood.

Further north along the Winslow levee, a broad Tamarisk terrace (Qa2) is present adjacent to the river. In Figure 20, channel splays on the right bank apparently associated with the flooding in 1993 appear to be more significant in this area than on other Qa2 surfaces.

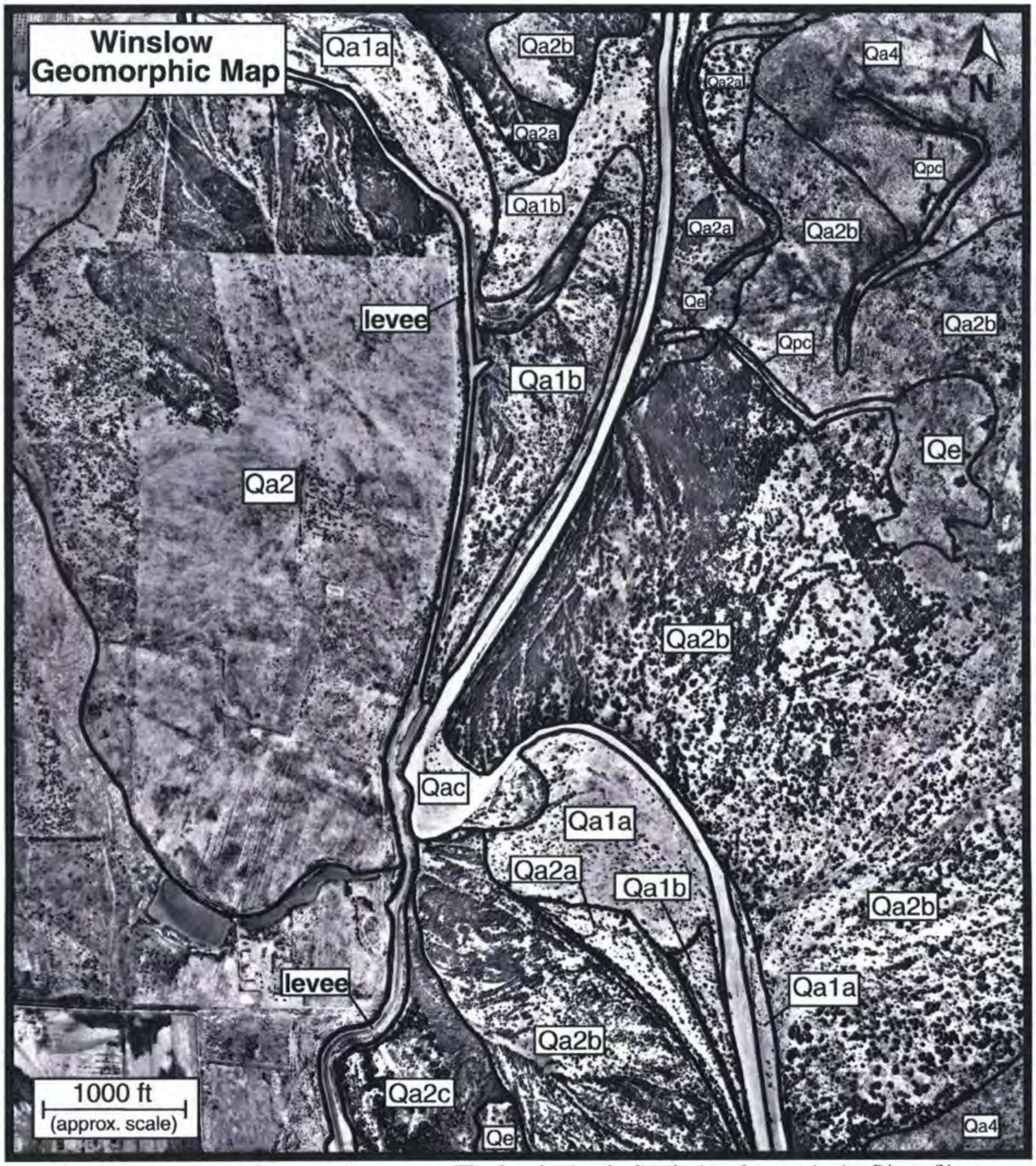


Figure 20. A portion of the geomorphic map near Winslow showing the distribution of map units (see Plates; Sheet 1). All of the alluvial units mapped within the levee formed historically (i.e., within the last 100 years); an extensive area of Tamarisk alluvium (Qa2) outside of the levee has been isolated from the river at this site. Flow is from bottom to top in the photograph.

The north bank of the river, in the west verging meander cut into the older Tamarisk alluvium (unit Qa2b), is also significantly higher than bank cuts in many other Qa2 surfaces in the Holbrook–Winslow reach. This high bank and densely vegetated surface on the Qa2b terrace appear to be factors in maintaining the accentuated meander at this location. The Qa2b surface in this area appears to grade to the Moenkopi terrace to the northeast with distance from the active channel. The behavior of the Little Colorado River in this reach is similar to that observed in other reaches, in that the river is incising older alluvium and migrating across a wide flood plain. The gradual transition in elevation from the surface of the younger Tamarisk alluvium (Qa2) to the Moenkopi terrace suggests that the river has migrated across a much wider floodplain at this site. Other characteristics that are unusual in this reach, when compared to other reaches, and indicate that the reach has been highly modified, include the narrow width of the active channel and the extreme height of the Qa2b surface above the active channel.

SEDIMENT AVAILABILITY BETWEEN HOLBROOK AND WINSLOW

The four alluvial units (Qa4, Qa3, Qa2 and Qa1) outlined on the geomorphic map and described in this report account for the majority of stored sediment that is available for transport in the study reach. Together with the active channel and paleochannels, these four alluvial units account for 72% of surface area on the geomorphic map. Where mapped separately from the alluvium, dune sand accounts for an additional 3% of the surface area of the map. The remaining surface area is covered by bedrock and modified terrain such as levees, highways, and embankments.

Estimating eolian transport of sediment through the study reach is beyond the scope of this study. Judging from the abundance of eolian landforms, it is obviously a process that deserves some consideration, both in removing sediment from the fluvial system and depositing sediment in positions on the landscape adjacent to the active river channel. It would be important to include wind transport as a variable if a detailed quantitative assessment of the sediment budget is conducted.

Overall, the impact of eolian sediment on the levees and bridges along the Little Colorado River is minimal. However, dune sand in the area of the I-40 bridge near Winslow is considerable. From observations during the course of the study, eolian landforms in the active channel are ephemeral features that are frequently modified by fluvial or eolian processes because there is little vegetation to anchor them in place. Based on these observations, it would appear that eolian features would have minimal impact to channel conveyance underneath bridges. Substantial eolian features do exist, however, on terraces adjacent to the active channel and within levied reaches, particularly in the Winslow levied reach. The present eolian features have been accounted for in modeling routines and do not appear to present a problem in levied reaches. However, a major change in the amount of eolian activity could potentially influence the capacity of the levees during large floods. Without additional work that documents trends in eolian activity along the Little Colorado River, it is difficult to predict future trends in eolian activity and determine whether these trends would significantly impact the capacity of the levees.

The estimate of available sediment in the study reach considered only the Desert Broom (Qa1), Tamarisk (Qa2) and Cottonwood (Qa3) alluvium. These surfaces consist of sandy sediments that are entrained by tractive forces an order of magnitude less than those required to entrain the heavy clayey soils that are abundant in the Moenkopi alluvium (Hjulstrom, 1939; Lane, 1955). These are also the surfaces that are the lowest in height and closest to the main channel and therefore are most likely to be inundated by floods at depths large enough to erode and transported sediment. Also, because they are closest to the active channel, these surfaces have the highest chance of being eroded by a laterally migrating channel. Although some bank exposures of the Moenkopi alluvium do exist along the length of the study reach and some sediment is delivered to the channel by bank failures, the volume of sediment is assumed to be minimal compared to the other surfaces.

The surface area for each geomorphic unit was multiplied by a minimum and maximum thickness of each deposit to estimate the volume in the map area (Table 4). The height above the present main channel of the respective terrace surface associated with each deposit was used as an approximation of the deposit thickness, shown in Table 4. The volume estimates for the Cottonwood (Qa3) and Tamarisk (Qa2) alluvium are very similar ranging from roughly 2 to 5×10^7 yd^3 of sediment. The Desert Broom terrace is more limited in areal extent and lower in height so that the volume estimate is smaller, roughly 4 to 7×10^6 yd^3 of sediment. These estimates do not include the area of the map covered by paleochannels, some that flow across these surfaces, and account for roughly 2% of the surface coverage on the geomorphic map. It also does not account for dunes that may be mobilized during flood flows or redistributed by wind.

Table 4. Statistics for geomorphic map units.

Map Symbol	Map Unit	Surface Area (Acres)	Percent Coverage	Thickness (feet)	Volume (yd^3)
Qac	Active channel	1,767	5.9		
Qa1	Desert Broom alluvium	2,256	7.5	1–2	3.64 to 7.28×10^6
Qa2	Tamarisk alluvium	6,414	21.2	2–5	2.07 to 5.17×10^7
Qa3	Cottonwood alluvium	2,797	9.3	5–10	2.26 to 4.51×10^7
Qa4	Moenkopi alluvium	7,808	25.9		
Qpc	Paleochannels	654	2.2		
Qe	Dunes	950	3.1		
Qau	Undifferentiated alluvium	567	1.9		
m	Modified terrain	880	2.9		
R	Bedrock	2,798	20.2		

SEDIMENT AVAILABILITY IN THE UPPER BASIN AND TRIBUTARIES

The drainage basin of the Little Colorado River upstream of Holbrook and its tributaries also contributes significant volumes of sediment that may transport or deposit through the study reach. To assess available sediment from these sources, a reconnaissance of major tributaries and the main stem of the Little Colorado River upstream of the study reach was undertaken in the area shown in Figure 21. The scope of this study did not permit an assessment of sediment availability along the entire length of tributaries and the main stem Little Colorado River upstream of Holbrook in a manner similar to the analysis completed between Holbrook and Winslow. However, the estimates made during this reconnaissance should provide an estimate of sediment availability in the representative reaches.

The basis of the study site selection was primarily access. Representative cross sections were measured in the field at six sites using a laser rangefinder. Evaluation included an estimate of the amount of uncon–solidated alluvium available for transport. Only sandy alluvium in the fluvial terraces was considered available. Much of the older valley fill is semi–consolidated, clay–rich alluvium and was not included in the estimate because of its cohesive properties. A greater velocity is necessary to entrain clay–size particles from a semi–consolidated deposit as opposed to unconsolidated sand (Hjulstrom, 1939; Lane, 1955). In addition, since the clay–rich valley fill is located in the banks or farther away from the main channel, the velocity would be lower than in the main channel or across the low terraces adjacent to the channel and thus would further limit the erosion and transport of finer–grained sediment from the valley fill.

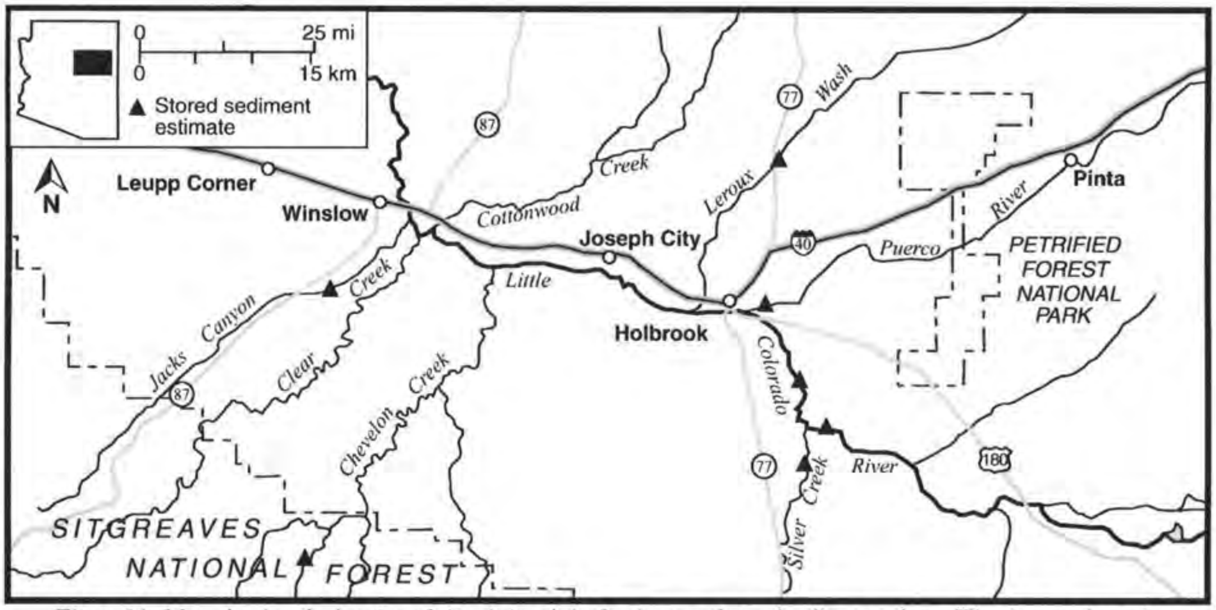


Figure 21. Map showing the location of sites (triangles) of estimates of stored sediment volume. The sites are located on major tributaries and the main stem that supply sediment into the study reach.

Since no subsurface data was available to identify the depth to bedrock along each cross section, assumptions about the subsurface cross sectional geometry were made. In cross sections where bedrock was observed in the channel and banks, a straight line was drawn to connect the points where bedrock was observed. Figure 22 illustrates an example. The area of sediment above this line is considered the minimum estimate of available sediment. Similarly, a line was also drawn to connect the same points assuming the geometry reflects the erosion of the channel by a migrating and slightly incising river within the valley. Additional uncertainty is introduced when bedrock was not observed in the channel. In these cases, it is difficult to determine a depth of alluvium that is stored in the channel. Assuming limited incision, an estimate was derived by calculating the amount of sediment available above the local base level in the channel. The volume defined for each cross section incorporates both of these estimates (Table 5).

Table 5. Stored sediment volume estimates.

River	Site	Cross Section Based Estimate (ft^2)	Reach–Based Estimate (yd^3/mi)
Little Colorado	Upstream of Silver Creek	270	5.2×10^4
Little Colorado	Old Cableway	150	2.9×10^4
Silver Creek	Upstream of Woodruff Dam	800	1.6×10^5
Puerco River	Upstream of the confluence with Little Colorado River	9,200–16,150	$1.8\text{–}3.2 \times 10^6$
Leroux Wash	Rt. 77 Bridge	5,400	1.1×10^6
Chevelon Canyon	Chevelon Crossing	46	9.0×10^3

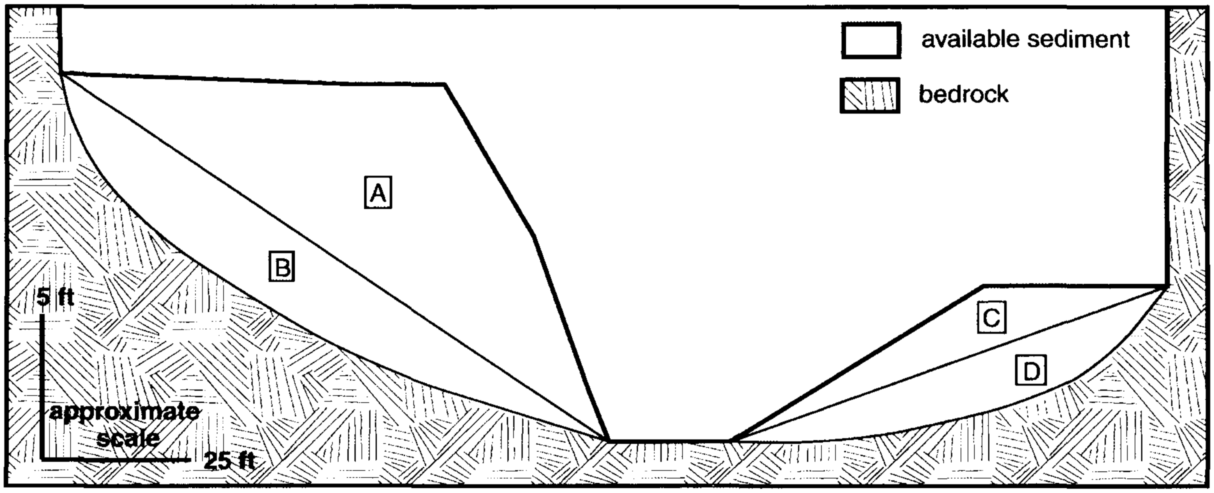


Figure 22 Illustration showing the methodology used for estimating sediment storage in a cross section. The minimum estimate for sediment stored in the cross section was derived by adding sections A and C assuming that the bedrock contact under the alluvium was linear between the exposures in the channel bed and on the terrace surface. The maximum estimate for sediment stored in the cross section was derived by adding sections A, B, C, and D.

LITTLE COLORADO RIVER UPSTREAM OF SILVER CREEK

An estimate of available sediment was calculated from a measured cross section roughly two miles upstream from the confluence of the Little Colorado River and Silver Creek near an unnamed tributary, shown in Figure 21. The river at this site has formed a canyon in the Coconino Sandstone, and the Moenkopi and Chinle Formations. The channel geometry is controlled by bedrock on both banks and in the bed of the main stem and upstream tributary. Figure 23 illustrates the cross section where two sandy terraces, whose surfaces are 8 and 14 feet above the main channel, respectively, are inset into fine–grained valley fill. The sandy terraces appear correlative to the Desert Broom (Qa1) and Tamarisk (Qa2) alluvium described between Holbrook and Winslow. However, the sediment forming the older valley fill resembles the Moenkopi alluvium and comprises the majority of sediment observed in the cross section. Because of the fine–grained, semi–consolidated nature of the valley fill, it is considered to have minimal erosion potential, and therefore is not included in the estimate of available sediment. From the topography and observations at access points along the river, the sediment storage appears to be similar in the reach from the surveyed cross section to the confluence with Silver Creek. Stored sediment in this cross section is estimated to be roughly 270 ft^2. Assuming that the sediment in the measured cross section represents an average value in the reach, a volume of $5.2x10^4$ yd^3/mile of sediment available for erosion and possible transport is estimated, as listed in Table 5.

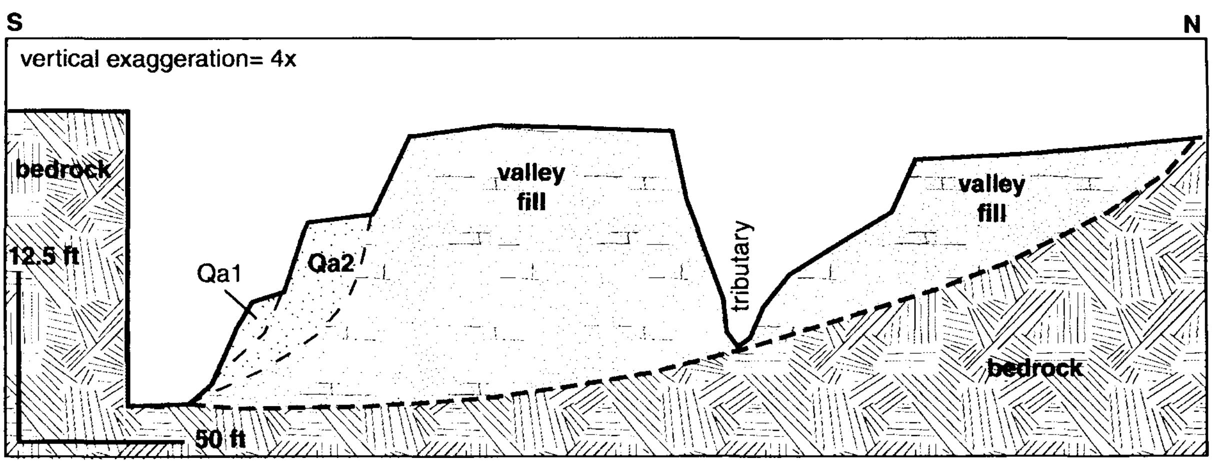


Figure 23. Cross section showing young alluvium (Qa1 and Qa2) stored along the Little Colorado River upstream of Silver Creek. The cross sectional area of stored sediment is equal to 270 ft^2.

LITTLE COLORADO RIVER AT THE OLD CABLEWAY

An estimate of stored sediment was calculated in a cross section measured at the Old Cableway near Woodruff Butte, roughly 1.5 miles downstream of the bridge over the Little Colorado River at Woodruff, Arizona. Figure 21 shows this location. The old cableway is near the location of the discontinued USGS stream gage on the Little Colorado River at Woodruff, ARIZONA (USGS station No. 09394500), and has since been removed. This cross section is controlled by bedrock in the channel bed as well as in the adjacent terraces and valley fill, as Figure 24 shows. Stored sediment in this cross section consists mainly of older valley fill with minor sandy terraces that are tentatively correlated to the Tamarisk alluvium in the study reach. Not including the semi–consolidated clay–rich valley fill, the area of stored sediment in the cross section is 150 ft^2. It is difficult to estimate a volume along this reach of the river because of the apparent variability of the alluvium in cross section. However, a gross estimate of 2.9×10^4 yd^3/mile can be made assuming that the variability observed at this site is consistent through the reach near Woodruff.

SILVER CREEK

An estimate of stored sediment was calculated in a cross section measured across Silver Creek roughly 2.5 miles upstream from its confluence with the Little Colorado River, shown in Figure 21. Figure 25 shows a relatively broad sandy terrace covered with vegetation and a lower inset sandy terrace that appears to be inundated more frequently. The surface of these terraces are 12 feet and 5 feet above the active channel, respectively. Based on the character of the surficial deposits and their topographic position relative to the river, the terraces appear to correlate to the Tamarisk (Qa2) and Desert Broom (Qa1) alluvium, respectively. Correlations in this area are considered tentative due to the unknown effect of bedrock control on the channel geometry and the influence of Woodruff Dam on sediment storage. That dam is located 2.25 miles downstream. The crest elevation of Woodruff Dam is roughly 5,200 feet. An estimate of stored sediment was calculated from a cross section measured across Silver Creek at a point roughly a mile upstream of where the channel bed elevation was equivalent to the dam crest elevation. Figure 26 shows this location. The area of stored sediment in the cross section is roughly 800 ft^2. Again, assuming the area of stored sediment in the cross section is representative, the volume of stored sediment in this reach is roughly 1.6×10^5 yd^3/mile. The canyon upstream of this reach narrows considerably and the volume of stored sediment decreases significantly.

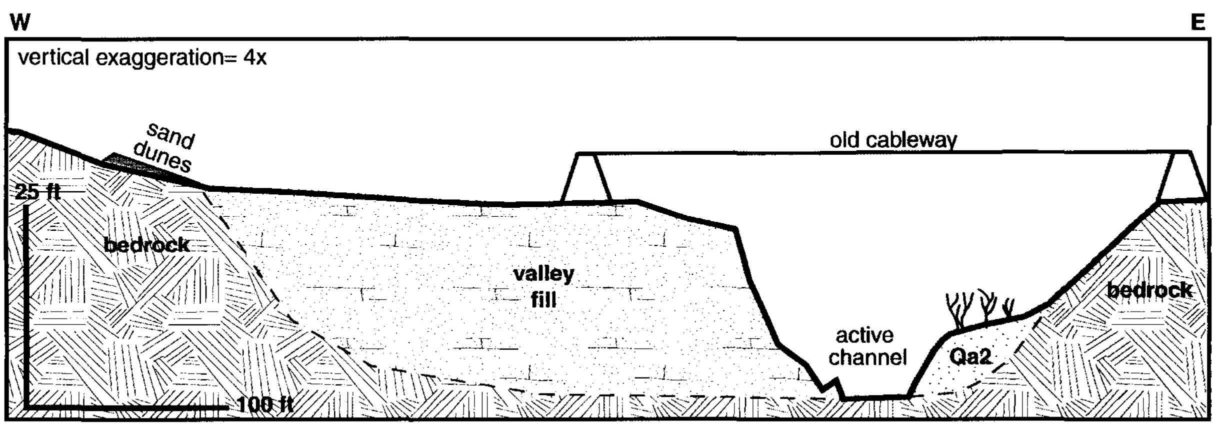


Figure 24. Cross section showing young alluvium (Qa2) stored along the Little Colorado River at the Old Cableway site. The cross sectional area of stored sediment is equal to 150 ft^2.

Figure 25. Photograph of Silver Creek looking upstream at stored sediment along the canyon bottom. At this location, densely vegetated sandy terraces line the active channel along a bedrock canyon reach of Silver Creek. Note Dr. Klinger standing on the cliff near the left edge of the photograph.

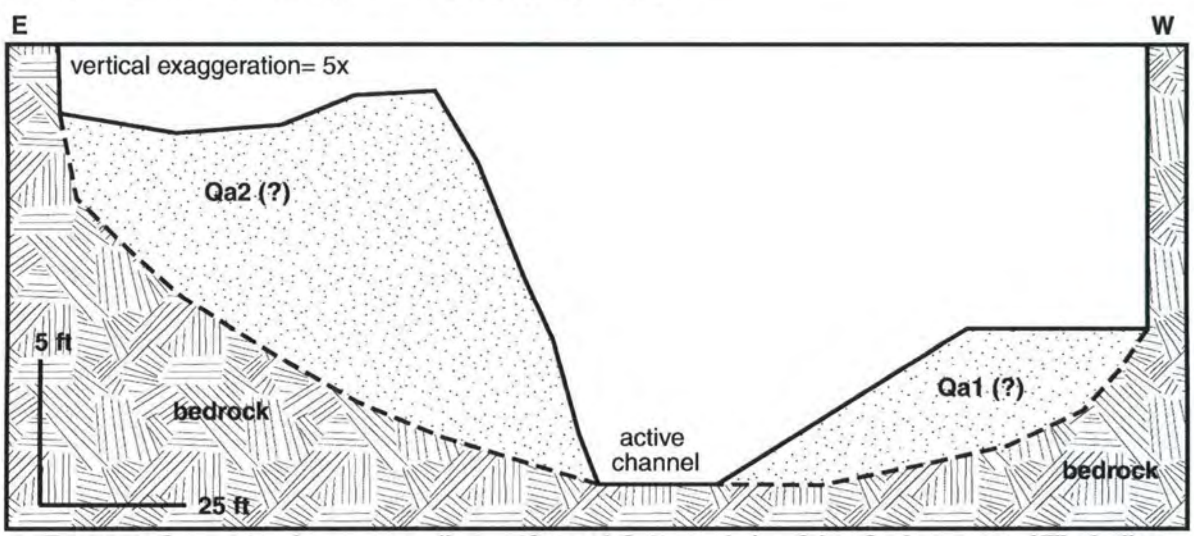


Figure 26. Cross section showing young alluvium (Qa1 and Qa2) stored along Silver Creek upstream of Woodruff Dam. The cross sectional area of stored sediment is equal to 800 ft².

PUERCO RIVER

Two cross sections were constructed across the Puerco River near its confluence with the Little Colorado River to estimate sediment storage. The cross sections were drawn from the 2–foot contour interval topographic maps developed for this study and used in the sediment model. The cross sections were sited at locations where the presence of bedrock on both sides of the river provided a constraint on the channel width. Because of the sinuous nature of the Puerco River in this reach, cross sections were plotted perpendicular to the overall flow direction rather than the direction of the active channel. Since bedrock was not observed in the channel bed through this reach, the volume of stored sediment was estimated to the base of the main channel. While this may underestimate the volume of stored sediment available for transport, given the apparent degraded state of the river channel both downstream of Holbrook and in the upstream portion of the Little Colorado River near Woodruff, the volume of sediment that might be scoured from the bed is considered to be insignificant in comparison to the volume of sediment stored elsewhere in the cross section.

Figure 27(a) shows the first cross section located roughly one mile upstream from the confluence with the Little Colorado River. This cross section is dominated by Qa3 and Qa1 surfaces. The Qa3 surface is roughly 5–6 feet above the active channel and is characterized by irregular topography related to dune activity. High dunes form along the front edge of the terrace and are roughly 10 feet high. The Qa1 surface is roughly 2–4 feet above the active channel and has irregular topography due to recent fluvial activity. A back channel along the back edge of the Qa1 surface is locally incised deeper than the bed of the active channel. The estimate of stored sediment in this cross section was made to the depth of this back channel. The cross sectional area of stored sediment at this location is 16,150 ft^2, equating to roughly $3.2x10^6$ yd^3/mile (Table 5).

Figure 27(b) shows the second cross section roughly 3.5 miles upstream from the confluence. The section extends from bedrock on the left bank to the railroad grade on the right bank. The cross section was only plotted to the railroad grade rather than bedrock on the right bank since stored sediment on the opposite side of the railroad cannot be accessed by the Little Colorado River. On the left bank, two terraces that are 3 and 5 feet above the active channel correlate to the Qa1 and Qa2 surfaces, respectively. A wide back channel on the right bank is separated from the Qa2 surface by a 150–foot wide dune field and has its deepest point along the railroad grade. This back channel is roughly 2 to 3 feet higher than the active channel so the estimate of stored sediment in this cross section was made to the depth of the active channel. The cross sectional area of stored sediment at this location is 9,200 ft^2, equating to roughly $1.8x10^6$ yd^3/mile (Table 5).

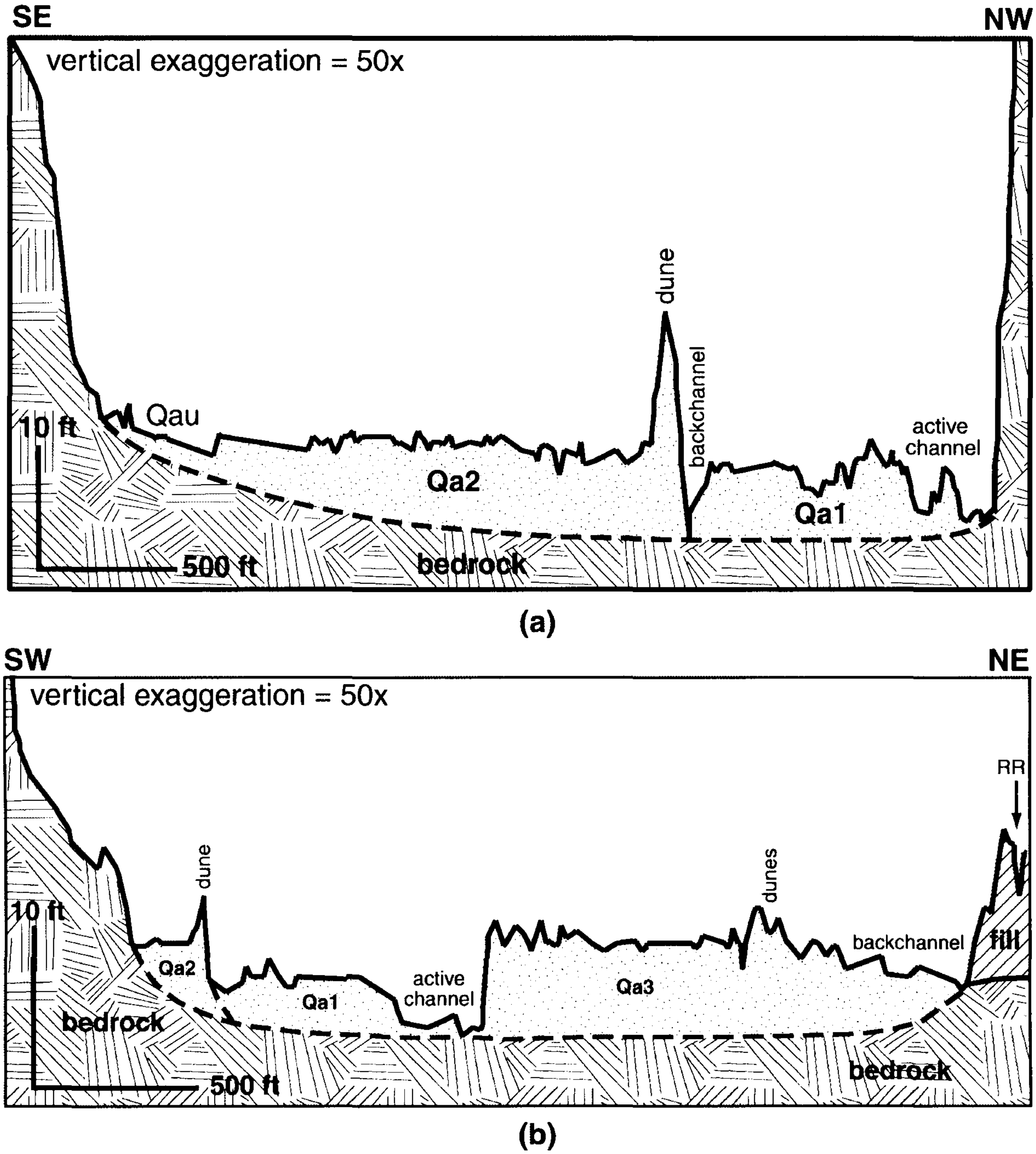


Figure 27(a).Cross section showing young alluvium (Qa1, Qa2, and Qau) stored along the Puerco River roughly one mile upstream of the confluence with the Little Colorado River. The cross sectional area of sediment is equal to 16,150 ft^2; (b). Cross section showing young alluvium (Qa1 and Qa3) stored along the Puerco River roughly 3.5 miles upstream of the confluence with the Little Colorado River. The cross sectional area of stored sediment is equal to 9,200 ft^2.

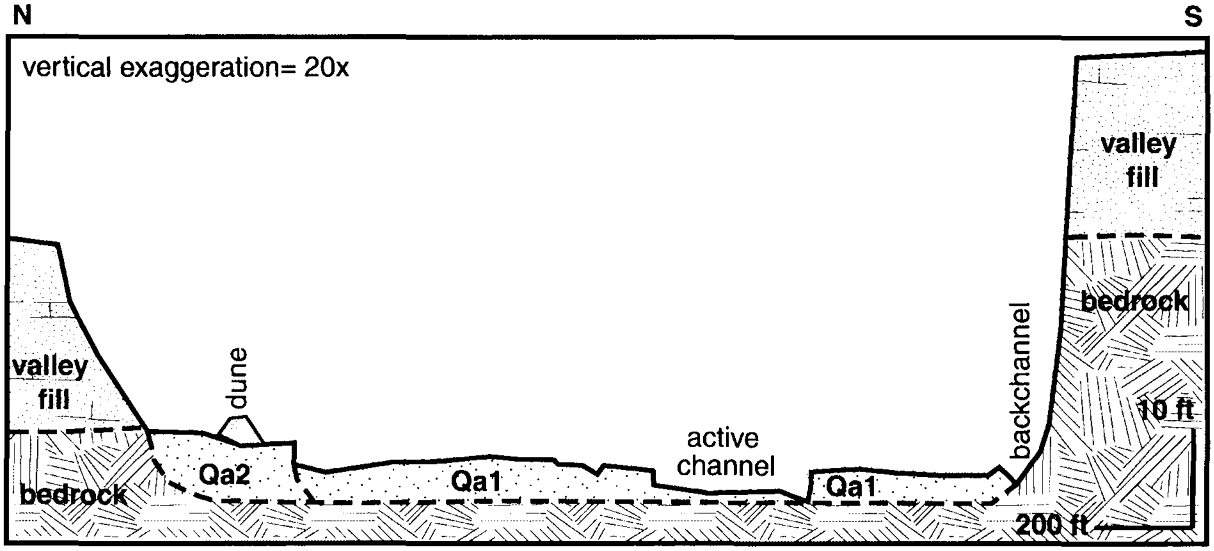


Figure 28. Cross section showing young alluvium (Qa1 and Qa2) stored along Leroux Wash upstream of the Arizona Route 77 bridge. The cross sectional area of stored sediment is equal to 5,400 ft^2.

CHEVELON CREEK

An estimate of stored sediment was calculated in a cross section measured across Chevelon Creek roughly 35 miles south of Winslow at Chevelon Crossing, shown in Figure 21. Site selection was based primarily on access in the upper basin; thus, this estimate is one representation of sediment availability on Chevelon Creek. The cross section was surveyed in the Chevelon Campground just upstream of the bridge at Chevelon Crossing. Figure 29 shows how the channel in this reach is filled with large angular boulders. It is a straight, wide trapezoidal geometry with steep bedrock slopes of Coconino Sandstone. A pair of low sandy alluvial terraces, probably correlative to the Desert Broom alluvium, flank the channel. A higher gravelly terrace is preserved along the left bank. The alluvial terrace along both banks grades upslope into colluvium over bedrock. The calculated area of stored sediment in the cross section at this site is estimated to be roughly 46 ft^2. This equates to roughly 9.0×10^3 yd^3/mile of material (Table 5).

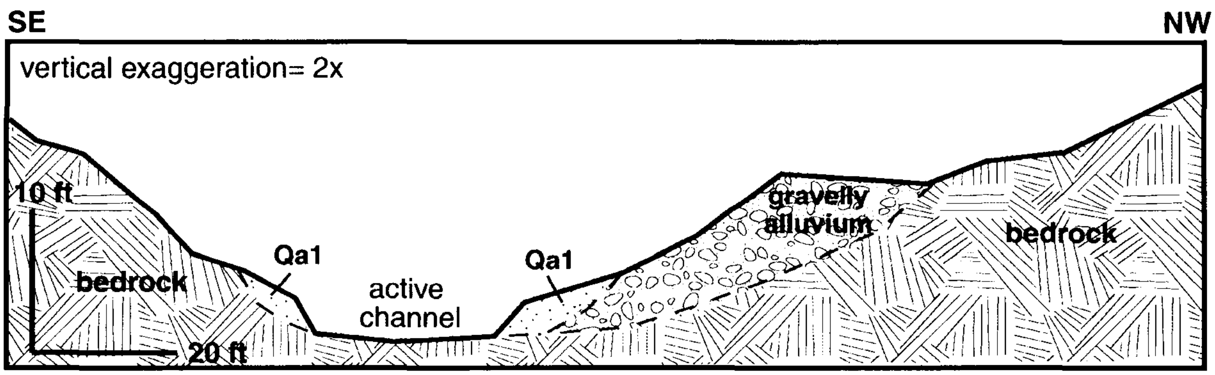


Figure 29. Cross section showing young alluvium (Qa1) stored along Chevelon Creek near Chevelon Crossing. The cross sectional area of stored sediment is equal to 46 ft^2.

JACKS CANYON

Reconnaissance along Jacks Canyon near Rock Station just west of Route 87 was undertaken in an effort to estimate the stored sediment in the drainage. A thin veneer of fine–grained sediment is present along the left bank and coarse–grained alluvium preserved along the right bank forms a 20–foot bluff along a channel that is otherwise incised into bedrock. Due to the negligible amount of sediment at this location, shown in Figure 30, no cross section was measured. Based on observations made at this location and at the Highway 99 crossing, roughly 2.5 miles upstream of its confluence with the Little Colorado River, it appears that there is minimal sediment stored in the Jacks Canyon drainage.

Figure 30. Photograph of Jacks Canyon looking downstream from an old bridge approach near Rock Station. The photograph shows a thin veneer of alluvium over bedrock in the channel and overbank areas.

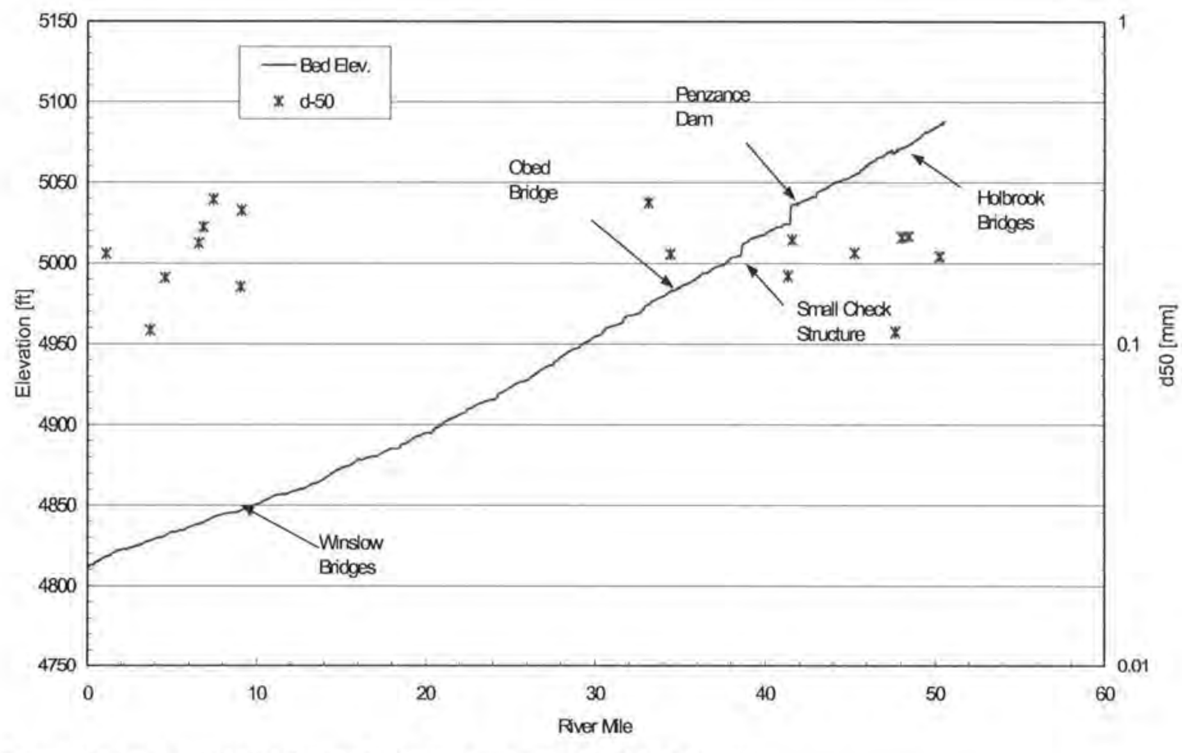
PART II – SEDIMENTATION

The hydraulic conditions and sediment transport of the Little Colorado River from the Puerco River confluence to downstream of the Winslow levee have been simulated using a computer model. Modeling the sediment transport through this river system provides insight to the current and future status of the river and helps answer if the river aggrading, degrading or stable. The sediment model was used to determine these conditions on a small scale (considered to be the length of the model) or a large scale (e.g. near man made structures or at a specific location in the river) or intermediate scales. In addition to predicting the local, intermediate or large scale conditions, model results were used to answer "what if" questions and provide an estimate of the future conditions of the system. Predictive simulations have been performed for three geometric channel adjustments, including channel realignment, levee relocation and the removal of Penzance Dam, and five hydrologic scenarios. These will be discussed later in this report.

DATA COLLECTION AND HYDRAULIC ANALYSIS METHODOLOGY

BED MATERIAL DATA

Bed material from the Little Colorado River and its tributaries was collected by Reclamation and Navajo County personnel and analyzed at a Navajo County soils laboratory for grain size distribution. Appendix C contains the inventory of the bed material samples taken, in addition to the sieve analysis results. In total, 57 surface bed material samples were collected over more than 50 miles of stream. Most of the sampling was done on the Little Colorado River, but the following tributaries were also sampled: Puerco River, Silver Creek, Leroux Wash, Joseph City Wash, and Cottonwood Wash. Figure 31 contains a plot of the d_{50} (the median bed material size) and bed elevation as a function of river mile in the main stem of the Little Colorado River. The median bed material size does not vary more than 0.2 mm throughout the reach. The river slope shows a gradual decrease in the downstream direction, typical of alluvial rivers.



River mile 0 is beginning of model approximately 9 river miles downstream of the I-40 bridge in Winslow.

Figure 31. Bed profile and d_{50} as a function of river mile in the Little Colorado River.

AERIAL PHOTOGRAPHY AND GEOMETRIC DATA

Cooper Aerial Surveys collected aerial photography on August 20, 2000. Reclamation (Phoenix Area Office) produced a topographic map (AutoCAD 2000) of the study reach from that aerial photography at a scale of 1:10,000. The topographic map begins upstream of the confluence of the Puerco River and the Little Colorado River, and extends roughly nine river miles downstream of the I-40 bridges at Winslow. River mile 0 (RM 0), the origin of the coordinate system, is at the downstream limit of the topographic survey. The hydraulic and sediment models use the same longitudinal coordinates. This system locates the I–40 bridges in Winslow at river mile 8.3 (RM 8.3), and the railroad bridge in Holbrook at river mile 43.4 (RM 43.4). The locations of other structures within the reach are contained in Table 6.

Table 6. Location of relevant structures in the modeled reach.

Structure	Distance (ft)	Distance (River Mile)
Hwy. 77 bridge	230,829	43.7
Utility crossing	229,648	43.5
Holbrook RR bridge	229,220	43.4
Penzance dam	199,806	37.8
Small diversion	187,511	35.5
Obed bridge	167,846	31.8
Winslow RR bridge	46,200	8.8
Rt. 66 bridge	45,683	8.7
E. Bound I–40 bridge	43,837	8.3
W. Bound I–40 bridge	43,735	8.3

Cross sections were produced at selected locations along the river reach within the topographic model using BOSS RMS–2000 (see Appendix D). These cross sections were imported into HEC–RAS 3.0, producing hydraulic models for the reach. Spacing of these cross sections is not greater than 500 feet considering interpolated cross sections. The same geometry was used in the GSTARS–2C sediment model. The GSTARS–2C program dynamically simulates sediment transport and bed evolution in the river channel and overbanks. GSTARS–2C is the newest version in the GSTARS model series and will soon be released for public use. Yang describes the details of the model (Yang, et al., 2003).

Two hydraulic geometries from the topographical model are necessary to hydraulically model both low flows that stay within the main channel, and higher flows with a significant amount of flow occurring on the overbank. Separate high flow geometry is necessary because as the overbank starts to convey flow the channel length effectively becomes shorter and the river straightens. The low–flow geometry models discharges less than 5,000 ft^3/s. The high flow geometry models flow rates greater than 5,000 ft^3/s. A standard numerical verification compares the water surface elevations calculated by the in–channel geometry and overbank geometry at 5,000 ft^3/s. This comparison was successful following minor adjustments to both geometries. The high flow geometry containing the overbank information was used as the input for the sediment model, and is listed in Appendix D. Some of the HEC–RAS cross sections have been vertically extended due to a lack of sufficient channel geometry to contain the extreme flows. This often occurred when there was insufficient overbank geometry on the topographic map. Some cross sections extended over a mile without the proper relief to contain the high flows. In either case, this lack of information does not influence the outcome of the sediment model because overbank flows great distances from the channel are not being modeled.

HYDRAULIC DATA

The purpose of the hydraulic modeling is to obtain geometric input to the sediment model (GSTARS–2C), provide an understanding of the hydraulic conditions in the river and to obtain geometric and hydraulic input to the incipient motion/transport capacity model. Reclamation does not intend for the hydraulic modeling to be used to determine water surface elevations for a flood event. Because the hydraulic model was created for the purpose of input for sediment modeling, results from the HEC–RAS models are not presented in this report.

The hydraulic model simulates the bridges in the reach, with the exception of Obed Bridge in Joseph City. Navajo County provided the bridge surveys. There are two in–channel structures in the reach, Penzance Dam and a small diversion structure downstream of Penzance, near the Cholla power plant. These structures themselves do not provide any water storage, as they are filled with sediment. A survey of Obed Bridge was not provided by Navajo County. However, this does not influence the model results near the bridge because the structure itself has a much smaller influence on the hydraulic model compared to the natural constriction at the site created by the southern bridge approach. The model considers that constriction.

Because measured water surface elevations are not available, only limited calibration of the hydraulic model could be performed. This is common for streams with little historical data. Therefore, other measures were taken to insure an accurate model. The major calibrating parameter is bed roughness (Manning 'n'). Roughness coefficients were carefully chosen in this model based on previous studies (AGK Engineers, 1992, Cella, Barr, Evans and Associates, 1981 as reported in Sabol, 1993, and USACE, 1991) and engineering judgment. The channel roughness values used in these studies varied from 0.02 to 0.035, depending on location. Based on the previous studies, a global main channel roughness of 0.025 was determined to be a proper Manning 'n' value for the reach described in this report. Flood plain roughness varied in the previous reports from 0.077 to 0.15. The flood plain roughness parameter is more difficult to determine because its value is largely determined by the density and type of vegetation in the flood plain. In this case the flood plain vegetation is primarily Tamarisk. In the hydraulic model the global flood plain roughness used was 0.07. This parameter is somewhat lower than is warranted for this type of overbank vegetation; however, the more densely vegetated overbanks were modeled as ineffective flow areas. This representation is accurate because the dense vegetation prevents conveyance in the overbanks. The ineffective overbank areas were set to have a height of seven feet above the overbank ground surface. This height allows extreme flows to over–top the ineffective areas and add to the flow capacity when water surfaces would inundate the top of the vegetation.

The discharges input into these hydraulic models are the result of flood–frequency analysis and flow–duration curves using the methods described in Bulletin 17B (United States Water Resources Council, 1981) at the USGS stream gages in Table 7. An analysis was also performed on the combined record of USGS gage No. 09397000 and USGS gage No. 09397300 because of their close proximity to each other. The 50–year and 100–year discharges are plotted in Figure 32. To compute the discharges in between the gages, the discharge was linearly interpolated based on the drainage area. The computed flood discharges are shown in Table 8. The discharges are a linear function of computed contributing drainage area.

Table 7. USGS gages used for deriving discharges.

Station ID	Station Name	Drainage Area (mi^2)
9394500	Little Colorado River At Woodruff, AZ	7,775
9397000	Little Colorado River At Holbrook, AZ	11,115
9397300	Little Colorado River Near Joseph City, AZ	12,045
9401000	Little Colorado River at Grand Falls, AZ	20,700

Table 8. Flows used in the hydraulic model.

Location on LCR	Dr. Area (mi^2)	Q2 ft^3/s	Q2.33 ft^3/s	Q5 ft^3/s	Q10 ft^3/s	Q20 ft^3/s	Q50 ft^3/s	Q100 ft^3/s
Puerco Confluence	11,462	8,760	9,781	14,928	20,141	26,016	35,044	42,977
Leroux Wash	12,271	8,747	9,812	15,311	20,987	27,587	38,055	47,560
Joseph City Gage	12,384	8,746	9,816	15,365	21,105	27,806	38,475	48,200
Joseph City Wash	12,421	8,745	9,818	15,382	21,144	27,878	38,613	48,410
Chevelon Creek	13,206	8,733	9,848	15,754	21,964	29,402	41,535	52,856
Clear Creek	13,827	8,723	9,872	16,048	22,614	30,607	43,846	56,374
Jacks Creek	14,122	8,719	9,883	16,188	22,922	31,180	44,944	58,045
Cottonwood Wash	15,822	8,692	9,949	16,992	24,700	34,480	51,272	67,674

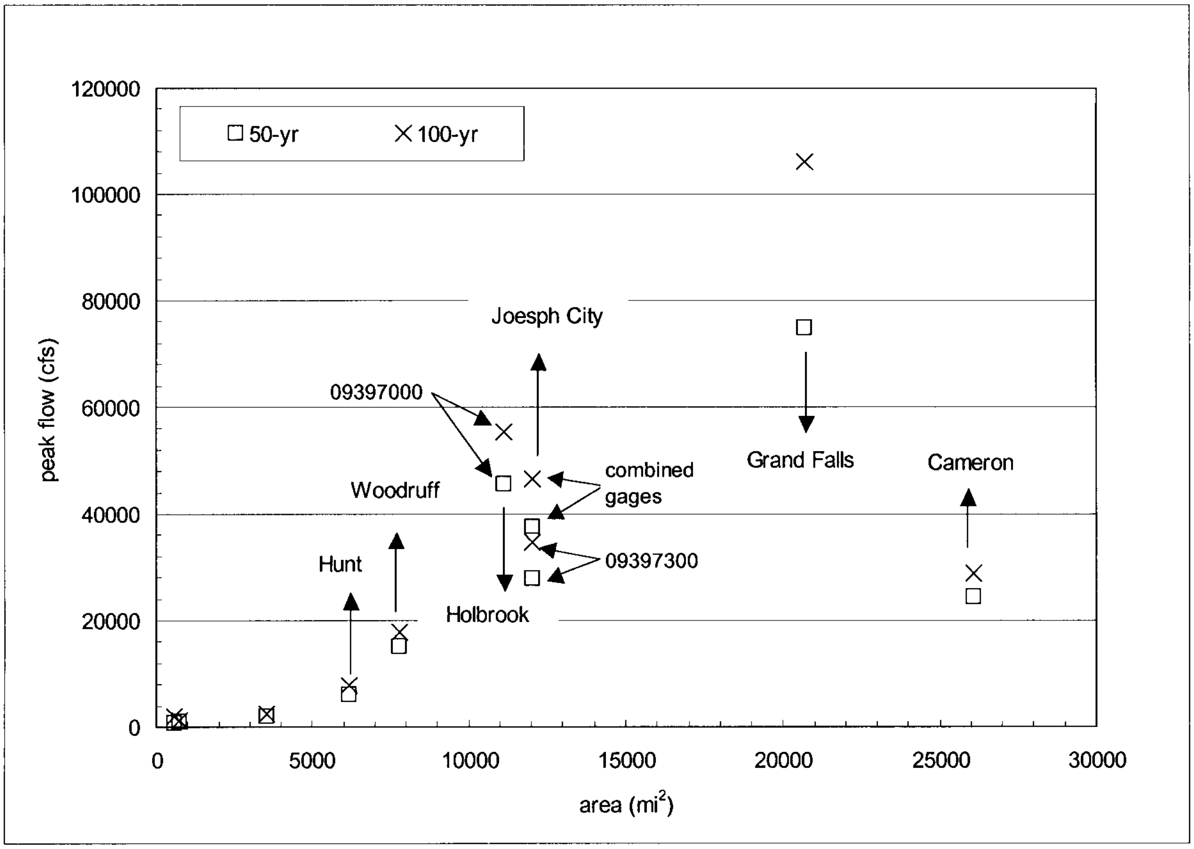


Figure 32. Peak flow as a function of drainage area for the Little Colorado River.

SEDIMENT TRANSPORT CAPACITY AND STABLE CHANNEL ANALYSIS

Prior to a complete sediment modeling effort, a separate analysis of the sediment transport capacity and incipient motion was performed. A computer program was written to calculate the sediment transport capacity and incipient motion criteria for the Little Colorado River. This program reads the hydraulic output from the HEC–RAS model and then computes the sediment transport capacity using Yang's (Yang, 1973) formula at each river cross section based on input bed material gradations. This is a static analysis and does not account for bed geometry changes. This program also computes the critical sediment diameter (the largest sediment size that is mobile) using Soulsby and Whitehous' 1997 fit to the Shield's diagram (Shields, 1936) at each cross section. The results from this program should be viewed as qualitative, showing relative indications from one location in the river to another. These results were used as a guide for comparison to the results from the sediment model GSTARS–2C. Should the GSTARS–2C results have shown drastically different results from the capacity analysis, further investigation would have been required. The results from the GSTARS–2C model agree with the capacity analysis although some of the peaks for deposition are less in the more robust GSTARS–2C model, discussed later in this report.

Figure 33 shows incipient motion results from this program. The results establish that all bed sediment is mobile at almost all locations in the reach at discharges greater than 10 ft^3/s (considered the minimum significant discharge for this study). The incipient motion model results show that at 10 ft^3/s the critical diameter, d_C (the critical diameter is the diameter of bed material that is just moved by the discharge) is roughly 0.7 to 1.1 mm. Figure 34 shows an analysis of the bed material in the Little Colorado River. The analysis shows that the d_{84} (the diameter that 84% of the particles are finer) in the river channel does not exceed 0.5 mm. That indicates that the bed is probably mobile at all significant discharges.

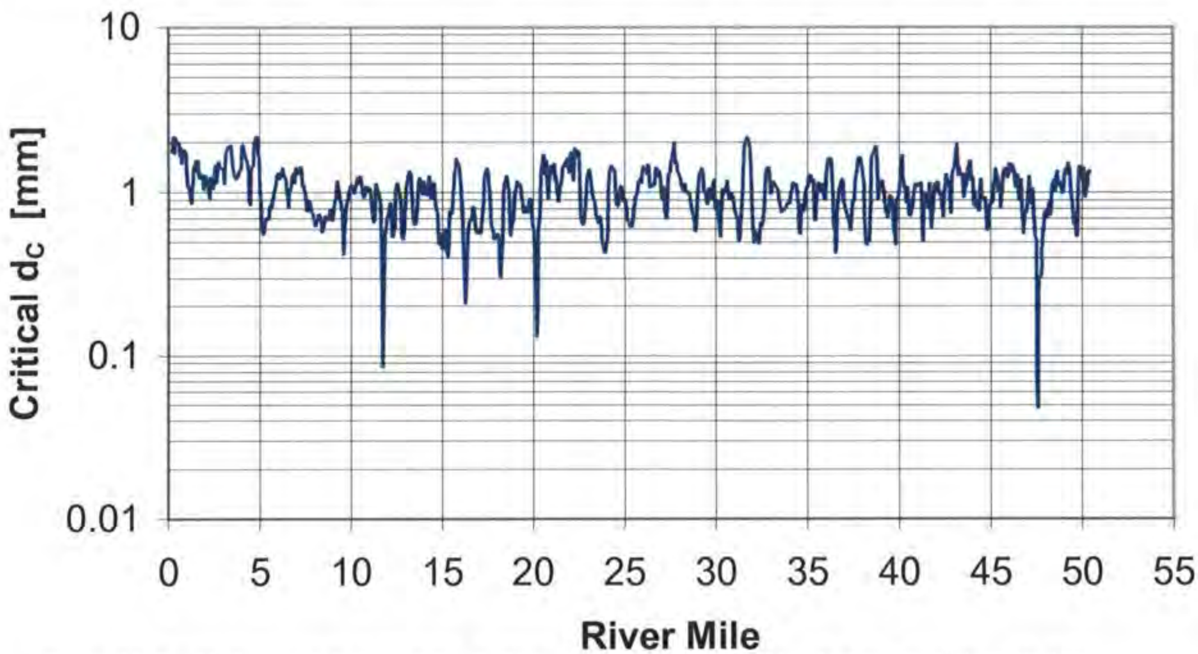


Figure 33. Graph showing critical diameter, d_C for a discharge of 10 ft^3/s. Note that nearly all locations have sediment sizes that will be mobile at minimal discharge.

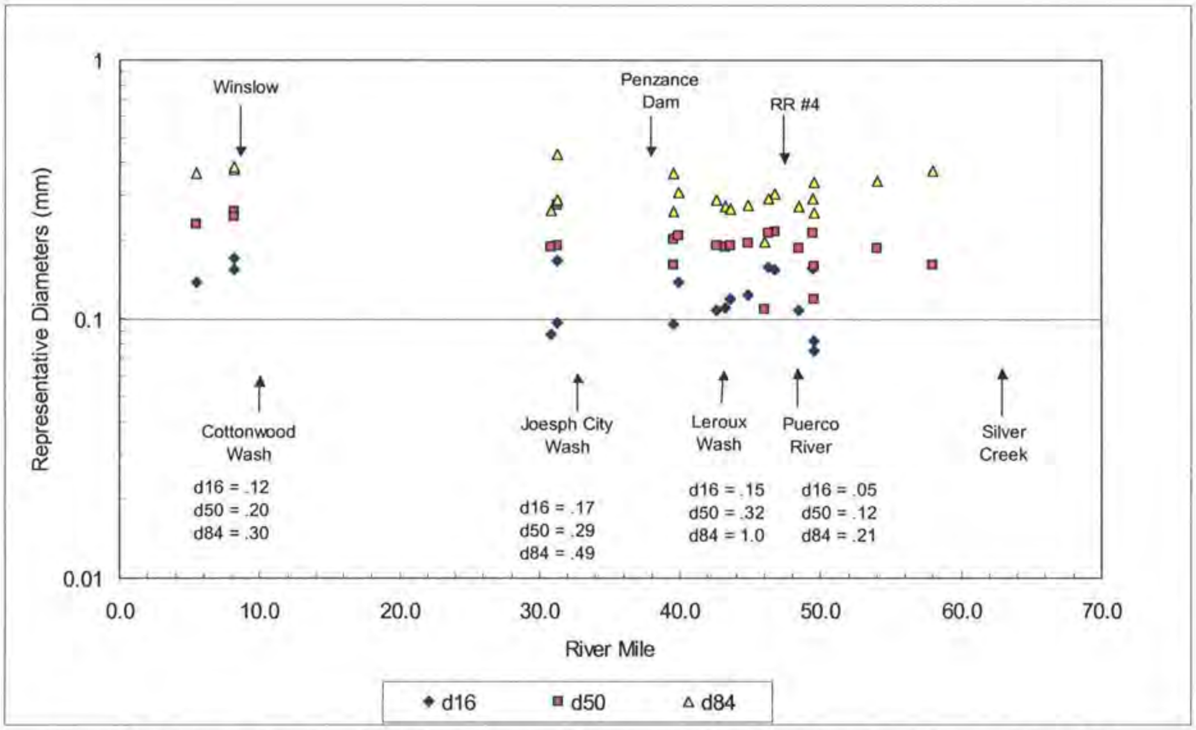


Figure 34. Sediment sizes throughout the study reach. Note that the d_{50} for most locations is between 0.2 and 0.3 mm and the d_{84} is not larger than 0.5 mm. Data taken from Appendix C.

Although the pattern in the Holbrook–Winslow reach appears to be one of stability, bridges, levees and perhaps natural grade controls (such as bedrock) in the Holbrook–Winslow reach are likely contributing to some localized accumulation of sediment. A few short sections of the river near hydraulic controls indicate a tendency for localized aggradation or channel change. The incipient motion model delineates these aggradation zones by determining the capacity of the discharge to carry sediment in suspension (a higher predicted concentration equates to a higher capacity for the river to carry sediment). Figure 35 shows the sediment carrying capacity, determined by the incipient motion model, for the 50–year flood in Holbrook (35,000 ft^3/s). The figure shows the key landmarks where meaningful deposition might occur. The reach between Holbrook and Joseph City shows sections where hydraulic controls create conditions of decreased capacity. Between Joseph City and Winslow, where the river lacks hydraulic controls, the river is stable. Hydraulic controls also influence the Winslow reach, indicating potential deposition. These results should not be viewed as quantitative values. Appendix E shows incipient motion model results for all other discharges.

In addition to the transport capacity model, a channel stability model (Greimann, 2003) determined the relative stability of the Little Colorado River in the Holbrook – Winslow reach. The model used in this study provides the same results as SAM however it is more flexible, allowing the user to determine which methods are used to determine Manning 'n', which sediment transport formula is used, and how the minimization is performed. The minimization options are slope or the velocity–slope product. The velocity–slope product was used for this evaluation. In the results presented (Table 9) the Brownlie (Brownlie, 1983) equation is used to determine Manning 'n' values and Yang's (Yang, 1973) sediment transport equation is used to determine width, depth, slope and concentration. The stability model outputs width, depth, slope and predicted Manning 'n' values for a stable channel of alluvial material. The channel is assumed trapezoidal in this simulation and a composite roughness is used for the channel and sidewall. For this reason, the calculated Manning 'n' value is slightly higher than that determined for the main channel in the hydraulic model, the actual surveyed cross–sectional shape and area.

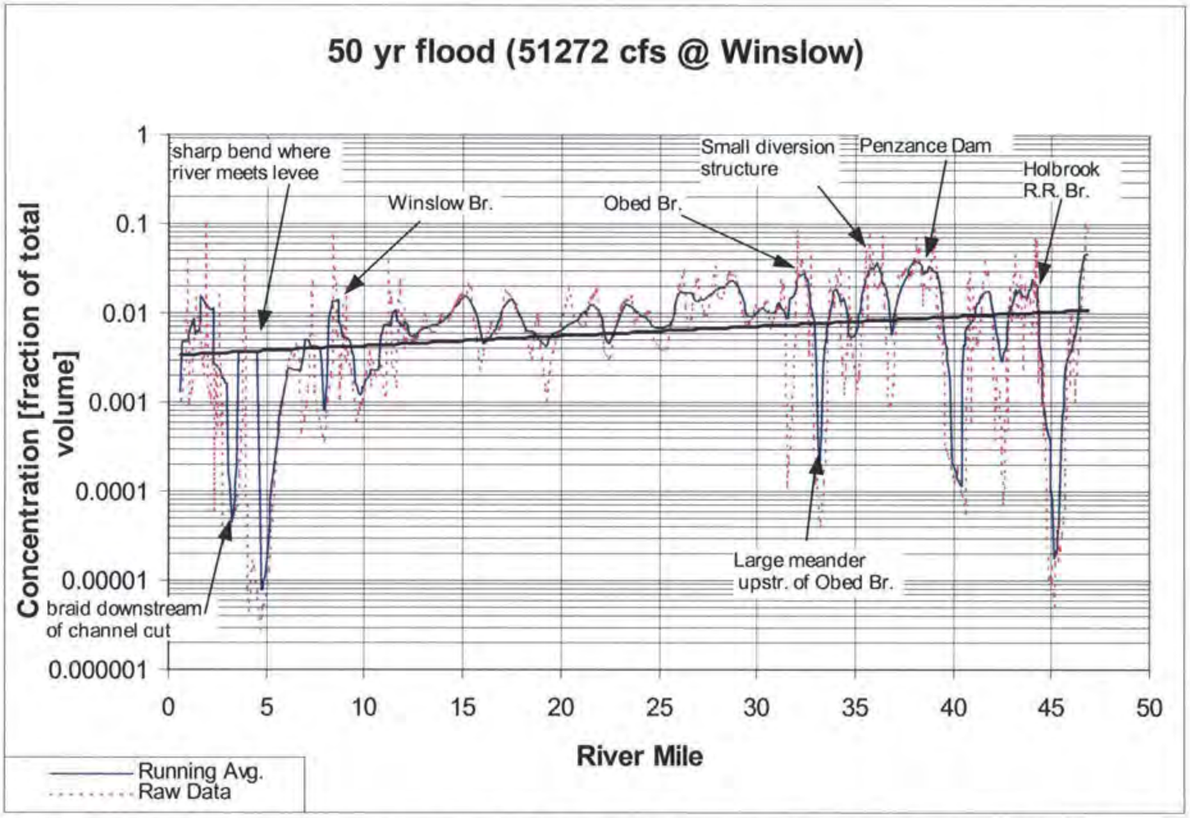


Figure 35. Predicted sediment carrying capacity for the 50 yr. flood (51,272 ft^3/s at Winslow). The solid blue line represents a running average of roughly 1 mile (10 data points each roughly 500 feet apart) and the dashed pink line is the raw data. The solid black line is an exponential regression of the data showing the overall decrease in capacity in the downstream direction. This line can be viewed as an indicator of a stable channel, with values above the line indicating higher sediment carrying capacity and values below the line indicating lower sediment carrying capacity. These are qualitative results.

Table 9. Stable channel results, flow rate is 5,000 ft^3/s.

Run No.	Conc. (mg/l)	Manning 'n'	Bot. Width (ft)	Top Width (ft)	Depth (ft)	Slope (ft/ft)	VS Min. (ft/s)
1	1,000	0.031	306	314	4.2	0.0010	0.00363
2	1,500	0.031	344	351	3.6	0.0012	0.00494
3	2,000	0.030	403	409	3.0	0.0015	0.00617
4	2,500	0.029	472	477	2.6	0.0018	0.00735
5	3,000	0.029	598	603	2.1	0.0022	0.00849

The stability of a river is governed by its ability to transport the entire incoming sediment load. If it is able to transport more than what enters the reach, then degradation will occur. If it is unable to transport the amount entering the reach, then aggradation will occur. The results in Table 10 indicate the computed stable channel geometries for various concentrations of suspended sediment. The flow rate input to this model was 5,000 ft^3/s, considered to be the channel forming flow for this reach of the Little Colorado River. Assuming a suspended sediment concentration of 1,500 mg/l (excluding wash load), the results indicate that the stable main channel is roughly 350 feet wide and 3.6 feet deep with a slope of 0.0012. The Little Colorado River is well represented by this geometry, indicating that the river is currently in a degraded, but stable condition. The average channel geometries for selected reaches of the Little Colorado River are shown in Table 10. These findings support the results of both the incipient motion model previously discussed and the sediment model, discussed in the following section. Note that in the reaches without man–made constrictions the widths are greater, indicative of the natural and predicted channel geometry. The vegetation in the Winslow reach and the structures in Holbrook reach inhibit the stable channel analysis.

Table 10. Average main channel width, hydraulic depth and slope for selected reaches of the Little Colorado River at 5,000 ft^3/s.

Puerco R. to Hlbrk.			Holbrook to Penzance			Obed Br. to Winslow			Winslow to End		
Top Width	Hyd. Depth	Slope	Top Width	Hyd. Depth	Slope	Top Width	Hyd. Depth	Slope	Top Width	Hyd. Depth	Slope
246.8'	4.1'	0.0012	136.3'	5.3'	0.0011	312.2'	3.8'	0.0010	160.2'	5.9'	0.0007

GSTARS–2C SEDIMENT MODEL

The dynamic sediment transport model chosen for evaluating sediment conditions in the Little Colorado River is GSTARS–2C. This model is capable of solving complex river engineering problems with limited data and resources. GSTARS–2C utilizes the energy equation to compute backwater calculations. This model also incorporates the stream tube concept, allowing for a transverse variation in sediment and flow parameters. There are 12 sediment transport equations available, allowing the user to adapt the model to a wide variety of river and bed material situations.

Flow rate and sediment concentrations are required input for upstream boundary conditions in GSTARS–2C. The downstream boundary condition is a rating curve table, with values taken from the hydraulic model. Additional input is stream geometry (including structures), channel and flood plain roughness and bed sediment composition. GSTARS–2C output consists of new thalweg and water surface elevations, bed sediment composition, cross section information including width and depth, volume of sediment aggradation or degradation for each cross section, sediment concentration and the porosity of the bed. Unlike the hydraulic, incipient motion, and transport capacity models, the GSTARS–2C model updates dynamic conditions over time and uses input from a hydrograph that varies with time step.

The incoming suspended sediment load was determined using Yang's 1973 sediment transport equation to create a sediment rating curve. GSTARS–2C uses this rating curve to determine the incoming sediment concentrations at various flow rates. Yang's 1973 equation was also used to determine sediment loads throughout the reach. The rating curve used to determine sediment input to the GSTARS–2C model does not favor a dominant flow coming from the Puerco River or the main stem of the Little Colorado River. The rating curve was determined using the bed material downstream of the Puerco River confluence, incorporating sediment sizes brought in by both systems. Should one river have a dominating effect over the other, sedimentation in the Little Colorado River from Holbrook to Winslow could be very different based on sediment availability in the two systems (See Table 5).

Because incoming sediment and flow data was not available for the tributaries to the Little Colorado River, they were not included in the model. A single steady flow was used throughout the entire reach for each time step, with flow rate varying with each time step. Each tributary input could have been determined similar to the upstream boundary conditions, however due to the uncertainties inherent in calculating these data, a greater uncertainty would have been placed upon the entire model without necessarily improving the results.

The stream geometry determined from the aerial photographs and imported to the hydraulic model was also imported into GSTARS–2C. Minor changes to the geometry were necessary in order to optimize the geometry for sediment transport calculations. Some cross sections were eliminated and other geometric information was adjusted such as channel length in order to improve the stability of the model. Although all bridges in the reach (with the exception of Obed Bridge) were included in the hydraulic model, only the Holbrook railroad, the Winslow railroad and Route 66 bridges were included in the sediment model. It was determined that these bridges had a potentially significant influence on the river system based on information obtained from the hydraulic modeling results. The bridge geometry used in the sediment model was the same as that used in the hydraulic model.

Main channel roughness coefficients for the sediment model were chosen to have a Manning 'n' of 0.025 throughout the reach, similar to the hydraulic model. Because using ineffective flows to represent flood plain roughness does not provide the same benefit in the sediment model as it does in the hydraulic model, the vegetated flood plains in the sediment model were represented with a Manning 'n' of 0.15. If ineffective flows had been used in the sediment model the results would have indicated artificial floodplain deposition.

The time step used in the GSTARS–2C model varies with flow rate. A time step of 0.5 hours was used until a higher flow was encountered. In that case the time step decreases incrementally to 0.1 hours for the largest flows (greater than 15,000 ft^3/s).

MODELING RESULTS

When evaluating the results of this 1–D sediment model it is important to consider the accuracy of the values presented. The state of the science of modeling sediment transport has not yet advanced to the level required for predicting bed changes to within a foot or less over a reach of this length (45 miles). The information taken from the data presented should be indicative of a tendency toward aggradation or degradation and modeled values, not absolute certainties regarding exact aggradation or degradation amounts.

It was not possible to calibrate this sediment model due to a lack of historical data. The cross sections from the 1995 Sabol aerial survey are not closely spaced and would not provide an accurate representation of the geometry. Another important factor is that there was no significant rainfall in the short period between the 1995 survey and the 2000 survey. The Joseph City gage (USGS station No. 09397300) indicates no flow greater than 3,000 ft^3/s during that time period so it can be safely assumed that very little channel change occurred between the surveys.

Data from several runs of the sediment model GSTARS 2–C will be presented. The scenarios modeled include various input hydrology and channel modifications. All of the hydrologic scenarios were run starting with the original geometry. The geometric scenarios are presented and discussed following the hydrologic scenarios.

HYDROLOGIC SCENARIOS

Hydraulic input to the sediment model used historical gage data from the Holbrook gage (USGS station No. 09397000). A basic assumption made by using the 25 years of available data is that the future hydrology will match past hydrology, specifically, flows that occurred from 1949 – 1973. A 10–year base hydrograph (Appendix F, Figure F1) served as the basic input and was used for the various geometric scenarios, discussed later in this section. The 10 years chosen for the hydrograph consist of the five wettest and five driest years from the 25–year record, determined by total annual volume. The wettest years were 1952, '55, '67, 68 and '73. The driest years were 1950, '51, '53, '56 and '60. The hydrograph was then put together with wet and dry years placed in chronological order to simulate a normal 10–year period. Partial peak information was used to enhance the daily values used in each of the hydrographs. When partial peak information was available for a specific date, it was used to simulate a 24–hour hydrograph, maintaining a consistent volume throughout the 24–hour period. Incorporating the peak information better simulates the natural flow conditions in the river by increasing the flow rate to match the peaks for short durations, rather than using a daily average for a 24–hour period. Because it was not possible to calibrate the sediment model with previous geometry, projecting too far into the future produces less accurate results. A 10–year period is adequate to reveal reaches or locations of aggradation or degradation. For these reasons the 10–year base hydrograph was chosen as the primary model input. There were a total of five separate hydrologic scenarios run with the original geometry. These are discussed below.

A hydrograph was created from the 10–year base hydrograph with a synthesized 50–year flood incorporated (35,000 ft^3/s in Holbrook) in the last year of the simulation. The hydrograph is shown in Appendix F, Figure F2.

A 10–year dry hydrograph was created to include the five driest years on record (1950, '51, '53, '56 and '60) at the Holbrook Gage and then repeats them. This scenario was run to answer the question whether or not drier periods create more aggradation in the reach. The hydrograph used in this scenario can be seen in Appendix F, Figure F3.

Another hydrologic scenario includes the 25 years of record available at the Holbrook gage repeated to make a 50–year simulation. The hydrograph is shown in Appendix F, Figure F4. This scenario was run primarily due to the predicted aggradation in the results of the 10–yr. base hydrograph occurring upstream of Holbrook to the confluence with the Puerco River. The data was compared to the findings of the United States Army Corps of Engineers 1991 General Design Memorandum (GDM) for the Holbrook Levee.

The final hydrologic scenario is the 60,000 ft^3/s flood of record in Holbrook. This 100–year event was scaled down from the Standard Project Flood peak of 107,000 ft^3/s published in the United States Army Corps of Engineers (USACE, 1991) 1991 GDM for the Holbrook Levee. This hydrograph is shown in Appendix F, Figure F5. Data from this scenario was also compared to the findings of the previously mentioned United States Army Corps of Engineers report.

10–YEAR BASE HYDROGRAPH

The first data set presented shows the results of the 10–year base hydrograph modeled using the original geometry. These results show that the Little Colorado River between Holbrook and Winslow is stable and not significantly aggrading or degrading. The reach between the Puerco River confluence and the Holbrook Railroad Bridge indicates between 1 and 2 feet of aggradation.

There are several ways of demonstrating sedimentation in the Holbrook–Winslow reach. The first set of results compares grain size distributions for the initial and final time steps. A comparison of the d_{50} is a good representation of the grain size without having to display the entire spectrum of grain sizes at each cross section. Figure 36 shows that the d_{50} does not show a significant increase or decrease over time, an indicator of channel stability. The short reaches that do show a reduction in grain size are mostly regions of low velocity. A reduction in grain size is an indication of sediment deposition. This occurs near structures in the river, specifically at the Holbrook railroad bridge, near the Winslow bridges, downstream of Bushman acres and in the reach between the Puerco River confluence and Holbrook.

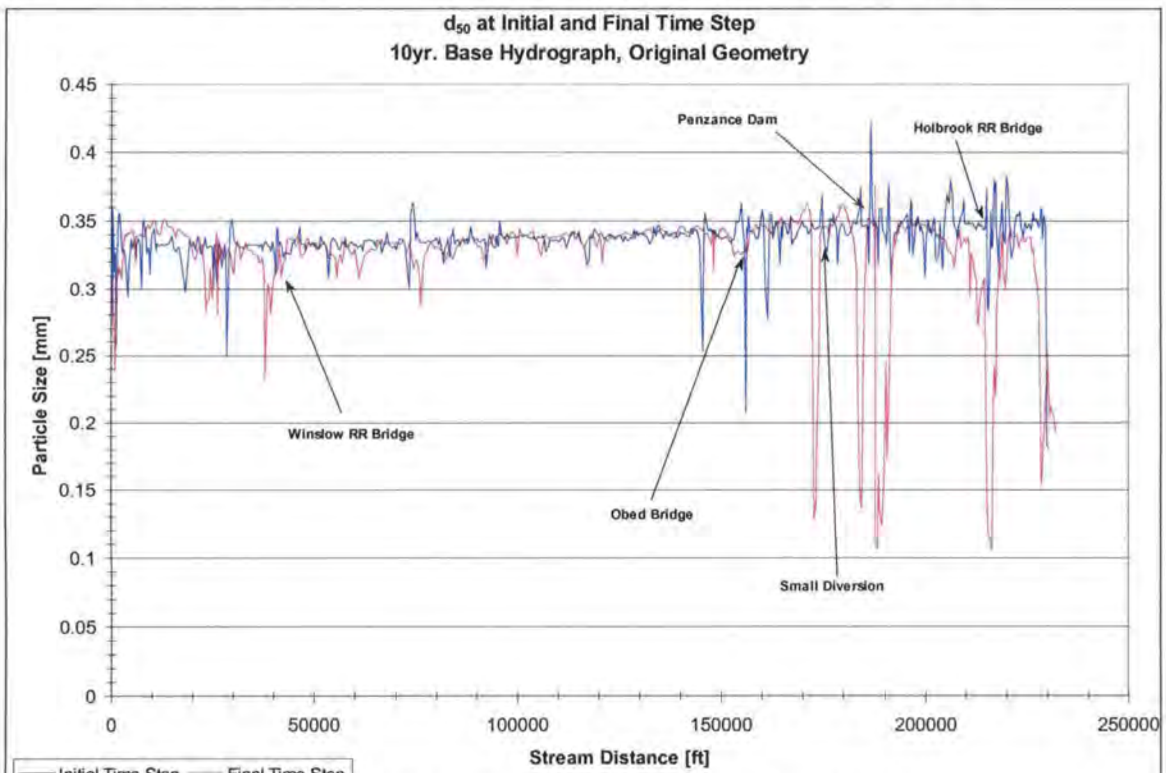


Figure 36. Initial and final d_{50} for the entire reach using the 10–year base hydrograph.

Another means of demonstrating aggradation and degradation is to show the extent of vertical change of the thalweg. In Figure 37 thalweg aggradation/degradation is shown for the entire reach. Throughout the undisturbed portions of the reach the vertical change is negligible (less than roughly 1 feet). The reaches with existing structures show some evidence of local aggradation or degradation, matching the decrease of particle size in Figure 36. The local aggradation or degradation at these structures is related to local hydraulic conditions created by the structure. It is likely that a large flow event will remove the accumulated sediment in these areas. Although the model indicates significant degradation near Penzance Dam and the small diversion, severe degradation is not anticipated. The supercritical flows that exist over these structures could not be properly duplicated in the model. This results in artificial degradation in these areas that is present in all charts for these two locations.

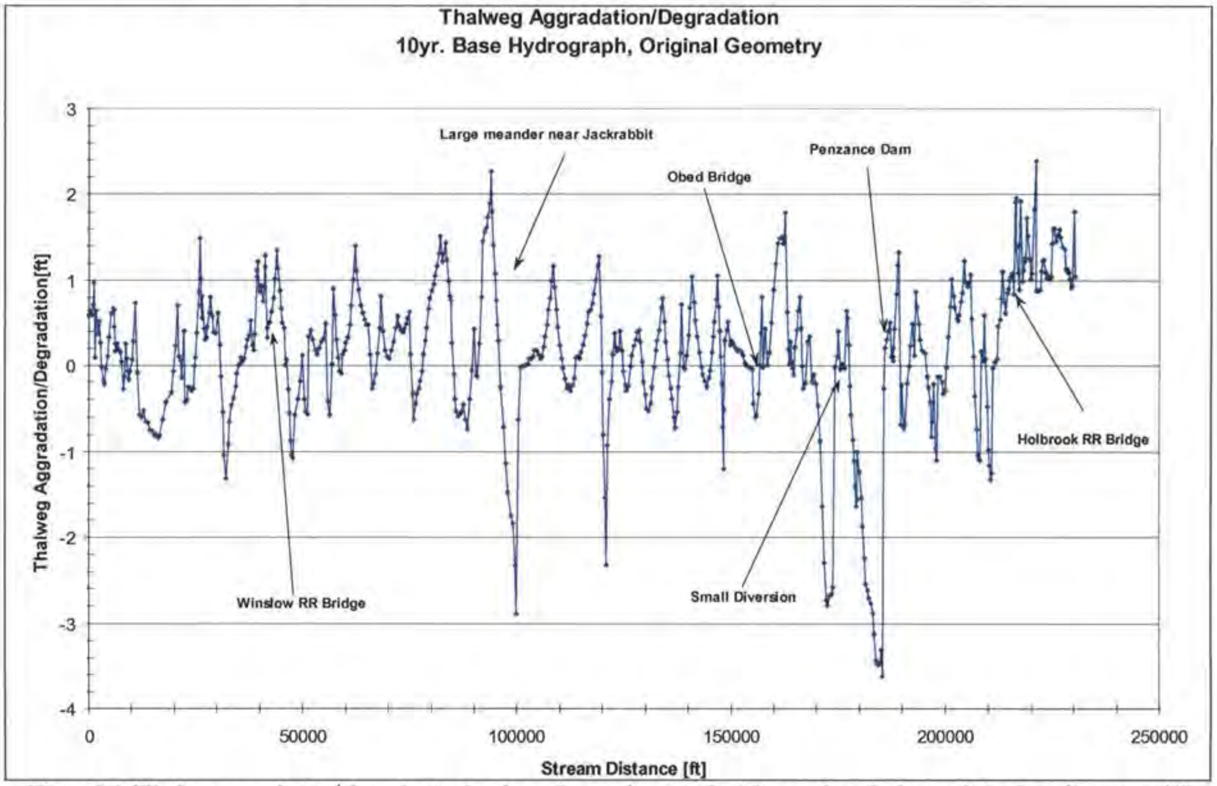


Figure 37. Thalweg aggradation/degradation for the entire reach using the 10–year base hydrograph in the sediment model.

An exception to the aggradation and degradation trends only being near in–stream structures is the large meander in the Jackrabbit area. This meander is just upstream of Chevelon Creek. Although the model indicates considerable degradation and aggradation at this location the proper interpretation here is that some plan form change to this portion of the river is more likely to occur than the indicated level of thalweg change. A plan form change at this location is of little concern because the extended river channel flows between bedrock and the railroad and has a flood plain wide enough to meander across.

Figure 38 shows the existing and projected thalweg profiles of the entire reach from the confluence of the Puerco River to downstream of Winslow. Appendix G contains plots of shorter reaches at a higher resolution for comparison of the profiles. The profiles show that the thalweg does not experience significant aggradation or degradation. One exception is the reach from the Puerco River to Holbrook. This reach shows 1 to 2 feet of aggradation over the 10–year period. The railroad bridge in Holbrook and the large meander upstream of the Route 77 bridge are the apparent cause of this model result. These features seem to be creating a hydraulic control that significantly influences the sediment transport capacity in this reach. This process occurs in two steps, between years 0–6 and 7–10. Temporal changes to this reach are graphed in Appendix H. In the first step (0 – 6 years) aggradation begins at the railroad

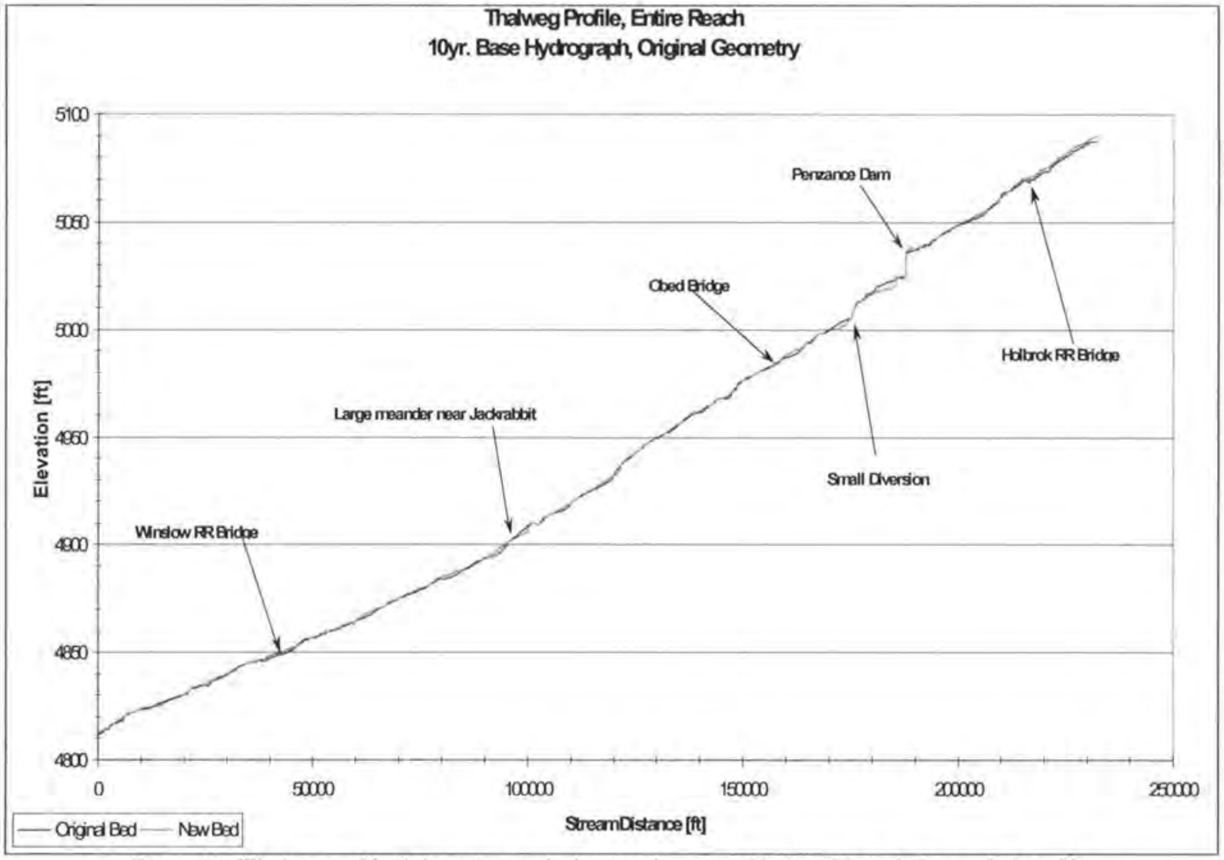


Figure 38. Thalweg profile if the entire reach showing the original bed profile and the new bed profile.

bridge and proceeds upstream to the large meander upstream of Holbrook. In the 8th year, aggradation begins at the meander upstream of Holbrook and progresses to the confluence of the Puerco River after 10 years. This aggradation trend will be examined again using the results of the 50–year simulation.

Knowing the volume of sediment deposited in each cross section is of importance because thalweg aggradation or degradation may not always provide the full scope of what is occurring in each cross section. Figure 39 shows the projected volume of sediment deposited at each cross section in the Holbrook and Winslow reaches. These values are cumulative spatially and temporally. The model indicates deposits of roughly 3.5×10^5 yd^3 of suspended sediment over the modeled 10–year period.

The conclusion from the 10–year base hydrograph data set is that the Little Colorado River is not undergoing widespread aggradation. The aggradation that is occurring is limited to short sections of the river near hydraulic controls. The reach from the Puerco River confluence to the railroad bridge in Holbrook appears to be undergoing some aggradation, as much as 1 to 2 feet.

10–YEAR HYDROGRAPH WITH 50–YEAR FLOOD

The results from the 10–year hydrograph with a 50–year flood event show little difference in thalweg changes from the 10–year base hydrograph. The amount of thalweg change can be seen in Figure 40, where it is plotted against the results from the 10–year base hydrograph. The most significant change is from the confluence of the Puerco River to Holbrook. The model indicates roughly 1 – 3 feet of aggradation in this reach, with the portion upstream of the large meander aggrading the most. This appears to be the only reach aggrading to any extent. All thalweg profiles for the 10–year hydrograph with a 50–year flood are contained in Appendix I. The sediment deposits resulting from the 10–year hydrograph with the 50–year event increase from roughly 3.5×10^5 yd^3 to 4.0×10^5 yd^3. Figure 41 shows the sediment volumes for the 10–year hydrograph with a 50–year flood.

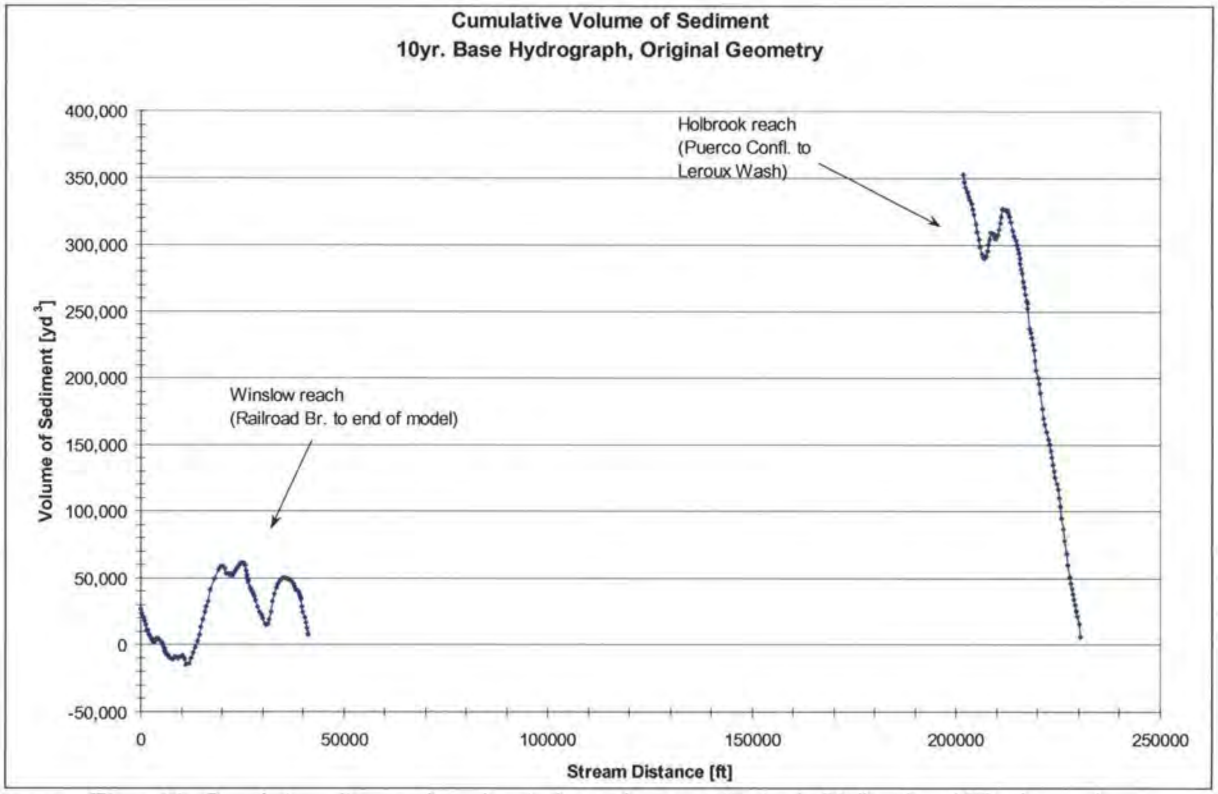


Figure 39. Cumulative sediment volume deposited at each cross section in the Holbrook and Winslow reaches.

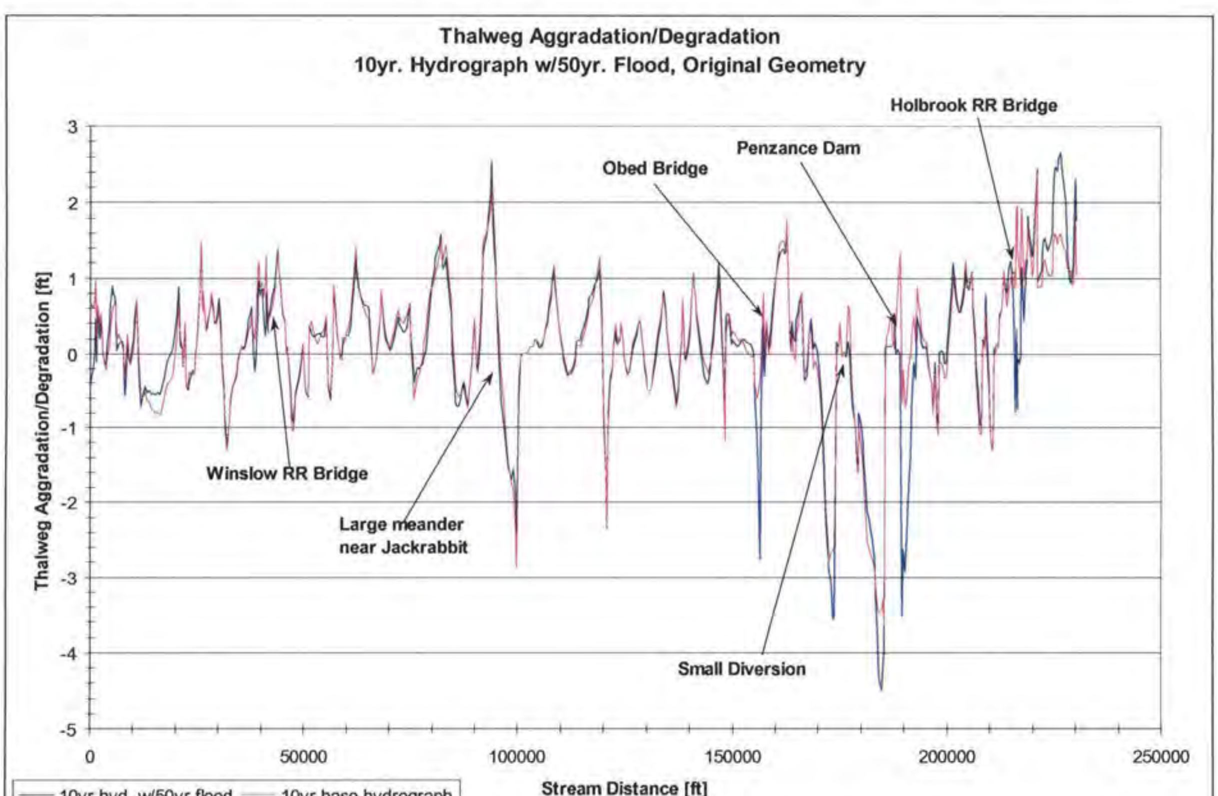


Figure 40. Thalweg aggradation/degradation for the 10–year hydrograph with a 50–year flood event. The results from the 10–year base hydrograph are also shown for comparison.

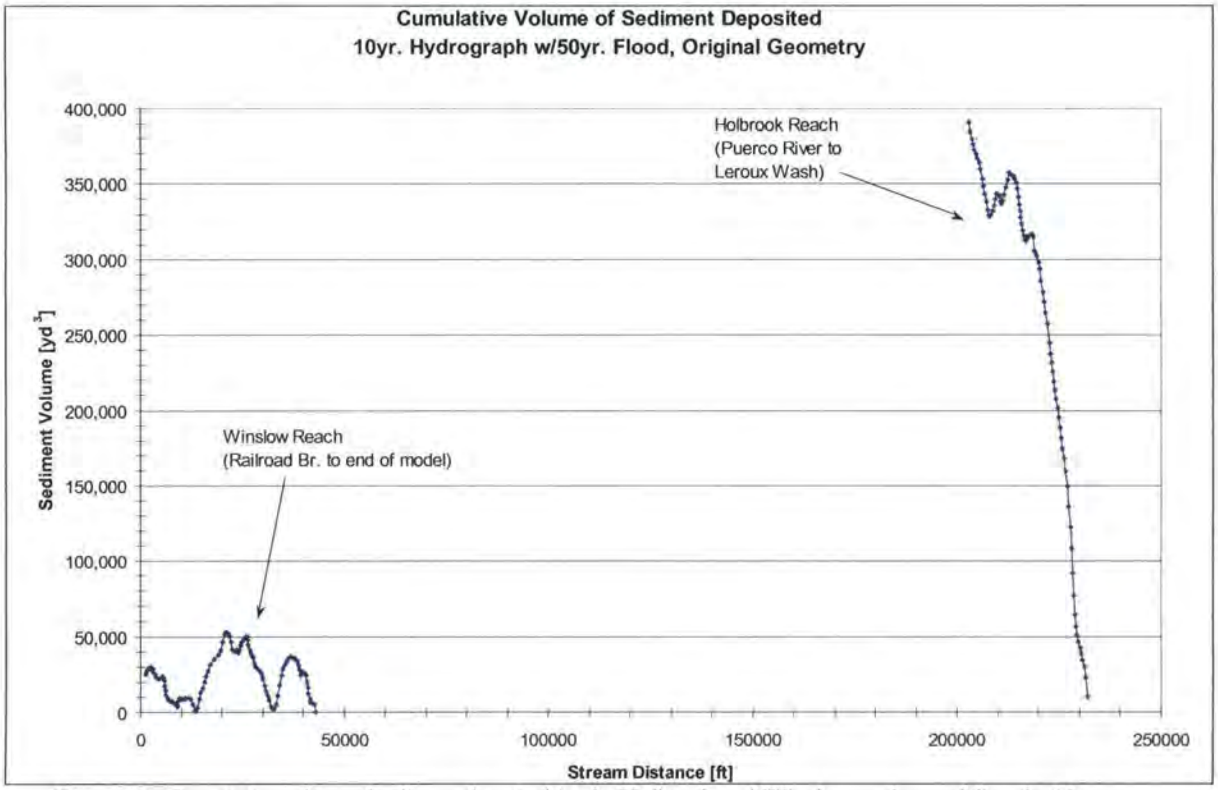


Figure 41. Cumulative volume of sediment deposited in the Holbrook and Winslow reaches modeling the 10–year hydrograph with a 50–year flood event.

10–YEAR DRY HYDROGRAPH

The results using the 10–year dry hydrograph show little aggradation in any reach. Again, the only reach that shows any consistent aggradation is from the Holbrook railroad bridge to the large meander upstream. The maximum thalweg aggradation in this reach is less than two feet and does not extend upstream of the large meander as it does in the other hydrographs. A plot of the thalweg aggradation/degradation is shown in Figure 42. This figure combines the results of the 10–year base hydrograph with the 10–year dry hydrograph, to illustrate the differences. The volume of sediment deposited during this hydrograph is roughly a third less than the 10–year base hydrograph. Roughly $1.0x10^5$ yd^3 are deposited during the 10–year dry hydrograph in Holbrook (Figure 43). Thalweg profiles can be seen in Appendix J.

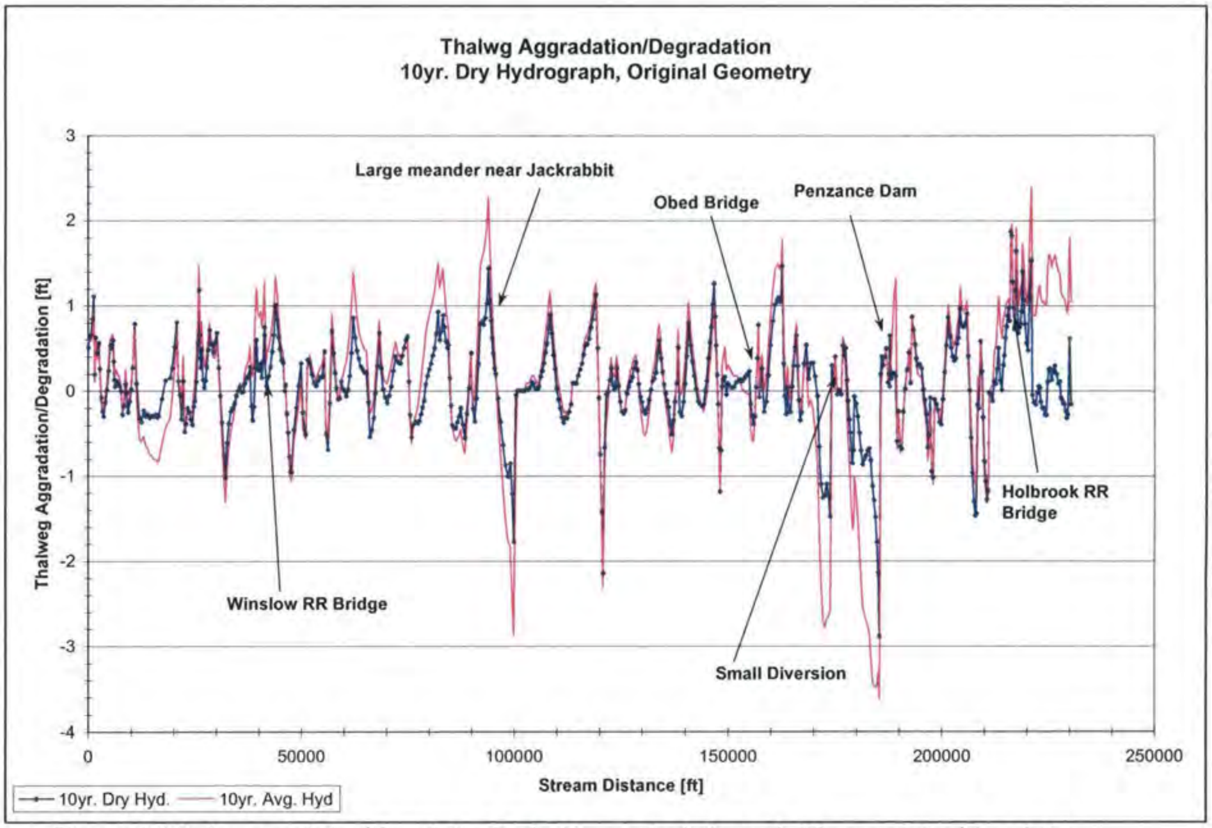


Figure 42. Thalweg aggradation/degradation for the 10–year dry hydrograph. The aggradation/degradation resulting from the 10–year base hydrograph is also plotted to allow for comparison. Degradation indicated near Penzance Dam and the small diversion is not real.

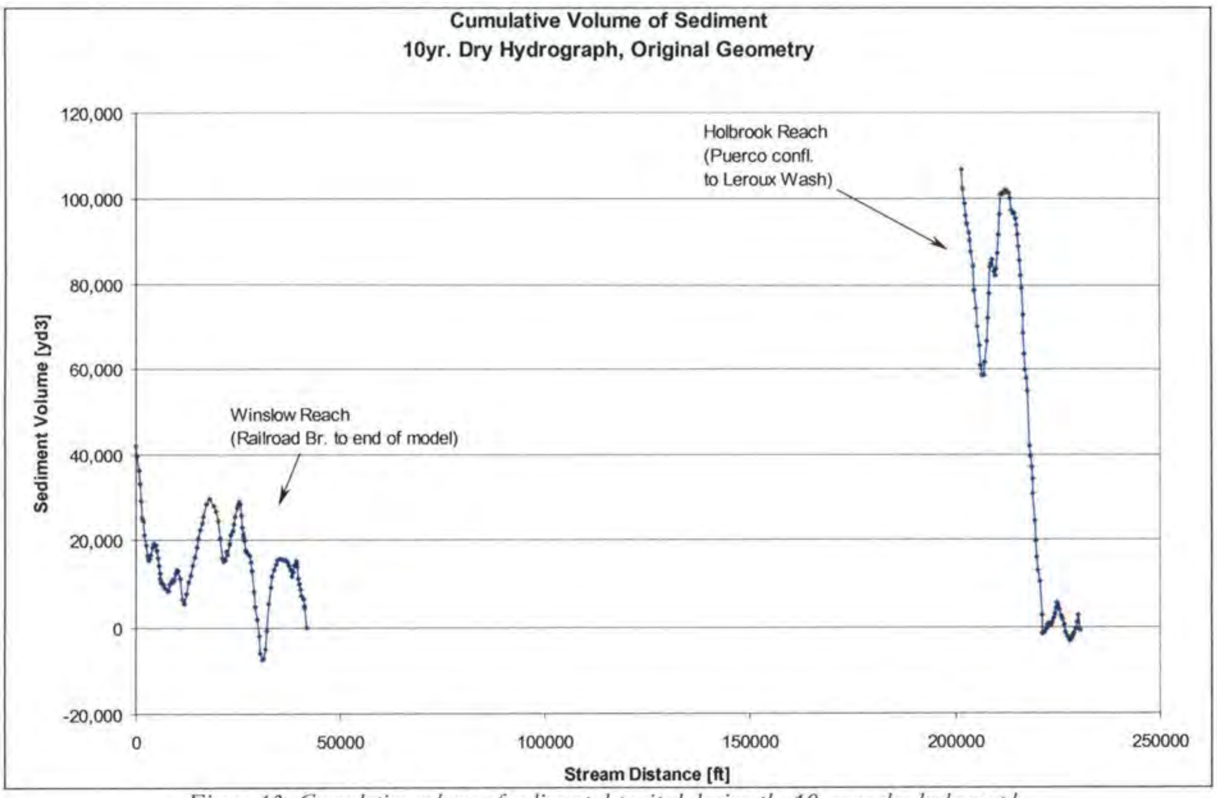


Figure 43. Cumulative volume of sediment deposited during the 10–year dry hydrograph.

50–YEAR HYDROGRAPH

A 50–year hydrograph was not used as the primary hydrograph due to the uncertainties associated with such a long projection using an uncalibrated model. Hydrologic uncertainties combined with plan form changes over 50 years create less reliable projections than are obtained using a 10–year period. The results from the 50–year hydrograph indicate little additional aggradation when compared to the results using the 10–year base hydrograph, with the exception of the reach from the Puerco confluence to the Holbrook railroad bridge. The aggradation in this reach peaks at just over six feet. The amount of thalweg aggradation and degradation is shown in Figure 44. As stated previously, the degradation indicated by the model near the small diversion dam and Penzance Dam is artificial. The greatest amount of aggradation in the Holbrook reach containing the levee is 4.3 feet. From the upstream end of the Holbrook levee, the amount of thalweg aggradation decreases linearly to 2.1 feet at the Holbrook railroad bridge. These values strongly agree with the findings of the sediment study performed by the United States Army Corps of Engineers and reported in the 1991 GDM for the Holbrook levee. The 1991 GDM predicts 4.5 feet of aggradation from the Route 77 bridge to the upstream end of the levee and 2.3 feet between the Route 77 bridge and the Holbrook railroad bridge. Where our results differ is downstream of the Holbrook railroad bridge to Leroux Wash. The 1991 United States Army Corps of Engineers GDM predicts 4.1 feet of aggradation in this reach and this report shows, on average, less than 1.0 feet of aggradation with no peak greater than 1.5 feet away from the influence of the railroad bridge. The thalweg profile for the Holbrook reach is shown in Figure 45. These results are important because they confirm the findings of the sediment study performed by the United States Army Corps of Engineers in 1991 that were used to design the height of the levee. Appendix K contains thalweg plots for other reaches as well as volume and aggradation/degradation amounts.

The Holbrook railroad bridge likely contributes to the aggradation in the upstream portion of the modeled reach. This bridge provides very little clearance below the low chord and is an obstruction to the flow, creating a backwater effect and reducing the sediment carrying capacity. The channel in this location is also constricted between the north levee and the south levee near the Holbrook bridges. This also creates a backwater effect and reduces capacity in this reach. Removing the south levee and exposing the southern flood plain to flow will not likely make an improvement because the flood plain at this location is cut off by the approach to the railroad bridge. There are two culverts passing under the southern approach. However, these will provide minimal passage because they are likely to become blocked with debris during a high water event.

60,000 FT^3/S FLOOD

The 60,000 ft^3/s flood was run in GSTARS–2C as an individual event not associated with any other flows. This flood lasts roughly 76 hours and uses the original geometry. The results indicate that thalweg aggradation is minimal during the flood however scour at bridges may be significant. The changes to the thalweg elevations can be seen in Figure 46. The maximum thalweg aggradation indicated during this flood is 1.5 feet at a location roughly 8,300 feet upstream of the Route 77 bridge. The model indicates scour at all the bridge locations in the reach however a separate scour analysis would be required to obtain more accurate values. The Obed Bridge location scoured the most even though the bridge features were not modeled at this location. Scour occurs in the model because of the channel constriction at these locations, causing increased velocities. Thalweg profiles and volume plots are shown in Appendix L.

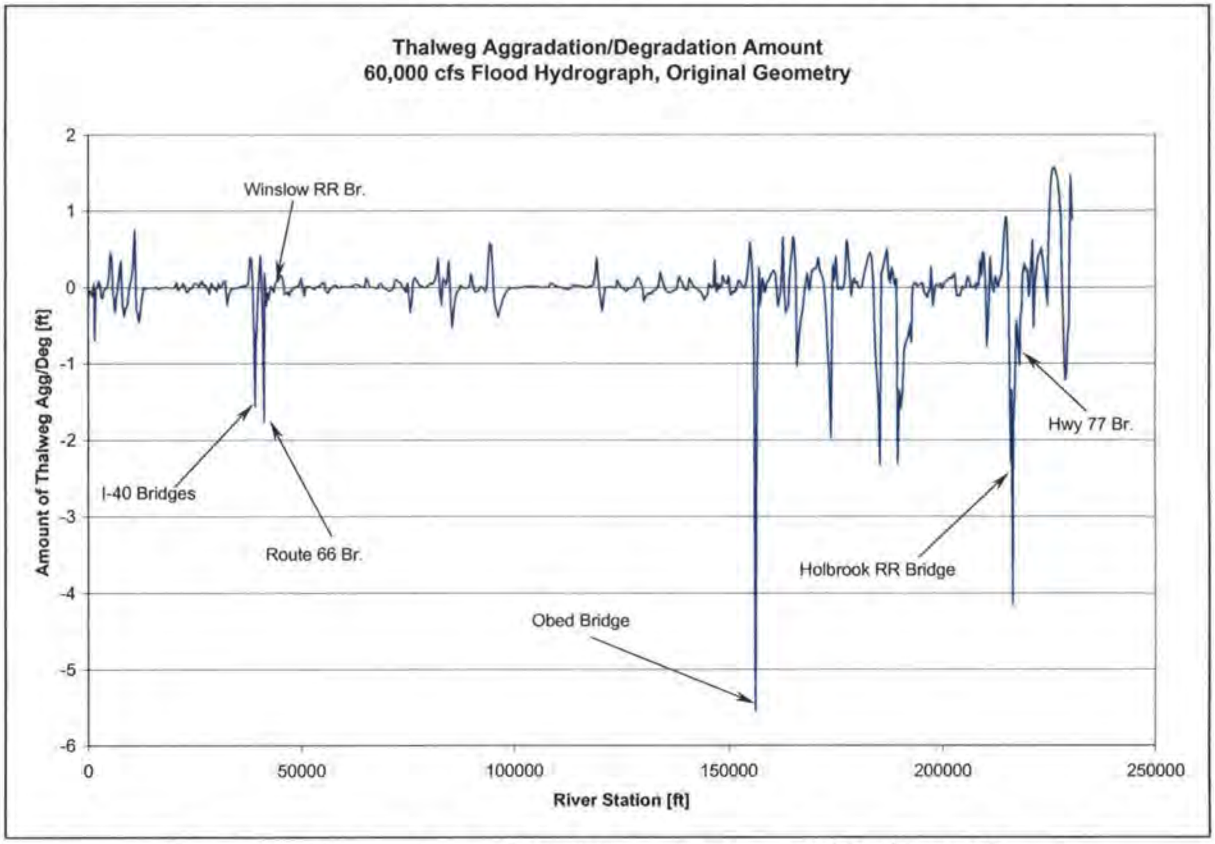


Figure 46. Amount of Thalweg aggradation and degradation resulting from a 60,000 ft^3/s flood. The scour indicated is not the result of a scour analysis.

It is important to mention the likelihood of aggradation occurring in the overbank areas during major events such as the 50–year or 100–year flood. Although indications may be that thalweg elevations change very little for the 60,000 ft^3/s event, it is likely that channel changes will occur, particularly in reaches where large meanders exist (e.g. near Jackrabbit and upstream of the Route 77 bridge). Meanders may become cut off or channel narrowing or widening might occur.

GEOMETRIC SCENARIOS

In addition to the hydrographic scenarios, various geometric scenarios were run with the GSTARS–2C model in order to predict the response of the river should the proposed actions be implemented. Not all proposed actions were evaluated. The actions that were not evaluated are 1.) vegetation removal and 2.) the removal or reconstruction of the Apache Railroad bridge in Holbrook. These are discussed in subsequent paragraphs. The proposed actions that were evaluated include 1.) setting the levee back near Bushman Acres in Winslow, 2.) Cutting a pilot channel to move the river away from the levee just downstream of Bushman Acres and 3.) Removing Penzance Dam. All of these scenarios were run using the 10–year base hydrograph and comparisons are made to the results using the original geometry with the 10–year base hydrograph. These are also discussed in detail in subsequent paragraphs. These scenarios were determined as part of this study and were not suggested by previous studies.

The model indicates an average of just under one foot of localized aggradation between the Winslow railroad bridge and the westbound I–40 bridge for the 10–year base hydrograph using the original geometry (this can be seen in Figure 37). Although this is not a significant amount of aggradation this is one of the reasons for modeling the levee set back and the channelization (scenarios 1 and 2 in the preceding paragraph). Another reason is to inform Navajo County of possible sedimentation issues should scenarios similar to these be implemented for other reasons. Neither scenario indicated any improved sedimentation effects near the bridges; therefore it not recommended that either scenario be implemented for the purpose of improving sediment transport. There may be a gain in water surface elevation if one or both of these scenarios are implemented however this is beyond the scope of this study. Additional aggradation following the implementation of these scenarios is not anticipated. The scenarios are explained in detail below.

VEGETATION REMOVAL

Vegetation removal near the Winslow levee was considered as a possible scenario however it was not evaluated as part of this report. The primary reason for not evaluating this scenario is because the removal of vegetation in the overbank areas will not likely improve conditions for sediment transport in the Winslow reach. The mechanism for aiding soil stability would be lost upon removal of Tamarisk and therefore make more sediment available for possible transport and subsequent deposition downstream. This could result in plan form changes in the Winslow reach. This process is not only unfavorable with respect to sediment deposition near Winslow but is also very difficult to model, as is the inevitable re-growth of Tamarisk in later years. Although GSTARS–2C is capable of using multiple stream tubes, sediment interaction between a channel and its flood plain requires a two–dimensional evaluation.

REMOVAL OF THE HOLBROOK RAILROAD BRIDGE

Although removing the Holbrook railroad bridge would eliminate the hydraulic control and likely prevent the anticipated aggradation upstream of the bridge, this scenario was not evaluated. Justification for the removal or significant modification of the bridge is difficult because the modeled aggradation in this reach was considered by the United States Army Corps of Engineers in the design of the Holbrook levee.

WINSLOW LEVEE SET BACK

The proposed levee realignment is shown in Figure 47. The proposed levee is roughly 6,000 feet long, replacing roughly 7,100 feet of the existing Winslow levee. The geometry in the 'levee set back' scenario was created in HEC–RAS by setting back the existing levee (matching existing crest elevations) the proper distance in order to simulate the wider flood plain. A constant flood plain elevation was assumed using the existing elevations between the channel and the existing levee. The roughness used in the newly created flood plain was 0.15, the same value used in the rest of the model for heavily vegetated areas. This value was chosen because the assumption must be made that the new floodplain would become overgrown with Tamarisk similar to the existing flood plain in this area. This geometry was run using the 10–year base hydrograph. The thalweg profile in the Winslow reach is shown in Figure 48. For comparison purposes, Figure 48 also shows the results from the original geometry using the same hydrograph. Figure 49 shows predicted thalweg changes for the levee set back geometry along with the results obtained with the original geometry using the same 10–year hydrograph. When the results of the levee set back are compared to the original geometry it becomes apparent that no degradation is induced at the Winslow bridges. Implementation of this scenario is not expected to provide any improved sedimentation at the Winslow bridges however there may be a benefit in water surface elevation during a high flow event. This would have to be analyzed separately.

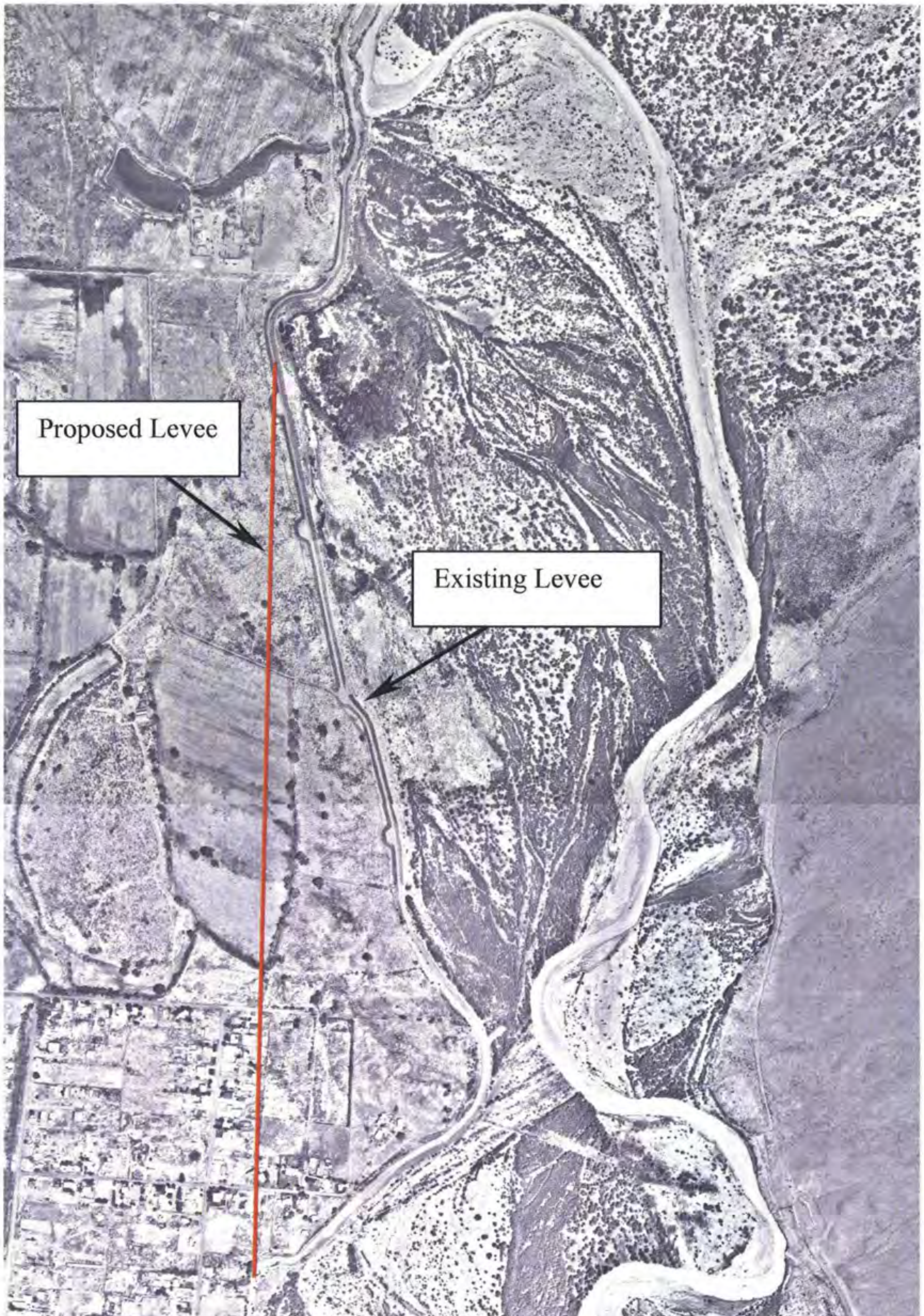


Figure 47. Proposed levee realignment (in red) for the 'levee set back' scenario. This is near Bushman Acres.

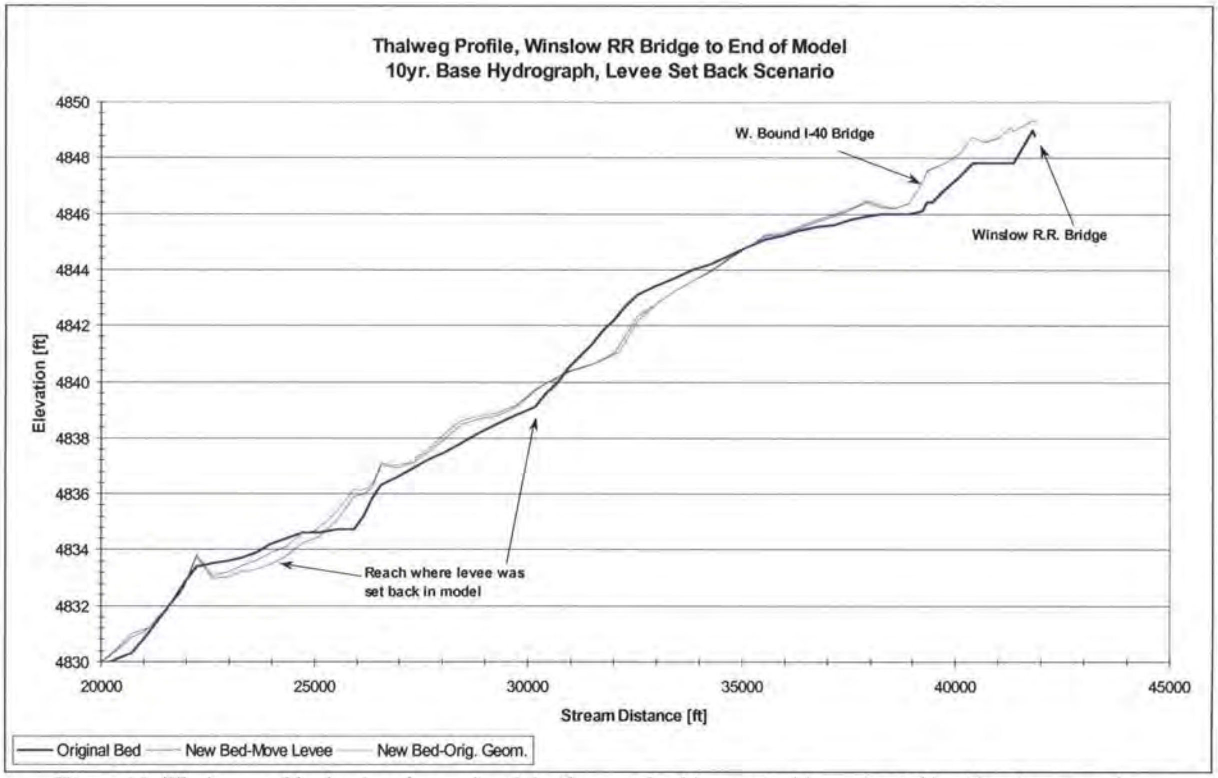


Figure 48. Thalweg profile showing the results of the 'levee set back' scenario (shown in pink). Also shown are the original bed profile (in blue) and the results of the original geometry (green), run with the same hydrograph.

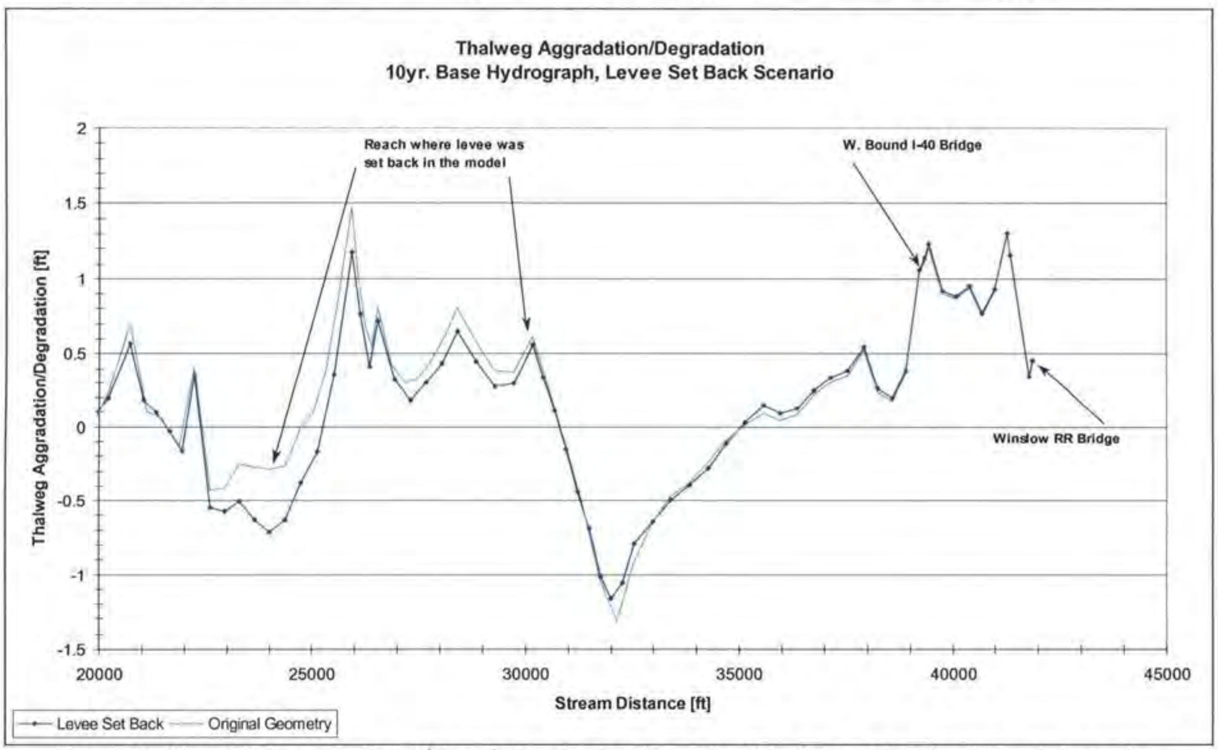


Figure 49. Plot of thalweg aggradation/degradation showing the results of the 'levee set back' option and the results using the original geometry. Both geometries were run using the 10-year avg. hydrograph.

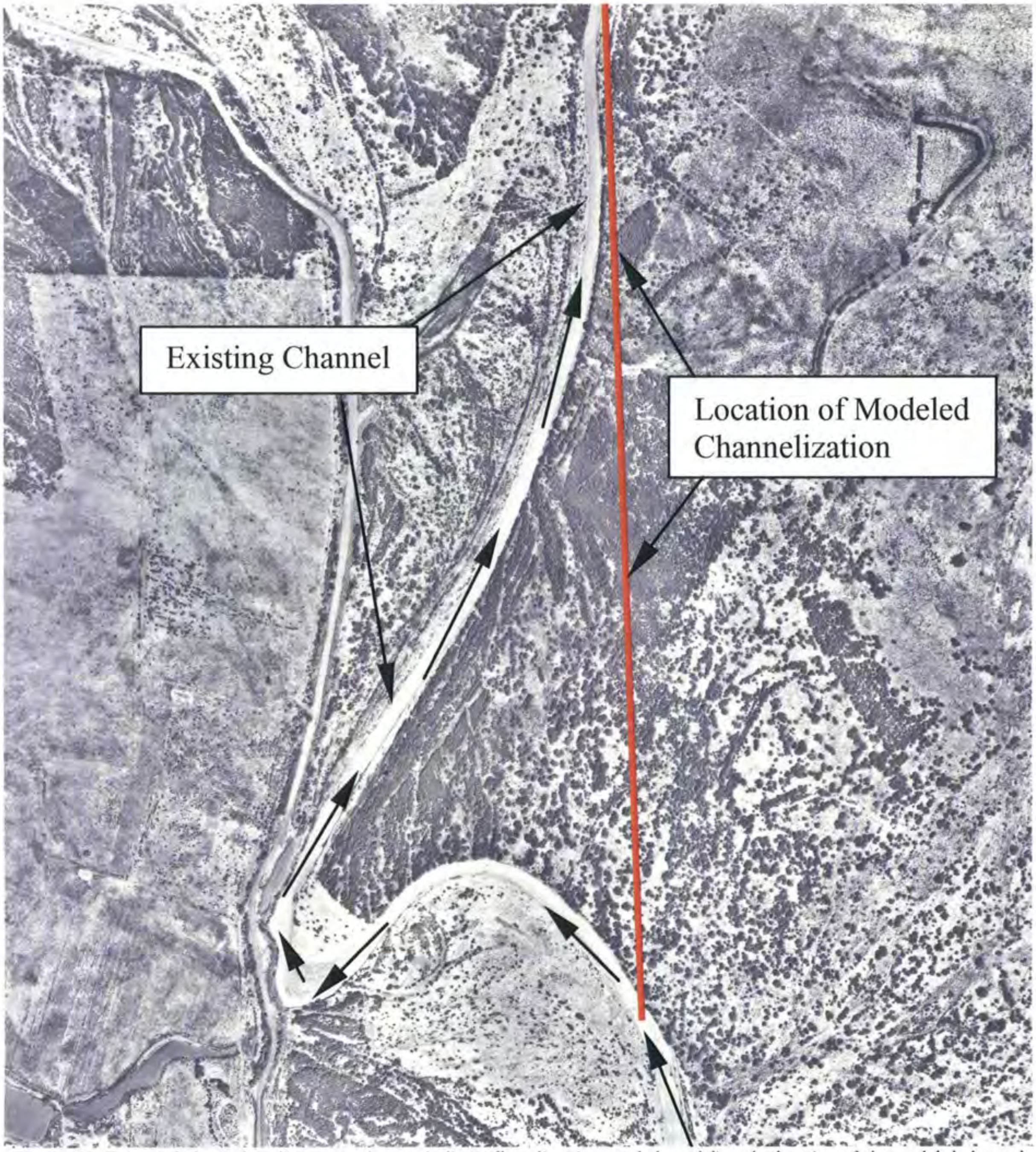


Figure 51. Proposed channel realignment. Arrows indicate flow direction, and the red line the location of the modeled channel.

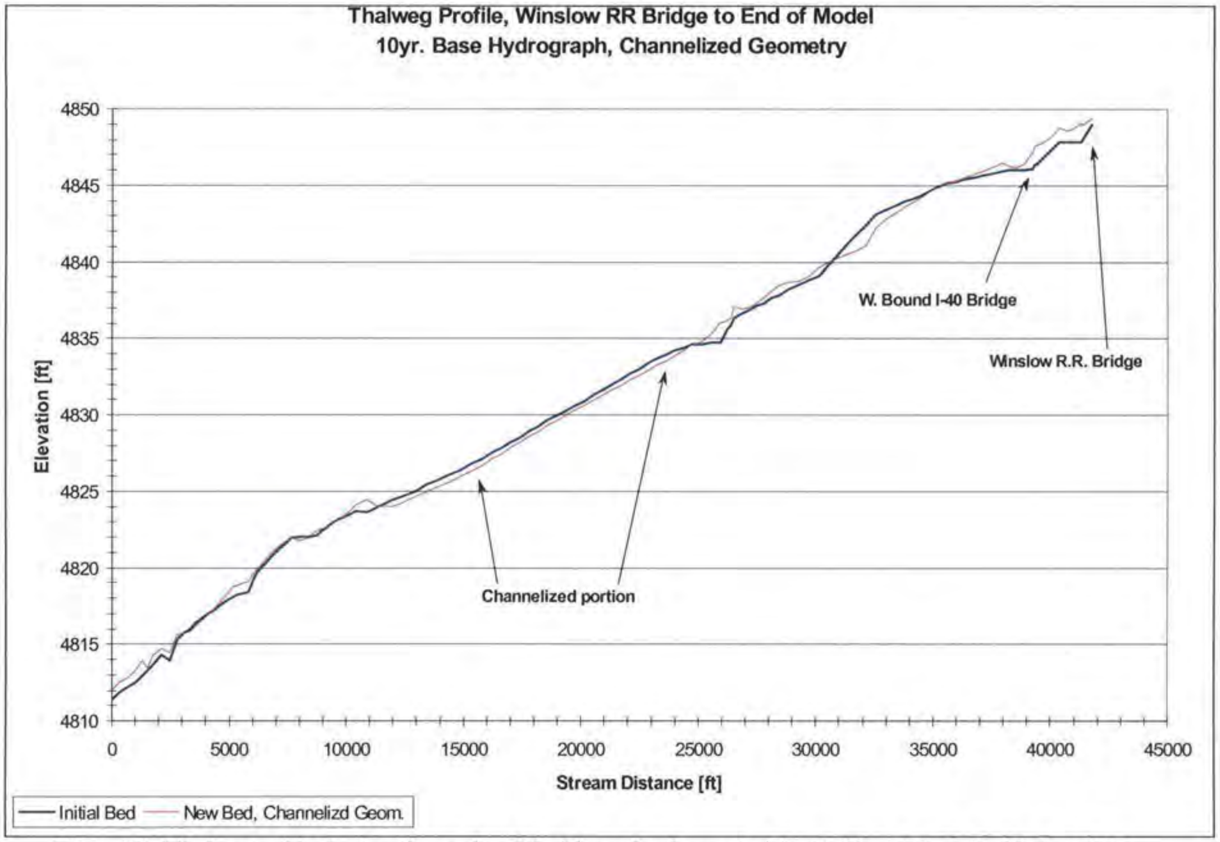


Figure 52. Thalweg profile showing the results of the 'channelized geometry' (in pink) and the initial bed condition, (in blue). This geometry was run using the 10 yr. base hydrograph.

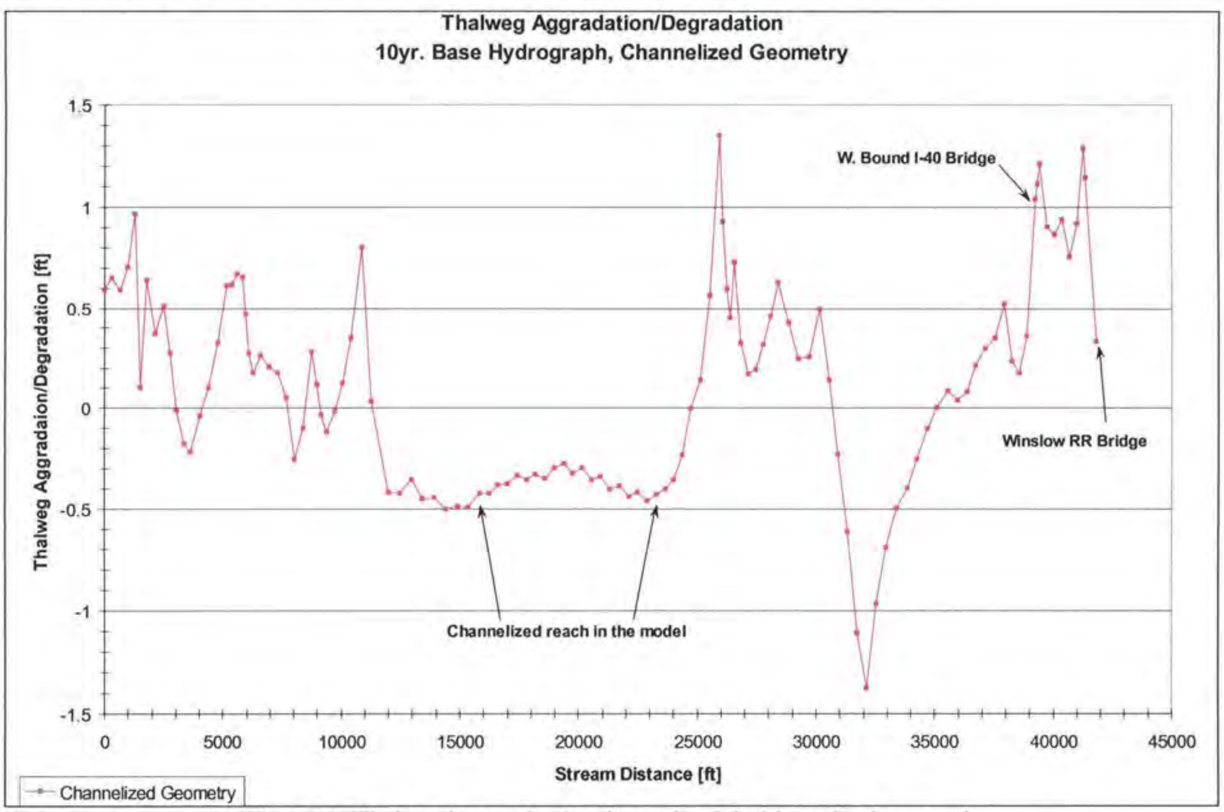


Figure 53. Thalweg changes showing the results of the 'channelized geometry'.

REMOVAL OF PENZANCE DAM

Modeling the removal of Penzance Dam was included in this report because there is some disagreement in the literature about the extent of its upstream influence. A letter written in December, 1942 by the Acting Commissioner of the Bureau of Reclamation states that the removal of Penzance Dam would eliminate aggradation in Holbrook. The United States Army Corps of Engineers responded with a memorandum in December of 1943 that aggradation in Holbrook would continue regardless of what happened with Penzance Dam due to sediment input from the Puerco River. The findings of the dam removal simulation in this report support the position of the United States Army Corps of Engineers memorandum written in 1943.

When the dam was removed in the model the bed was allowed to erode and the upstream influence extended as far as Leroux Wash. This is most easily demonstrated with the thalweg profile, shown in Figure 54. There was no indicated accumulation of sediment in the downstream reaches upon removal of the dam. It appears that the river was able to transport the sediment accumulated behind the dam. The bed slope in this reach increased slightly from 0.0013 prior to dam removal to 0.0014 following dam removal. It is not anticipated that removing Penzance Dam will in any way influence the accumulation of sediment in the Holbrook area and is therefore not recommended.

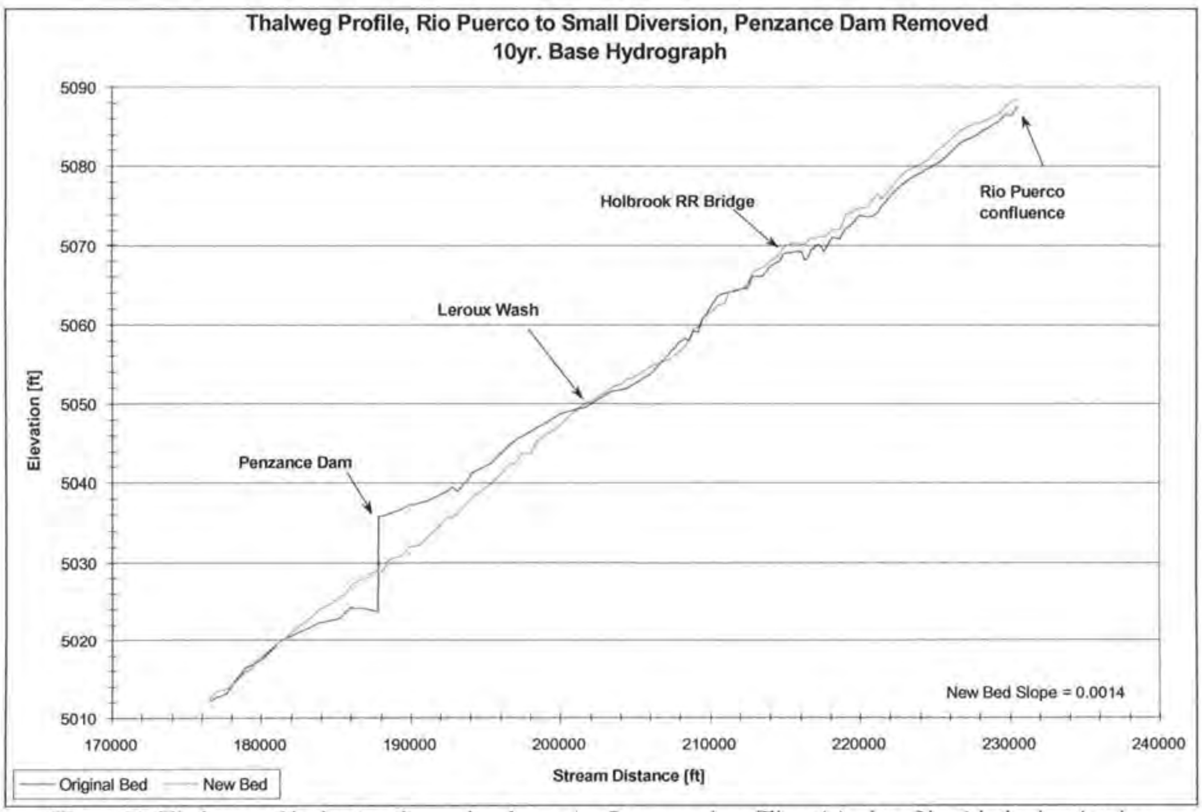


Figure 54. Thalweg profile showing the results of removing Penzance dam. The original profile with the dam in place is shown in blue, the resulting profile after running the 10–year base hydrograph is in pink.

HISTORICAL COMPARISON

Using available historical information, comparisons have been made contrasting the survey for this study to the surveys of previous studies. Where necessary, adjustments have been made to match the current datum, NAVD 88. When comparisons are made to historical data results show little, if any, recent aggradation. Figure 55 shows historical cross sections near the Route 77 bridge, data taken from Sabol (Sabol, 1993), where he used Bureau of Reclamation and Arizona Department of Transportation (ADOT) data. The bridge was moved 950 feet upstream of the old alignment in 1988. The 2000 cross section shown in Figure 55 accounts for this to match the location of the historical cross sections. The data indicate that there has been degradation since 1986, placing the current thalweg elevation near the indicated 1925 elevation. There is some doubt regarding the accuracy of the historical cross sections, but it is the best available. It is unclear which datum the 1925 cross section was surveyed to and if it was updated in the 1944 Bureau of Reclamation report to the then current 1929 NGVD. The degradation indicated in Figure 55 may be attributed to channel maintenance although there is little information available for dates when channel maintenance was performed. The most recent date known for pilot channel dredging is 1986, stated in the 1991 United States Army Corps of Engineers General Design Memorandum for the Holbrook levee.

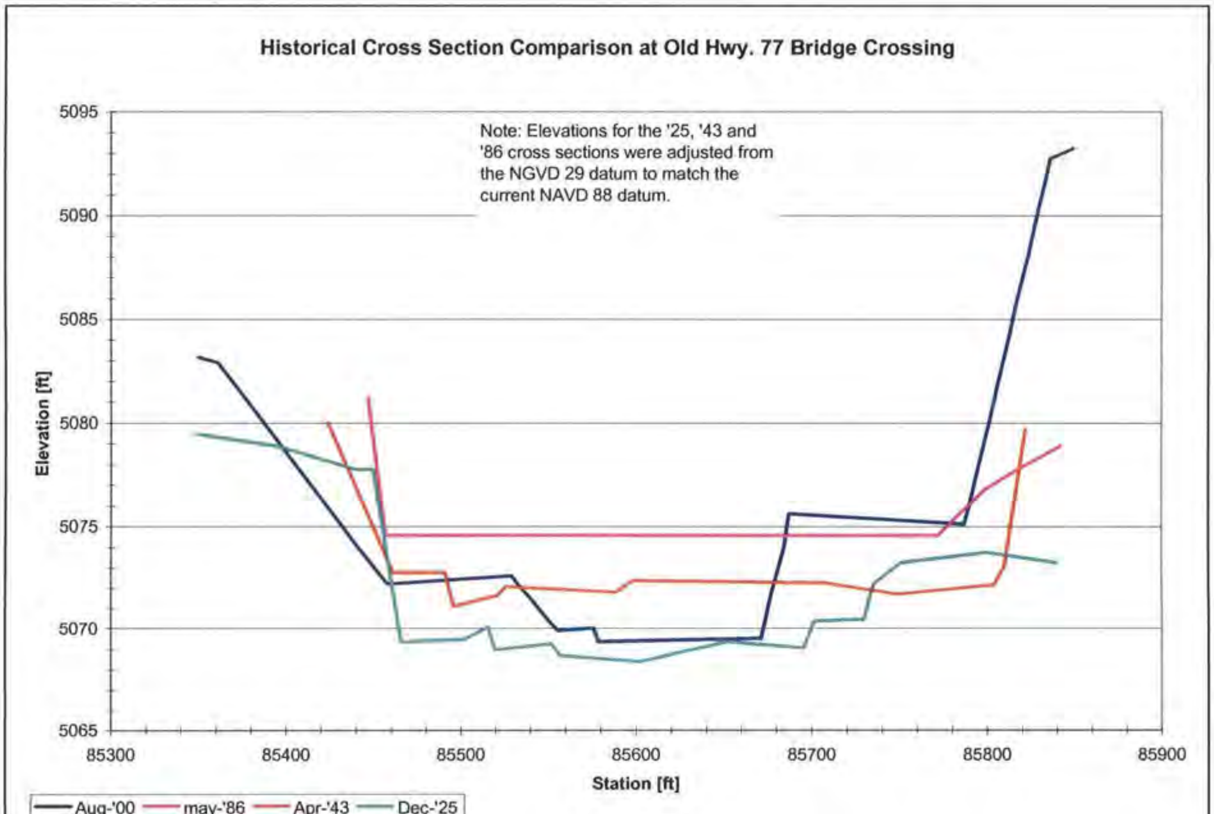


Figure 55. Historical cross section comparison at the previous location of the Arizona Route 77 bridge in Holbrook (between current Arizona Route 77 bridge and the Apache Railroad bridge). (Sabol, 1993).

Historical thalweg profiles also exist for the Holbrook reach. Figure 56 shows previously surveyed thalweg profiles compared to the 2000 survey. The historical information was obtained from the Sabol (Sabol, 1993) report using data from the United States Army Corps of Engineers. Again there are indications of degradation since 1982. Although there may be uncertainty regarding the previous surveys shown in Figure 55 and Figure 56 the results are consistent using Bureau of Reclamation, ADOT and United States Army Corps of Engineers data.

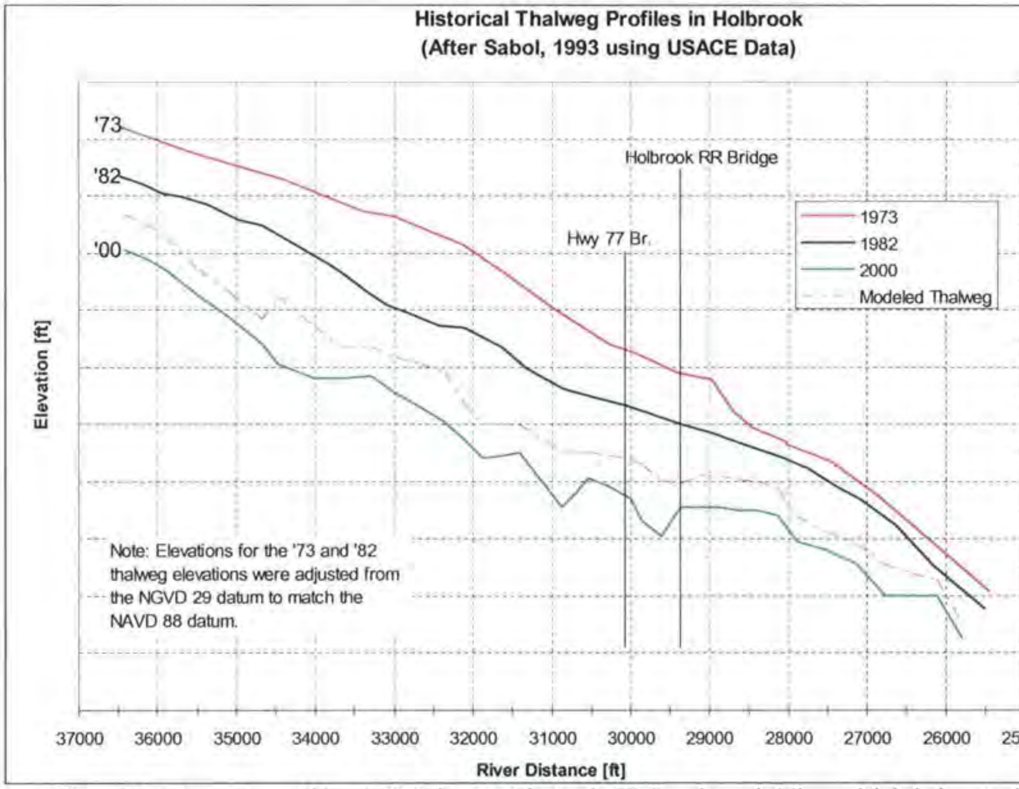


Figure 56. Comparison of historical thalweg profiles in the Holbrook reach. The modeled thalweg is the result of the GSTARS–2C run using the original geometry with the 10–year base hydrograph.

Appendix M contains comparisons of aerial surveys performed in 1995 (Sabol, 1997) and 2000 for this study. There are small discrepancies when these two surveys are directly compared. This is likely due to survey error (aerial surveys are +/– 1 foot or more, looser than tolerances used in land surveys), vegetation and possibly the interpolation routine used to extract elevations for the 2000 survey data. The survey routine finds the existing cross section end points (from the 1995 plan view map) and uses those coordinates in the 2000 topographical map. A straight line is drawn between the end points and the routine will search within 100 feet of the line to obtain an elevation from the topographic point file. This elevation is then interpolated to obtain an elevation at the cross section line. It is important to note that only the 2000 survey information contained in Appendix M was obtained in the manner described above. All other data for this report were taken from cross sections cut from the 2000 topographical map in BOSS–RMS.

There are two plan view maps showing the cross section locations. Not all of the cross sections were compared; rather only those that compared relatively well are shown in Appendix M. Many cross sections in the Winslow reach are doglegged. This presents problems matching cross section information since the doglegged cross section is longer. Other cross sections simply had poor correlation and were not included. It is expected that little channel change occurred between the surveys since only five years passed with very low flow volumes and no single event over 3,000 ft^3/s (as estimated by the Joseph City gage, USGS station No. 09397300).

Figure 57 and Figure 58 contrast the Holbrook (Apache) railroad bridge and the bed of the Little Colorado River after construction in 1980 and in September 2002 (respectively). The 1980 photo (Figure 57) is taken from the north bank and the 2002 photo (Figure 58) is taken from the south bank. Both photos were taken looking at the upstream side of the bridge. It is evident from the photos that visible aggradation has not occurred in the channel. The appearance actually suggests that the portion of the river in the photo has degraded, supporting the evidence presented in Figure 55 and Figure 56.

Figure 57. Apache Railroad bridge from north bank, upstream side. The 1991 United States Army Corps of Engineers General Design Memorandum (the source for this photo) dates this photo after its reconstruction in 1980.

Figure 58. Photo of the Apache Railroad Bridge taken in September 2002 from the south bank. Flood plain deposition or erosion is hard to discern due to the vegetation growth. The north levee can be seen at the end of the bridge near the upper right corner of the photo.

DISCUSSION

REGIONAL CORRELATION

Alluvial chronologies developed by previous researchers and summarized by Hereford (Hereford, 2002) in Figure 59 demonstrate multiple episodes of aggradation and incision within the last 3,000 years on the Colorado Plateau of Arizona. The episodes appear to be synchronous and of regional extent for the most part. Episodes of aggradation occurred between 2000 B.C. and 1200 A.D., 1300 and ~1900 A.D., and between 1940 and 1980 A.D. with episodes of degradation between each episode of aggradation. Based on regional precipitation records (Hereford et. al., 2002), it appears that the period between 1941 and 1979 was the driest period in the past one-hundred years. While in recent years it may appear that areas of the Colorado plateau are in a drought, on average, the regional precipitation is still greater than it was between 1940 and 1980.

Currently (e.g., post–1980), rivers in the Colorado Plateau appear to be in a state of degradation. Results from the present study are comparable to the regional chronology with a few exceptions. Although the timing of the first two aggradational episodes (the deposition of the Moenkopi and Cottonwood alluvium) are similar in the study reach, radiocarbon ages for the two deposits overlap, leaving no primary erosional interval. The erosional intervals between aggradation of the Cottonwood and Tamarisk alluvium and following aggradation of the Tamarisk alluvium are present and similar in timing to the regional chronology. In some areas, such as along the Paria River (Hereford, 2002) and in the Black Mesa region (e.g., Cooley and Akers, 1961; Cooley 1962; Karlstrom and Karlstrom, 1986; Dean, 1988; Karlstrom, 1988), unconformities in the arroyo stratigraphy represent erosional episodes between alluviation. Although it is possible that similar unconformities exist along the Little Colorado River, these relationships were not observed in exposures between Holbrook and Winslow. In contrast to stratigraphic sequences described elsewhere that have younger alluvium lapping onto and burying older units, the alluvium along the Little Colorado River seems to be distinct with little burial by younger alluvium. Each of the alluvial units described in this study appear to be inset into the next successively older unit. The only indication for periods of punctuated aggradation and degradation are preserved in the older Moenkopi alluvium (see Figure 11).

The Desert Broom alluvium is not discussed specifically in many regional studies and is assumed to be included within the modern channel alluvium. Based on similarities in morphology and position in the landscape, it appears that this unit is correlative to unit Qa1b mapped by Huckleberry (Huckleberry, 1996) as shown in Table 11. Huckleberry indicates that this unit was deposited between 1979–1990 and was abandoned by 1990. Based on observations made during this study, it appears that the surface of this unit incorporates sediment deposited in 1993.

The nomenclature used to delineate the Tamarisk alluvium varies between previous studies, but is considered by all authors to be flood plain or modern alluvium (Table 11). In Kolbe (Kolbe, 1991), the Tamarisk alluvium equivalent has multiple levels that are mapped as subunits of similar age. In this particular case, Kolbe mapped the subunits as an older unit deposited prior to 1931 and a younger unit that was deposited between 1931 and 1941. Deposition of the younger unit continued into the 1970's or 1980's. Hereford (Hereford, 1984) also describes several young alluvial units on the flood plain that were vertically accreted between the 1940's and 1970's.

The Cottonwood alluvium mapped along the Little Colorado River is considered to be equivalent to the Cottonwood terrace deposits of Hereford (Hereford, 1984) and the Naha Formation or Naha alluvium first described by Hack (Hack, 1942) and later by Cooley (Cooley, 1962), Webb (Webb, 1985), Webb and Baker (Baker, 1987), Dean (Dean, 1988) and Karlstrom (Karlstrom, 1988), illustrated in Figure 59. Previous studies estimate that the surface formed on these deposits was abandoned during the period of

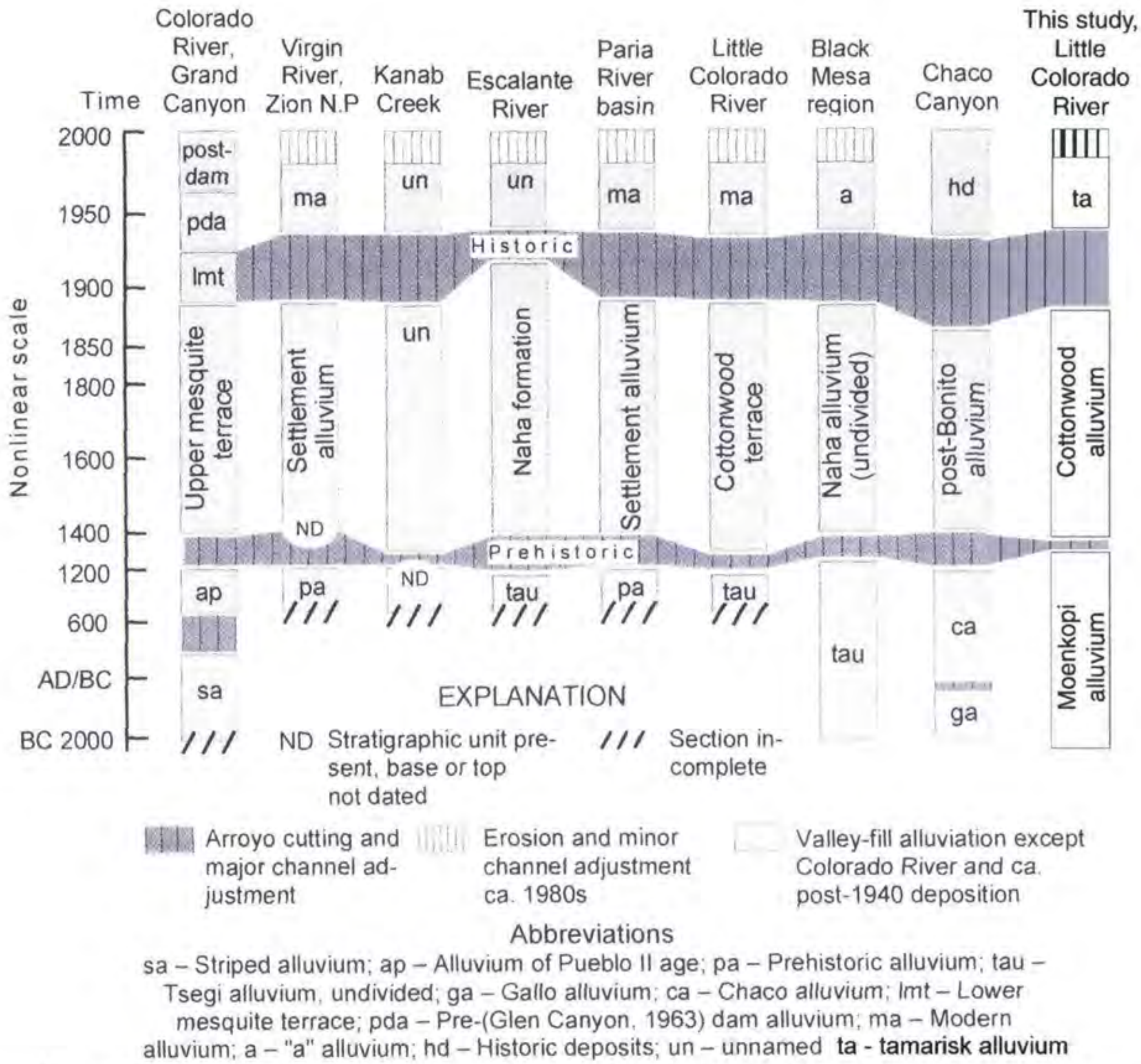


Figure 59. Correlation diagram of late Holocene alluvial units in the Colorado Plateau region of Arizona and southern Utah (modified from Hereford, 2002). Light gray segments of the section represent episodes of aggradation; dark gray segments represent episodes of degradation.

historical arroyo cutting that began around 1880 to 1900 A.D. With germination dates of cottonwood trees growing on this surface in the early 1900's (Table 3), the age of the Cottonwood alluvium of this study correlates well with the age of deposits described in previous studies.

The Moenkopi alluvium mapped along the Little Colorado River as part of this study is considered to be equivalent to the Tsegi Formation of Hack (Hack, 1942), described primarily to the north of the study area in the Black Mesa region (Karlstrom, 1988; Karlstrom and Karlstrom, 1986; Dean, 1988; Cooley, 1962; Cooley and Akers, 1961) and along the Escalante River (Webb, 1985; Webb and Baker, 1987). The Tsegi Formation is reported as being deposited between 2000 B.C. and 1200 A.D. Radiocarbon age estimates determined for this study indicate that the Moenkopi alluvium along the Little Colorado River was being deposited at 3,500 to 3,000 calibrated years B.P. This is equivalent to the era from 1550 B.C. to 1050 B.C. Radiocarbon ages from the youngest part of the Moenkopi alluvium indicate that deposition was continuing at roughly 910 to 660 calibrated years B.P. or the era from 1040 to 1290 A.D. These ages also correlate well with the age of the Tsegi Formation described in other studies.

Table 11. Correlation of map units.

This study (2002)	Hereford (1984)	Huckleberry (1993)	Karlstrom (1988)	Cooley (1962)	Hack (1942)	Kolbe (1991)
Active Channel alluvium (Unit Qac)		Qala				
Desert Broom alluvium (Unit Qa1)	Floodplain alluvium	Qa1b				
Tamarisk alluvium (Unit Qa2)	Floodplain alluvium	Qa2 (Qa3?)	a	Unit 1/2		A–1 A–2
Cottonwood alluvium (Unit Qa3)	Cottonwood Terrace	Qa3	Z	Unit 3	Naha Fm.	ZC
Moenkopi alluvium (Unit Qa4)		Qa4	Y	Unit 4 Unit 5	Tsegi Fm.	Y(?)

Historical arroyo–cutting during the past century has sparked controversy and debate over the cause of stream degradation. Four primary models, two chiefly independent and two dependent on climate, have been proposed to account for this behavior and are succinctly described by Hereford (Hereford, 2002)(see

Table 12). Hereford favors the fourth climate–dependent model, similar to his hypothesis that the majority of erosion occurs during wet conditions (increased frequency and intensity of ENSO). Increased frequency and intensity of ENSO conditions is linked to an increase in warm-season (June 15-October 15) rainfall, which produces the largest floods and the greatest sediment loads on Colorado Plateau rivers when compared to winter and spring floods (Hereford and Webb, 1992). Decreased frequency and intensity of ENSO conditions would therefore be associated with a decrease in warm-season rainfall and fewer large floods. In their analysis of historic variation of warm-season rainfall, Hereford and Webb (1992) find that a period of decreased 1-day rainfall and particularly 2-day rainfall began in the 1930's and continued to 1980. This period corresponds to the period of historic aggradation from 1940 to 1980 on the Little Colorado River as documented by Hereford from Winslow to Cameron (Hereford, 1984) and also in this study from Holbrook to Winslow. Other researchers have documented similar temporal trends in alluviation on the Colorado Plateau (Webb and Baker, 1987; Cooley, 1962; Cooley and Akers, 1961; Dean, 1988; Hall, 1977; Hereford et al., 1996a; Hereford et al., 1996b; Karlstrom, 1988; Karlstrom and Karlstrom, 1986; Kolbe, 1991; Love, 1977; Webb, 1985; Webb et al., 1991). To summarize, the alluvial model that Hereford puts forth is logical and is supported by both hydroclimatic and geomorphic data. It seems to adequately explain patterns in the study reach since the timing of aggradation and degradation and wet and dry cycles are similar to areas where the model has been applied.

Table 12. Four Models of Late Holocene Alluvial Processes.

Model	Commentary
Largely independent of climate	
(1) Complex response and intrinsic geomorphic thresholds Temporally random processes related to stability thresholds in fluvial systems such as over-steepening of channel gradient; complex response produces multiple terraces from a single disturbance of the watershed; sediment derived from reworking of preexisting valley fill (Schumm and Hadley, 1957; Schumm, 1977; Patton and Schumm, 1981; Boison and Patton, 1985; Waters, 1985; Patton and Boison, 1986; Elliott et al., 1999).	Important in small basins (<10 km^2 and over short time scales; Graf, 1989, p. 220–224), during arroyo cutting, or in some alluvial systems, but difficult to reconcile with the ability to regionally map and correlate late Holocene alluvium (Miller and Wendorf, 1958; Cooley, 1962; Cooley et al., 1969; Kottlowski et al., 1965, p. 295; Haynes, 1968, p. 599–600; Karlstrom, 1988; Hereford, 1986, 1987a, 1987b; Hereford et al., 1996a; McFadden and McAuliffe, 1997).
(2) Land use Historic arroyo cutting resulted from settlement and overgrazing that reduced plant cover and thus enhanced erosion (Swift, 1926; Bailey, 1935; Thornthwaite et al., 1942; Cooke and Reeves, 1976: Patton and Boison, 1986).	Fails to explain prehistoric arroyo cutting, does not address aggradation, is inconsistent with relationship of climate to historic erosion and modern alluviation, and probably did not increase sediment yield (Leopold, 1976; Hereford, 1984, 1986; Graf, 1986, 1989; Hereford and Webb, 1992).
Caused primarily by climate	
(3) Alluvial base–level control Rising (wet) or falling (dry) hydrologically controlled base level results in alluviation or erosion, respectively (Bryan, 1941; Antevs, 1952; Cooley, 1962; Haynes, 1968; Euler et al., 1979; Karlstrom, 1988).	Inconsistent with historic arroyo cutting that occurred during relatively wet conditions and frequent large floods. Inconsistent with modem alleviation that occurred during relatively dry climate and infrequent large floods (Webb, 1985; Webb and Baker, 1987; Balling and Wells, 1990; Graf et al., 1991; Webb et al., 1991). Relationship with water table and base level is uncertain.
(4) Erosion when wet and alluviation when dry Erosion occurs during wet conditions when streams are competent to carry heavy loads (Martin, 1963; Hall, 1977; Love, 1977).	Similar to interpretation developed here except not linked to hill slope processes and episodic changes in flood frequency. Almost the antithesis of alluvial base–level model.
Note: Holocene alluvial processes (termed cut–and–fill or erosion and aggradation) with application to the Colorado Plateau as discussed by Dean (Dean, 1988, p. 146–188) and Karlstrom (Karlstrom, 1988, p. 45–54) with a comment on each explanation as applied to the study area. †Taken from Hereford (Hereford, 2002).	

STATE OF THE LITTLE COLORADO RIVER

It is important to note that the design life of the Holbrook levee is 100 years, designed for protection from the 100–year flood event (60,000 ft^3/s) for a period of 50 years. In the second 50 years, aggradation is expected to begin limiting the capacity of the Holbrook levee to a point that in year 93 the levees will only provide protection from a 3–year flood event (USACE, 1991). The results of the GSTARS–2C sediment model using the 50–year hydrograph in this study predicted very similar aggradation levels to those arrived at by the United States Army Corps of Engineers for the design of the Holbrook levee. Aggradation amounts of 2.3 feet and 4.5 feet near the Holbrook levee are projections for a 50–year period. These estimates are similar to estimates made of historical aggradation, where roughly 3 to 4 feet of sediment was deposited from 1940–1980 forming the Tamarisk terrace during an aggradational episode in the study reach. This terrace is consistently present along the study reach (see Plates), showing that it is not related to a specific bridge or levee, and is currently incised 2 to 5 feet by the Little Colorado River. Primary deposition of the Tamarisk terrace appears to have ceased in the study reach by the late 1970's or early 1980's, although parts of the surface are still inundated during high flows. Observations made on September 11–12, 2002 during a high flow confirm this statement. The United States Army Corps of Engineers abandoned modeling efforts using HEC–6 after model simulations could not reproduce actual trends in sedimentation on the Little Colorado River. This demonstrates the difficulty in modeling sediment in the Little Colorado River. Due to this difficulty, monitoring future trends in sedimentation would provide for verification or calibration of the current sediment model.

The reason for designing the Holbrook levee for protection from the 100–year flood for only 50 years is that confidence in sediment modeling results is low when projections are made 100 years into the future. Overly conservative estimates obtained by the United States Army Corps of Engineers HEC–6 model dramatically increased design costs to a prohibitive level. The results of this report and the 1991 United States Army Corps of Engineers memorandum determined that sedimentation on the Little Colorado River is largely dependent on hydrology. In addition, future sedimentation on the Little Colorado River between Holbrook and Winslow depends on the dominance of the Puerco River or the Little Colorado River hydrology. The sediment availability in these two systems is very different (see Table 5). Based on cross section surveys along both systems, sediment storage in the Puerco River is greater by two orders of magnitude when compared to the Little Colorado River upstream of its confluence with the Puerco River. Flows originating in the Puerco River drainage will produce greater sediment input to the Holbrook and Winslow reach than will flows originating from the Little Colorado River basin upstream of the Puerco River confluence. It is possible that if the dominant input to the Holbrook reach comes from the Little Colorado River the system could become degradational (USACE, 1991).

In the reach between Holbrook and Winslow, model results show little aggradation or degradation. This reach is considered to be stable and has degraded to a minimum elevation as evidenced by exposed bedrock at specified locations along this reach (see Figure 1). The fact that the oldest terraces are highest above the river and the youngest are the lowest and that young alluvium has not filled to the top or overtopped the older deposits suggests that for the past 3,000 years, the Little Colorado River in the study reach has been in a overall state of degradation or incision. This overall pattern is superimposed by the episodes of aggradation and degradation previously described. For the past 100 years, the channel has degraded no more than 10 feet and aggraded no more than 5 feet. This would indicate that for the past 100 years, there has been net degradation of no less than 5 feet. Hereford and other researchers in the region propose that the current period of degradation began in the 1980's. Data gathered along the Little Colorado River supports this conclusion. Since the system is at or near its minimum elevation, the potential for continued degradation is low. Reach–based changes in bed elevation would therefore have to take the form of aggradation. Roughly 1.5 feet of aggradation is anticipated within a mile upstream of Obed Bridge over the next 10 years. Model results using the 50–year hydrograph do not indicate any further aggradation.

The sediment model results indicate that the portion along the Little Colorado River near Winslow will be stable. The greatest amount of indicated aggradation is less than 2 feet near the railroad and US Route 66 bridges. The remaining portions of this reach are expected to alternate between aggradation and degradation on the order of 1 foot or less over a 10–year period. Additional aggradation is negligible for a 50–year projection. It is important to note that the findings of this report indicate that the channel is currently degraded at or near a minimum elevation. This suggests that any dramatic shifts in river behavior will likely be towards aggradation. This will be an important consideration for future plans involving levees in Winslow as well as Holbrook.

PART III – OVERALL FINDINGS

The Little Colorado River Sediment Study was performed to answer the three questions stated in the introduction. This discussion section will answer these questions based on the information presented in this report.

For the reach of the Little Colorado River between Holbrook and Winslow, is the river aggrading either regionally (due to climate change or other large scale factors) or locally (due to the hydraulic conditions created by the levees and bridges)?

The Little Colorado River is not undergoing regional aggradation. Between Holbrook and Winslow the river appears to be stable, indicating no significant aggradation based on the sediment model results using the results from all hydrographs. Geomorphic analysis also indicates that since 1980, the non–controlled channel is stable or slightly degrading. The presence of bedrock in the channel bed and abandoned meanders indicate systemic degradation. Partially buried Tamarisk indicates a period of historical aggradation that ended around 1980. The pattern of historical aggradation and degradation is consistent with previous findings in the Little Colorado River region and is a pattern that has repeated over the past 3,000 years in the study reach. This shows that the mechanisms controlling this pattern of river behavior are pre–European, regional, and must have a cause that is at least in part intrinsic to the behavior of this system. The model proposed by Hereford (Hereford, 2002), relying on wet or dry climatic conditions and the frequency of large floods, seems to be a reasonable model to explain patterns of aggradation and degradation.

Some local aggradation is anticipated at the bridges in this reach. The cause of the aggradation at the bridges is the structure itself and the constriction of the flood plain, namely the Obed Bridge in Joseph City and the US Route 66 and railroad bridges in Winslow. Between the Puerco River confluence and the Holbrook railroad bridge the Little Colorado River is likely to undergo reach–wide aggradation, as predicted by the sediment model using the 50–year hydrograph. The aggradation in this reach is caused primarily by the Holbrook railroad bridge and to some extent by the large meander upstream of Holbrook.

If the Little Colorado River is aggrading, what is the magnitude of the problem and what will be the future impacts of the aggradation to the levees and bridges?

Although the Little Colorado River is not currently aggrading, the period of historical aggradation (1940's thru the 1970's) deposited a depth of roughly 3–4 feet of sediment. It is possible to limit future aggradation based on past river response. Geomorphic mapping indicates that the system would not aggrade to an elevation higher than the oldest surfaces (10–20 feet). This does not apply to reaches with hydraulic controls. Observations of the main channel and tributaries upstream of and in the study reach suggest that available sediment is not limited. In the study reach, stored sediment estimates range from 4.7×10^7 to 1.0×10^8 yd^3, while reach–based estimates for the Little Colorado River upstream of the study reach and for tributaries range from 9.0×10^3 to 1.1×10^6 yd^3/mile.

There is little impact to Obed Bridge and the bridges in Winslow considering the aggradation predicted over a 50–year period is less than two feet. Reach–wide aggradation is not expected in the Winslow reach and therefore will not impact the Winslow levee. The aggradation predicted upstream of the Holbrook railroad bridge is not expected to exceed the aggradation anticipated in the design of the Holbrook levee, 4.5 feet. The aggradation at the Holbrook railroad bridge is predicted to be 2.1 feet. These levels of aggradation closely match the aggradation predicted by the United States Army Corps of Engineers for the design of the Holbrook levee. The aggradation indicated upstream of the Holbrook railroad bridge will not likely impact the Route 77 bridge. Model scenarios are based on 25 years of historical hydrology and assume a similar trend will continue. Future aggradation of the Little Colorado River is possible with an unforeseen change in hydrology.

If the future impacts will be significant, what cost–effective measures can be taken to reduce the impacts?

Because future sediment aggradation is not considered to be significant, taking immediate corrective measures is unnecessary. A monitoring plan has been included in this report so that a consistent database on the condition of the Little Colorado River in Holbrook and Winslow will be created and maintained. This database will prove useful in monitoring future changes of the river and will allow a quantitative analysis of its capacity.

The results of the geometric scenarios arrive at the common conclusion that no immediate action needs to be taken to influence the sediment transport in the Holbrook and Winslow areas. Justification for removal or modification of the Apache Railroad Bridge in Holbrook is not apparent because anticipated aggradation does not exceed the design of the Holbrook levee. The levee realignment and channelization in Winslow had no indicated impact on sedimentation either upstream or downstream of the specific projects. These scenarios were primarily performed to investigate the upstream and downstream sedimentation in the event these projects are carried out for the purpose of reducing the water surface elevation along the levee in Winslow. There appears to be no need to induce degradation in the Winslow reach, as the maximum aggradation over a 50–year simulation is less than two feet, occurring at the US Route 66 Bridge. The removal of Penzance Dam was simulated to define the upstream extent of the degradation. An earlier report by the Bureau of Reclamation (Reclamation, 1944) speculated that Penzance Dam caused roughly five feet of aggradation in Holbrook. The findings in this report conclude that the upstream extent of degradation, should Penzance Dam be removed, is Leroux Wash.

The various hydrologic scenarios cover a broad spectrum of possibilities. This is critical because of the inability to forecast rainfall over an extended period of years. The hydrologic scenarios have included all likely and reasonable flows in the Little Colorado River.

MONITORING PLAN

The purpose of this monitoring plan is to collect the data necessary to discern changes to the Little Colorado River channel over time relative to the channel changes predicted by the sediment transport model. It is very important to understand that the predictive capability of the sediment model is constrained by the original input data. The geomorphology and sediment model developed for this study is based on topographic data derived from aerial photography flown in August 2000. As such, the model is static in the sense that the channel geometry is representative of the river in August 2000. In addition, only 25 years of historical stream flow data on the Little Colorado River were utilized as input for the sediment model. Thus, any prediction of future aggradation or degradation along the river assumes that the stream flow in the future will be somewhat similar to the 25 years of data used in the model. Without obtaining new channel geometry, the model cannot be re–run in the future to 'update' the results. Therefore, in order to maximize the predictive capability of the sediment model, the river should be monitored for changes in the channel geometry, form, slope, and stream flow trends.

Information gathered from regular monitoring of the Little Colorado River can be compared to predicted results of the sediment model outlined in this report. This allows for a direct correlation of actual river behavior to future trends predicted by the sediment model. Should the monitored trends reveal information contrary to the predicted trends, the model contains certain parameters that can be adjusted to match the predicted trends with the observed trends, resulting in a calibrated model. Calibration of the model is something that could not be performed for the current study due to a lack of available data. With updated input data, a calibrated model could be run again to obtain new predictions. However, these predictions would still begin at the original baseline date of August 2000. Therefore, data gathered as part of a regular monitoring program would permit a more accurate model calibration. The new predicted trend could then be re–evaluated for future sedimentation on the Little Colorado River. If agreement cannot be reached through calibration of the current model, a new model would have to be developed starting with new geometry.

This monitoring plan was developed to outline the type of information that would be most useful given the results of the current sediment model. Fifteen cross sections that are either coincident with cross–sections in the sediment model or that can be easily correlated to model cross sections were laid out in two reaches, one near Holbrook and the other at Winslow, as shown in Figure 60 and Figure 61. These sites were selected due to the presence of levees, bridges, or other man–made structures that influence river behavior and represent infrastructure that can be or has been impacted by dramatic change on the river. In addition, at some of these sites the sediment model results indicate either appreciable aggradation or stability with localized aggradation in the future.

DATA REQUIREMENTS

The principle data required for this monitoring program are distance and elevation measurements for each cross section and a channel length measurement through each reach. The distance and elevation data are best collected by a field survey between permanent monuments that have been established at the ends of the cross sections. Permanent monuments should be established at the ends of the cross sections at or near the prescribed coordinates (listed in Table 13). These monuments may consist of standard benchmarks or reinforcement bar set in concrete. The monuments should be sited in an area that is easily located, considered stable (levee crest, roadway, etc.), and is not prone to disturbance or vandalism. Detailed notes describing location and distances to nearby landmarks such as telephone poles, fence posts, rail lines, bridge piers, trees, etc. should be developed for each cross section and incorporated into a permanent monitoring project database.

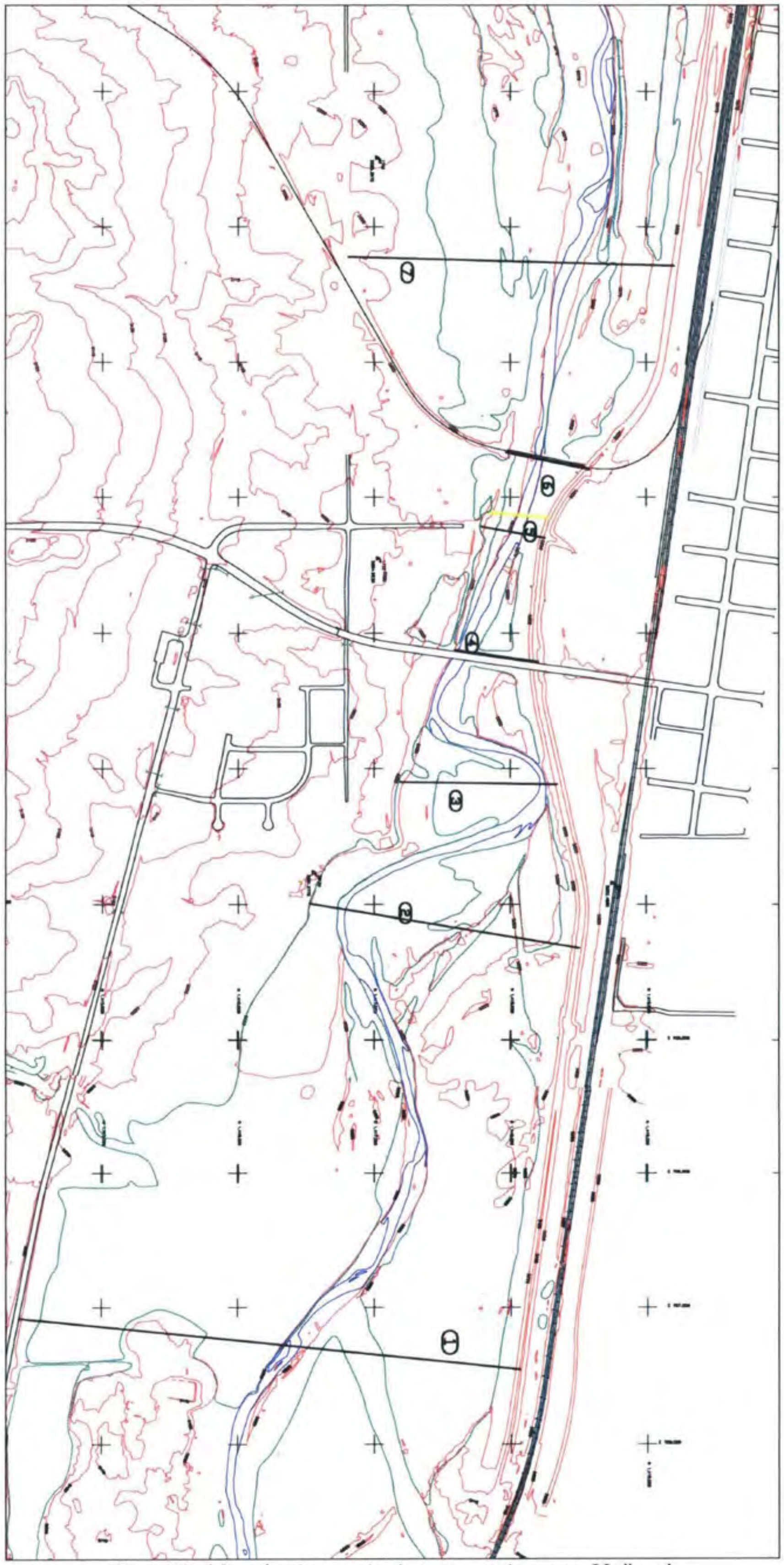


Figure 60. Map showing monitoring cross sections near Holbrook.

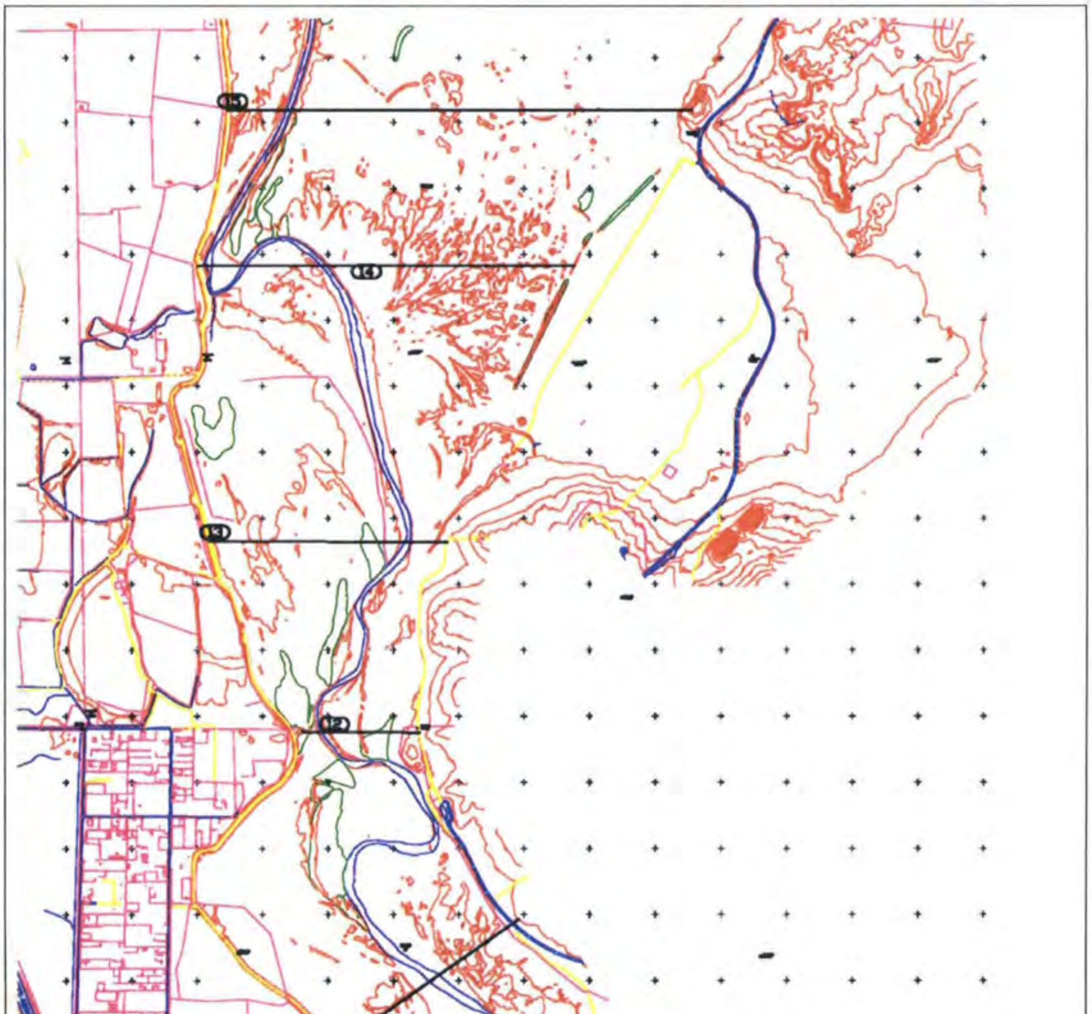


Figure 61. Map showing monitoring cross sections near Winslow.

A project database should be established to ensure that data gathered as part of the monitoring plan are not lost. The use of standardized forms should also be considered to ensure the consistency of the data collected. In addition, the distance and direction between the endpoint monuments should also be documented so that if a monument is lost, it can be reestablished without compromising the dataset for that cross section. Given the scope of this monitoring plan, once the monuments and the baseline conditions for each cross section have been established, the time required to acquire and process the data should not exceed more than 10 staff days annually. In order for the data collected as part of this monitoring plan to be utilized, a baseline dataset for each cross section must first be established. It is recommended that this baseline dataset be populated with data collected on a bi–monthly basis during the first year of monitoring. These data should then be averaged to provide the baseline that would be considered representative of the current river conditions.

Table 13. Coordinates of left and right cross section end–points with corresponding sediment model cross sections.

Cross Section No.	Left End Point	Right End Point	Length	Model XS No.
1	E 707,079.8	E 707,453.9	3680.5 ft.	1490
	N 1,414,393.0	N 1,418,062.4		
2	E 703,994.1	E 704,320.3	2009.7 ft.	1440
	N 1,416,525.2	N 1,418,508.2		
3	E 703,099.6	E 703,116.2	1155.4 ft.	1420
	N 1,417,189.1	N 1,418,344.2		
4	E 702,123.5	E 702,210.5	614.8 ft.	1390
	N 1,417,592.2	N 1,418,200.7		
5	E 701,218.4	E 701,301.7	576.3 ft.	1384
	N 1,417,786.9	N 1,418,253.4		
6	E 700,669.3	E 700,793.3	620.3 ft.	1370
	N 1,417,970.0	N 1,418,577.7		
7	E 699,223.7	E 699,290.6	2372.8 ft.	1360
	N 1,416,811.3	N 1,419,205.7		
8	E 553,954.8	E 554,688.3	754.5 ft.	320
	N 1,457,595.2	N 1,457,418.6		
9	E 554,009.0	E 554,816.3	819.5 ft.	290
	N 1,458,143.1	N 1,458,002.6		
10	E 553,853.2	E 554,816.9	1016.2 ft.	260 or 270
	N 1,460,161.3	N 1,459,838.9		
11	E 550,145.9	E 552,915.9	3367.5 ft.	230
	N 1,465,011.6	N 1,466,926.6		
12	E 549,613.3	E 551,405.0	1791.8 ft.	210
	N 1,469,766.5	N 1,469,754.8		
13	E 548,178.4	E 551,822.0	3643.6 ft.	195
	N 1,472,649.9	N 1,472,632.4		
14	E 548,013.8	E 553,763.8	5750.0 ft.	183 or 184
	N 1,476,823.8	N 1,476,828.4		
15	E 548,447.8	E 555,557.8	7110.2 ft.	170 or 180
	N 1,479,196.0	N 1,479,196.9		

After an initial baseline dataset is established, all cross section measurements should be repeated annually, on or about the same date. It is suggested that this survey be undertaken sometime in the fall because the base flow on the Little Colorado River at this time of the year is low and the vegetation along the river has lost its leaves. Little or no flow and dormant vegetation will facilitate data collection and improve the quality of the survey data by increasing the accuracy of the channel geometry measurements and reducing random error incurred due to foliage on the vegetation. Surveying at this time of the year should document any changes along the river that may have resulted from flooding during the previous year. An assessment of the data collected should be performed at 5–year intervals. This assessment would establish the range of expected variability in annual measurements, and be used as a comparison to predictions of the sediment model. Threshold criteria should be developed based on the baseline data collected during the first year and the sediment model predictions. The monitoring project should be continued for a minimum of 10 years. At the end of this period, the decision to continue monitoring of the project would be based on the result of the data assessment.

The amount of measurable stream flow in the river at the time of the cross section surveys should be recorded. These values are available from the United States Geological Survey gaging stations at Woodruff (USGS station No. 09394500), near Joseph City (USGS station No. 09397300), near Winslow (USGS station No. 09400350), and on the Puerco River near Chambers (USGS station No. 09396100). A record of the stream flow during the period of the survey should be included with the cross section surveys in the monitoring program database. In addition, if any new gaging stations are established, the data recorded at these gaging stations should also be added to the permanent database.

In addition to distance and elevation data acquired in the field survey of the cross sections, the channel length in the monitored reach should also be determined. Channel length is extremely important to the data analysis, as it is required to accurately calculate the channel slope and derive representative thalweg profiles. It is also very important to understand that the channel length is not equivalent to the distance between the measured cross sections. Figure 62 illustrates the difference in the two types of measurements. The measure of channel length can be collected by two different methods, field survey or from aerial photography. Due the length of the Winslow reach and the density of vegetation in many areas along the river, gathering this information may be quite time intensive. Gathering this information can also be complicated if there is any significant flow in the river at the time of the survey. Some of these logistical problems can be eliminated by scheduling the field survey at a time when flow is low or non–existent, the vegetation has lost it leaves, and with the use of GPS survey equipment.

It is strongly encouraged that aerial photography also be acquired on an annual basis coincident with the collection of channel geometry data (i.e., within several weeks). In addition to the invaluable record that it provides, aerial photography is more comprehensive in the sense of total data gathered and for documenting channel conditions that are not easily measured in the field. Information derived from aerial photography can add to and improve the quality of data in the database, and hence may be much more economical in terms of the incremental costs versus the data collected.

The primary purpose for acquiring aerial photography is to document any changes in the channel plan form associated with meandering or channelization, evaluate vegetation conditions and to identify the location and derive a length for the channel between measured cross sections, illustrated in Figure 62. Documenting changes in these parameters cannot be determined from survey data in the monitored cross sections alone. To gather this information in the field would be very time intensive and subject to numerous errors that could not be evaluated in later analyses. For example, between the years 1984 and 2000, the position of the active channel between cross sections 11 and 12, shown in Figure 61, has shifted from the left side of the flood plain to the right side. During this period, the channel has changed from a broad meander, to a straight channel, and back to a more tightly meandering channel. Most of this change occurred between the cross sections, so these changes might not have been documented in a field survey of channel geometry. At a minimum, the aerial photography acquired as part of this monitoring plan should include uncontrolled stereo coverage of the monitored reach flown at a scale of roughly 1:12,000 at least every five years and after every flood that exceeds Q20 (Table 8). With the placement of some permanent monuments, the photography could be rectified and utilized in later detailed analyses, should the occasion arise. While annual aerial photographic coverage of the monitored reaches would be optimal, it could potentially increase the program costs by as much as 50%.

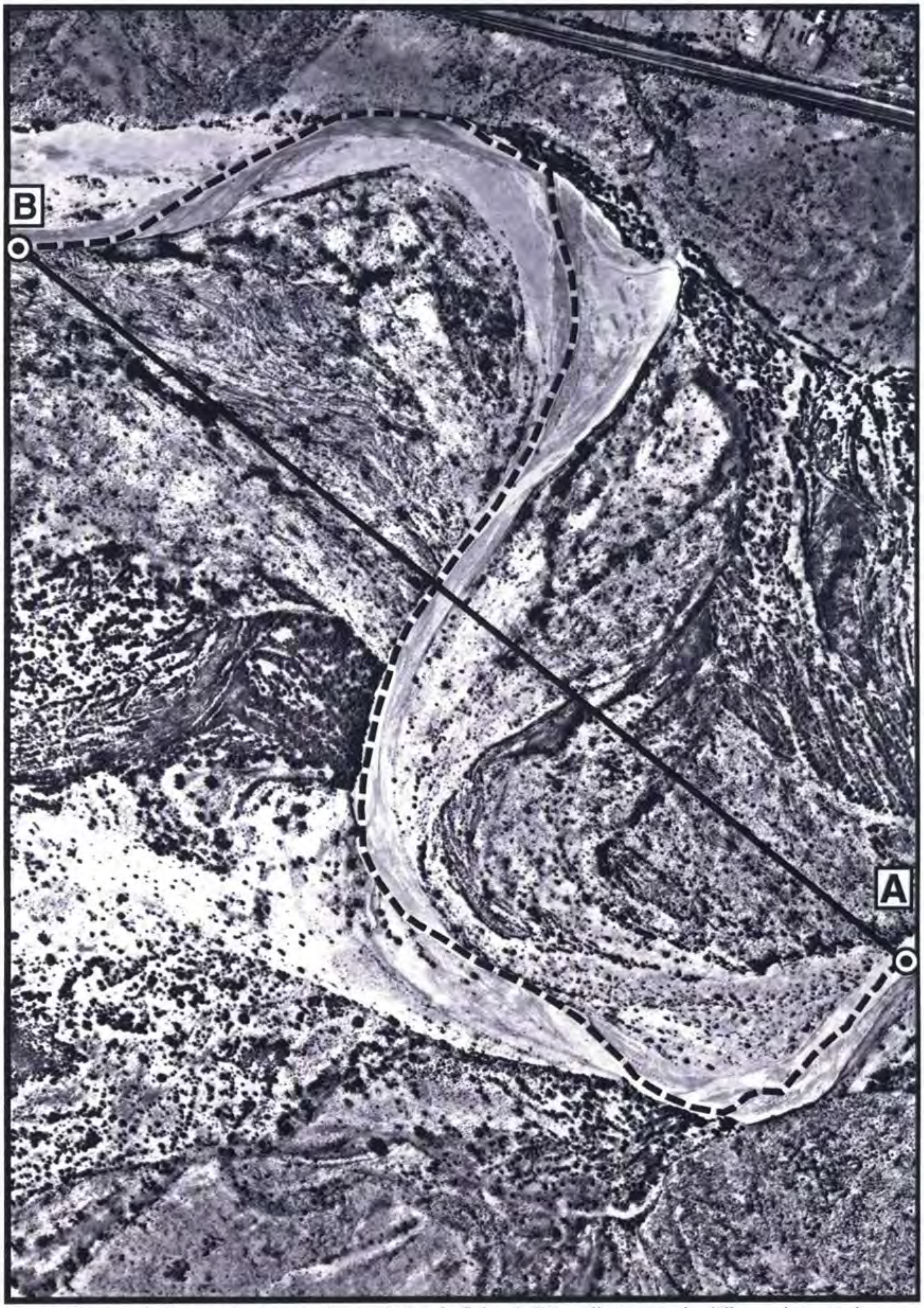


Figure 62. Aerial photograph of a meander on the Little Colorado River illustrating the difference between the channel length and valley length. If two cross sections were established at points A and B, the valley length, or distance between the thalweg in each cross section would be represented by the solid line A–B. However, the dashed line represents the channel length along the thalweg in each cross section from A to B. In this particular case, the difference between the two distances would have a significant effect on the channel slope measurement.

DATA ACQUISITION

When surveying each cross section, the maximum distance between points in a cross section should not exceed 100 feet. A minimum number of 25 points, excluding end–points, should be surveyed in each cross section. Obviously, the more survey points collected, the more accurate the cross section. Changes in elevation across the flood plain or in the channel of more than 2 feet should be included in the survey so that topographic breaks can be accurately represented in a graphical depiction of the cross section. This is accomplished by surveying a point at the top and bottom of the break. In addition, the following details must be noted during the survey and included in the monitoring database. All references to right or left should be made in the context of the feature's position while looking downstream.

- The position of the vegetation on the right and left sides of the active channel; for example, left edge of vegetation (LEV) and right edge of vegetation (REV). Figure 63A illustrates the definitions and locations of these features. When the active channel of the river consists of multiple threads, measure the position of the LEV and REV for each channel thread.

- The position of the channel bank on the right and left sides of the active channel. Because knowing the position of the top of the bank can be useful in analyzing other hydraulic characteristics of the river, the top edge of both banks should be noted. For example, top right bank (TRB) and top left bank (TLB), illustrated in Figure 63A. When the active channel of the river consists of multiple threads, measure the position of the TRB and TLB for each channel thread. Most banks will represent a topographic break in the cross section (see preceding paragraph), therefore a survey point should be measured at the base and top of each bank.

- The position of the left edge of water (LEW) and right edge of water (REW) when there is flow, illustrated in Figure 63A. When the active channel of the river consists of multiple threads, measure the position of the LEW and REW of each channel if flow is present.

- The position of the channel thalweg, the lowest point in the active channel, as illustrated in Figure 63A. In cross sections that contain multiple threads or channels, measure the thalweg for each channel.

- The position of any boundaries or relatively permanent features in the cross section such as roads, railroads, fence lines, levee crests, bedrock outcrops, large trees, etc.

Similarly, when surveying the channel length in the monitored reach, the maximum distance between points should be less than 100 feet. The channel length measurements should be collected as close to the thalweg as possible. Obviously, it would be advantageous to collect these data when there is little or no flow in the channel. Finally, each cross section should be photographed from both endpoints. Each pair of photographs should be annotated with the time, date, and cross section number and included with their respective cross section datasets in the monitoring program database.

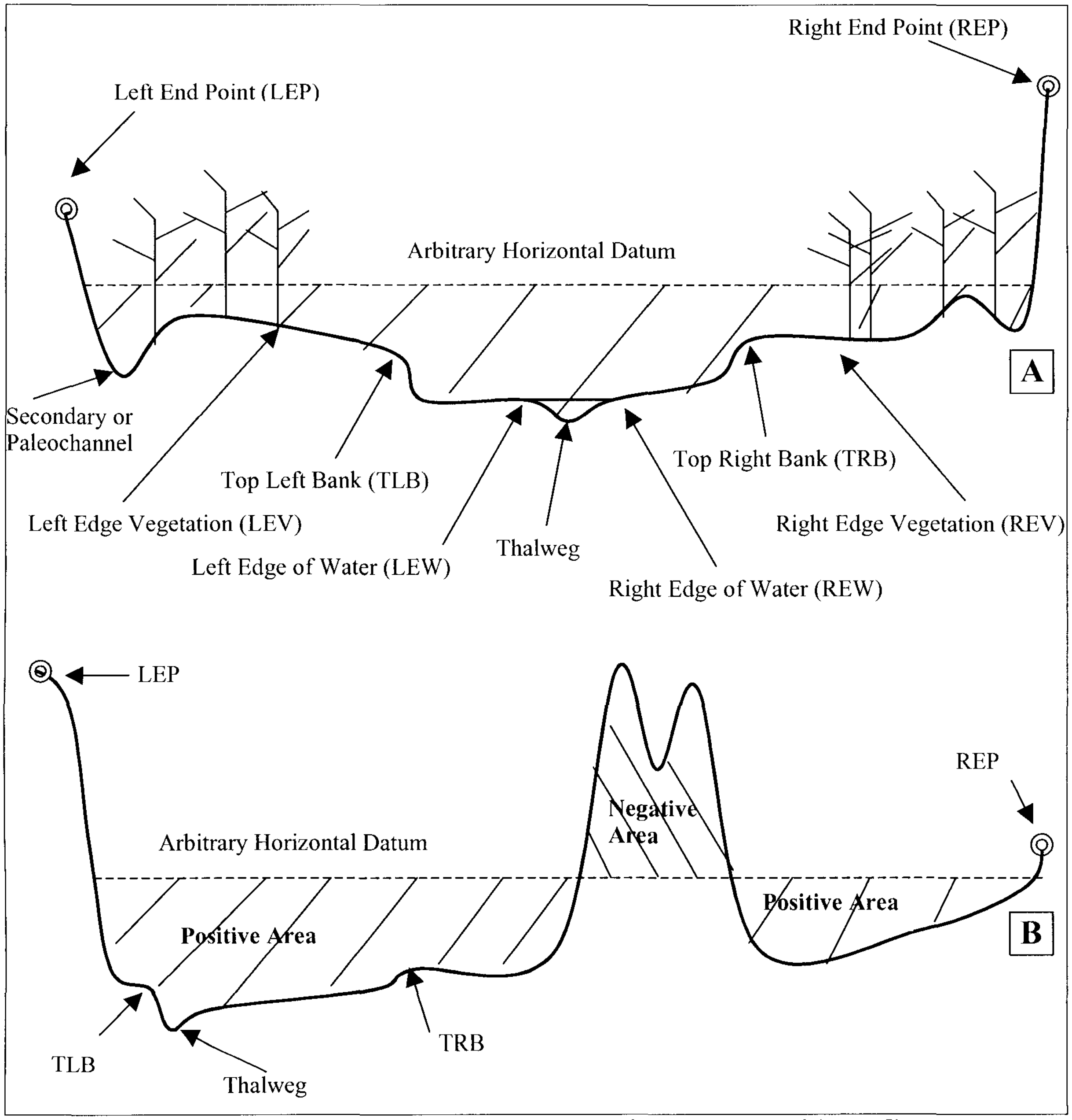


*Figure 63. **A.** Diagram showing typical cross section and placement of arbitrary horizontal datum. Channel features whose locations should be included in survey notes are indicated. The area between ground surface and horizontal datum. marked by the cross hatch pattern should be calculated for a comparative analysis. **B.** Diagram showing a cross section with a portion of the cross section above the datum. In these situations, areas need to be calculated as positive and negative areas.*

DATA ANALYSIS

The distance and elevation measurements from the cross section surveys and the channel length measurements collected from either the field survey or aerial photography will be used to assess the river conditions. Three basic parameters, the thalweg elevation, the cross sectional area, and the channel slope, developed using these data will be analyzed. These parameters are sensitive indicators of changes on the river that result from aggradation or erosion. The first parameter to be analyzed from these data is the thalweg elevation. The thalweg in a river channel is defined as a line connecting the lowest points along the channel bed. In this case, the thalweg elevation is defined as the lowest point in the active channel within each cross section. It is possible that the thalweg elevation will not coincide with the lowest point in the cross section. At several locations along the Little Colorado River, the active channel of the river is perched so the bed elevation in the active channel is actually higher than in isolated or abandoned channels on the flood plain. In many cases, these abandoned channels (i.e., paleochannels; see Plates; Sheets 1–18) or isolated back channels may only convey flow during large magnitude floods. Thus, it is extremely important that the position of the thalweg in the active channel be clearly noted in the cross section during the field survey and distinguished from secondary or paleochannels that may be present in the cross section. Figure 63 shows examples of this type of channel morphology. The position of the thalweg and secondary channels can also be determined on the aerial photography, thereby verifying field measurements and eliminating potential error resulting from field personnel unfamiliar with specific river characteristics and terminology.

Monitoring changes in the thalweg elevation can be helpful in detecting increases or decreases in the bed elevation resulting from aggradation or erosion. Therefore, thalweg data is best evaluated in a time series analysis. However, numerous years of data need to be gathered before the analysis will be meaningful. Each year data can be compared to previous data sets to evaluate systematic changes or trends in the bed elevation that may result from either erosion or aggradation. The thalweg elevation data in a given cross section can also be compared to the thalweg elevation data in adjacent cross sections. A comparison of these data in each cross section in a given reach could indicate if changes are localized or reach–wide.

The second parameter, the cross sectional area, can be evaluated using distance and elevation measurements in each cross section. The cross sectional area provides a means of measuring changes in the stored sediment in a given cross section. This value acts as a proxy for volume and is independent of such complicating factors as multi–thread channels, stream terraces of different ages, sand dunes, and vegetation encroachment. In this case, the cross sectional area simply represents the available space in the cross section measured between the ground surface in the cross section and a previously established horizontal datum for each particular cross section, as shown in Figure 63A. If the river aggrades in a particular cross section, the available space will decrease; if the cross section experiences erosion, the available space will increase.

It is important to note that each cross section has its own unique horizontal datum and that all cross sectional areas calculated in a given cross section must utilize the horizontal datum established for that cross section. The datum is established at an arbitrary elevation in the cross section that is located as close to the ground surface as possible yet allows for all of the measured points in the cross section to fall below the datum, as shown in Figure 63A. This minimizes the area in the cross section to the point that small changes in the area from year–to–year are readily detected in the analysis. In some cross sections, the flood plain may be covered by high dunes or a channel may have migrated from one side of the cross section to the other leaving a higher isolated portion of an abandoned terrace in the cross section. In order to locate the datum at a minimal elevation and facilitate the area computations in the monitoring program, some areas of the cross section may lie above the datum, as shown in Figure 63B. In these particular cases, the area of the cross section above the datum is considered negative area. In the analysis, the negative area of the cross section would then be combined with the positive areas to derive the cross sectional area.

The computed cross sectional area derived from the above analysis is used to evaluate river conditions in two different ways. First, compare this value to previous area measurements at the same location to evaluate the magnitude of change within the cross section. Secondly, compare this value statistically to cross sectional areas measured in adjacent cross sections in the reach to detect any deviation in trends within a reach. Figure 63 illustrates how the cross sectional area simply represents the available space in the cross section. Therefore, if the river aggrades in a particular cross section or through a particular reach, the available space will decrease. Conversely, if the channel experiences any degradation as the result of either bank erosion or bed scour in the cross section, the available space will increase.

The third parameter to be analyzed is channel slope or the thalweg profile. The channel slope is simply the change in the bed elevation over some distance along the channel. Changes in channel slope are closely related to the capability of the river to move sediment. The channel slope decreases as the channel aggrades and increases as it degrades. This is a broad generalization as channel slope is also dependent on other channel characteristics and stream flow. Therefore, it is important to understand which parameters are influencing the channel geometry and river behavior. The data required to calculate the channel slope includes channel length derived from either field survey or aerial photography and the thalweg elevations through the entire monitored reach. There is a variety of methods that may be employed to analyze this data. In this particular case, a time series comparison of thalweg profile or channel bed elevation plotted against the main channel distance should prove adequate. Again, it is important to recognize that the distance between cross sections is not necessarily equivalent to the channel length.

ADDITIONAL RECOMMENDATIONS

Based on an evaluation of the stored sediment in the tributaries to the Little Colorado River, the greatest potential for significant sediment influx is from Leroux Wash and the Puerco River (Table 5). Based on the results of this study and other studies in the region, there appears to be an apparent link between climate and the sediment transport capabilities of rivers. During extended dry periods the rivers in the region tend to shift to an aggradational state, while in wetter periods the rivers tend to degrade. Because smaller streams will respond more rapidly to these changes in hydrology and sediment supply due to their smaller basin area, this shift would be more easily detected and more pronounced in tributaries much sooner than on the larger trunk streams. For this reason, monitoring on Leroux Wash and the Puerco River might provide an indication of potential changes in the sediment transport capabilities on the Little Colorado River. However, depending on the periodicity of the data analysis, these changes might not be detected until associated changes were occurring on the Little Colorado River. Monitoring these tributaries would simply permit a more proactive response to changes in the stability of the river system.

CONCLUSION

Terraces mapped along the Little Colorado River between Holbrook and Winslow, Arizona document episodes of aggradation and degradation during the past 3,000 years. The timing of this aggradation and degradation is similar in timing to the alluvial history reported in nearby areas on the Colorado Plateau and thus appears to be part of a regional pattern. Episodes of aggradation occurred between 2000 B.C. and 1200 A.D., 1300 and ~1900 A.D., and between 1940 and 1980 A.D. The most recent episode of aggradation deposited roughly 3–4 feet of sediment in the study area. Episodes of degradation occurred between each episode of aggradation and from 1980 to the present. The favored theory for these episodes is climate–driven with periods of aggradation occurring during dry cycles and few large floods and periods of degradation occurring during wet cycles and multiple large floods.

Based on present channel conditions and the presence of bedrock in the channel at multiple locations, the Little Colorado River between Holbrook and Winslow currently appears to be slightly degrading or stable. Conditions along upstream sections of the river and in the larger tributaries appear to be similar. Modeling results from all hydrologic scenarios indicate that the Little Colorado River is expected to remain in a stable condition, with the exception of the upper portion of the study reach. Some aggradation is likely to occur in the reach between the Puerco River confluence and the Holbrook railroad bridge. This aggradation was considered by the United States Army Corps of Engineers in their design of the Holbrook levee and is therefore of little concern regarding the levee. Between Holbrook and the end of the model in Winslow the river is not expected to aggrade in more than a few specified locations. The model results show alternating aggradation and degradation for this reach with magnitudes of less than 1 foot. Estimates of sediment storage show that the amount of sediment available to be transported is essentially unlimited, thus the Little Colorado River system is transport limited.

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APPENDIX A

SOIL STRATIGRAPHIC DESCRIPTIONS

Profile No. LCR1 **Described by** Jeanne Klawon/Ralph Klinger **Date** 5/04/02 **Slope** 0 **Aspect** S

Map Unit 4 **Parent material** fine–grained alluvium

Location right bank, upstream from Obed Bridge at junkyard **UTM Coords** 12S 0562070, 3866810

Quadrangle Joseph City **Township/Range** ____ **Section** ____ **Elevation** ____

Horizon	Depth (Thickness) cm	Boundaries	Structure	Clay Films	Consistence			Texture	Gravel %	CaCO3 Morphology	Color (dry/moist)
					Stickiness	Plasticity	Dry				
Ak	0–15 (15)	aw	2cgr	none	vs	vp	sh	SiC	0	I	7.5YR5/3d 7.5YR3/3m
Bk	15–133 (118)	aw	3vcabk–cpr	3ppf	vs	vp	vh	SiC	0	II	7.5YR6/3d 7.5YR3/4m
2Cox	133–160 (27)	sw	1–2csbk	none	so	po	sh	fLS	0	I	7.5YR6/3d 7.5YR4/3m
3Bkb	160–183 (23)	as	1csbk	3ppf,po	vs	vp	h	SiC	0	none	7.5YR5/3d 7.5YR4/3m
3Coxb2	183–223 (40)	as	1mgr–sbk	none	vs	vp	sh	SiC	0	II	7.5YR6/3d 7.5YR4/3m
4Bkb2	223–321 (98)	as	2msbk	3ppf	vs	vp	eh	C	0	none	5YR5/3d 5YR4/3m
4C1	321–351 (30)	aw	2msbk	3ppo,pf	vs	vp	vh	SiC	0	none	5YR5/3d 5YR4/3m
4C2	351–403 (52)	cw	2msbk	2dpf	vs	vp	eh	C	0	none	7.5YR6/3d 7.5YR4/3m
4C3	403–439 (36)	as	3cabk	2dpf	vs	vp	vh	C	0	none	5YR5/3d 5YR4/3m
5C	439–448+ (50)		1vcsbk	none	s	p	sh	vfSiL	0	none	5YR7/4d 5YR5/4m

Profile No. LCR2 **Described by** Ralph Klinger, Jeanne Klawon **Date** 5/05/02 **Slope** 0–1° **Aspect** S

Map Unit 3 **Parent material** fluvial sand, silt and clay

Location left bank opposite APS Power Plant; upstream of LCR1 **UTM Coords** 12S 0562076, 3866316

Quadrangle Joseph City, AZ **Township/Range**____ **Section**____ **Elevation**____

Horizon	Depth (Thickness) cm	Boundaries	Structure	Clay Films	Consistence			Texture	Gravel %	CaCO3 Effervescence Morphology	Color (dry/moist)
					Stickiness	Plasticity	Dry				
A	0–6 (6)	aw	2gr–pl	none	s	p	sh	fL	0	es none	2.5YR5/4d 5YR3/4m
	6–10 (4)	aw	2pl–gr	none	s	p	so	SiL	0	es I	5YR6/4d 5YR4/3.5m
	10–60 (50)	cw	2?	none	ss	po	so–sh	fSL	0	es none	5YR6/3d 5YR4/4m
	60–76 (16)	cw	2?	none	so	po	so	fLS	0	es none	5YR5.5/4d 5YR4/4m
	76–108 (32)	cw	sg	none	so	po	so	fLS	0	es I–	5YR6/4d 5YR4/3m
	108–126 (13)	cw	m–sg	none	ss	po	so	fSL	0	es I–	5YR5/4d 5YR4/3m
	126–130 (4)	aw	sg	none	vs so	vp po	vh lo	fS C	0	es none	5YR6/4d, 4/4m 7.5YR6/4d, 4/4m
	130–151 (21)	aw	m–sg	none	so	po	lo	fS	0	es none	5YR5/4d 5YR4/3.5m
	151–160 (9)	aw	m–sg	none	so	po	lo–so	fLS	0	es none	5YR5/4d 5YR4/3m

Profile No. LCR3A **Described by** Ralph Klinger, Jeanne Klawon **Date** 5/08/02 **Slope** 0–1° **Aspect** N

Map Unit 4 **Parent material** fine–grained alluvium

Location eastern end of exposure at LCR3 **UTM Coords** 056211; 3866189

Quadrangle Joseph City, AZ **Township/Range** ______ **Section** ______ **Elevation** ____

Horizon	Depth (Thickness) cm	Boundaries	Structure	Clay Films	Consistence			Gravel %	Texture	CaCO3 Morphology	Color (dry/moist)
					Stickiness	Plasticity	Dry				
	0–2 (2)	aw	2fgr–pl					0		none	
	2–4 (2)	as	m					0		none	
	4–29 (25)	cs	2m–fsbk					0		none	
	29–41 (12)	as	2f–msbk					0		I–	
	41–53 (12)	aw	m					0		none	
	53–65 (12)	aw	m					0		I–	
	65–107 (42)	aw	m					0		I–	
	107–180 (73)	cw	3m–csbk					0		I–	
	180–340 (160)	as	3cabk–pr					0		I–	
	340–387 (47)	aw	2msbk					0		I–	
	387–425 (38)		sg					0		none	

Profile No. LCR3B **Described by** Ralph Klinger, Jeanne Klawon **Date** 5/06/02 **Slope** 0° **Aspect** N–NE

Map Unit 4 **Parent material** fine–grained alluvium

Location left bank, upstream of LCR3C **UTM Coords** 12S 0562088, 3866209

Quadrangle Joseph City, AZ **Township/Range** ____ **Section** ____ **Elevation** ____

Horizon	Depth (Thickness) cm	Boundaries	Structure	Clay Films	Consistence			Gravel %	Texture	CaCO3 Effervescense Morphology	Color (dry/moist)
					Stickiness	Plasticity	Dry				
A	0–15 (15)	cw									
Bk	15–72 (57)	aw								I	
C	72–130 (58)	aw									
2Abk	130–175 (45)	aw									
2Bwbk	175–197 (22)	cw									
2C	197–214 (17)	as									
2C2	214–283 (69)	as									
2C3	283–420+ (37)										

Profile No. LCR3C **Described by** Jeanne Klawon, Ralph Klinger **Date** 5/06/02 **Slope** 0° **Aspect** NE

Map Unit 4 **Parent material** fine–grained alluvium

Location left bank, upstream from Obed Bridge **UTM Coords** 12S 0562055, 3866235

Quadrangle Joseph City, AZ **Township/Range**_______ **Section**_______ **Elevation**_____

Horizon	Depth (Thickness) cm	Boundaries	Structure	Clay Films	Consistence			Gravel %	Texture	CaCO3 Morphology	Color (dry/moist)
					Stickiness	Plasticity	Dry				
spoil	0–10 (10)	cw									
C	10–60 (50)	as		none				0		I+	
Abk	60–83 (23)	cw	3cabk–pr	1dpo,pf	vs	vp	vh	0	C	e I	5YR5/3d 5YR4/3m
Bwbk	83–100 (17)	cw	3cpr	1fpo	ss	p	vh	0	L	e I	5YR5/3d 5YR4.5/3m
Cb	100–200 (100)	as	m	none	so	po	so	0	LS	es none	5YR6/3d 5YR5/3m
Cb2	200–210 (10)	cw		none				0			
Cb3	210–270 (60)	as		none				0			
Cb4	270–276 (6)	aw		none				0			
Cb5	276–313 (27)	aw		none				0			
Cb6	313–334 (21)	aw		none				0			
Cb7	334–358 (24)	aw		mone				0			
Cb8	358–410 (52)	aw		none				0			
Cb9	410–450 (40)			none				0			

Profile No. LCR3D **Described by** Jeanne Klawon, Ralph Klinger **Date** 5/6/02 **Slope** 0° **Aspect** NE

Map Unit 4 **Parent material** sandy alluvium

Location left bank, upstream from LCR3E **UTM Coords** 12S 0562041, 3866248

Quadrangle Joseph City, AZ **Township/Range** ______ **Section** ___ **Elevation** ______

Horizon	Depth (Thickness) cm	Boundaries	Structure	Clay Films	Consistence			Gravel %	Texture	CaCO3 Effervescense Morphology	Color (dry/moist)
					Stickiness	Plasticity	Dry				
spoil	0–38 (38)	aw									
C1	38–55 (17)	aw						0			
C2	55–140 (85)	as						0			
C3	140–200 (60)	aw						0			
C4	200–226 (26)	as						0			
C5	226–237 (11)	aw						0			
C6	237–309 (72)	cw						0			
C7	309–350+ (41)							0			

Profile No. LCR3E **Described by** Ralph Klinger, Jeanne Klawon **Date** 5/6/02 **Slope** 0° **Aspect** S–SE

Map Unit 4 **Parent material** fine–grained alluvium

Location left bank, upstream from site LCR3F **UTM Coords** 12S 0562039, 3866279

Quadrangle Joseph City, AZ **Township/Range** ______ **Section** ______ **Elevation** ______

Horizon	Depth (Thickness) cm	Boundaries	Structure	Clay Films	Consistence			Gravel %	Texture	CaCO3 Effervescense Morphology	Color (dry/moist)
					Stickiness	Plasticity	Dry				
A	0–2 (2)	aw	2mgr–pl	none	so	po	so	0	fLS	es none	2.5YR5/4d 2.5YR 4/3m
C	2–6 (4)	aw	m–1mpl	none	so	po	lo	0	fLS	es none	2.5YR5/4d 2.5 YR 4/4m
C2	6–43 (37)	aw as(locally)	m	none	ss	ps	so	0	L	es none	5YR6/4d 2.5YR4/4m
C3	36–39 (3)	as		none				0			
C4	43–85 (42)	as	sg	none	so	po	lo	0	fLS	e I–	5YR6/3d 2.5YR4/4m
C5	85–92 (7)	as	m	none	s	p	sh	0	SiL	es none	2.5YR6/4d 2.5YR4/4m
C6	92–99 (7)	as	m	none	ss	po	so	0	SL	es none	2.5YR5/4d 5YR4/4m
C7	99–128 (29)	as		none				0		none	
C8	128–143 (15)	aw		none				0		none	
C9	143–161 (18)	as		none				0		none	
C10	161–330 (69)		sg	none				0		e– none	7.5YR7/3d 7.5YR5/3m

Profile No. LCR3F **Described by** Jeanne Klawon, Ralph Klinger **Date** 5/6/02 **Slope** 0° **Aspect** S

Map Unit 4 **Parent material** fine–grained alluvium

Location left bank, meander bend upstream of LCR4 **UTM Coords** 12S 0562057, 3866282

Quadrangle Joseph City, AZ **Township/Range** ______ **Section** ______ **Elevation** ______

Horizon	Depth (Thickness) cm	Boundaries	Structure	Clay Films	Consistence			Gravel %	Texture	CaCO3 Effervescense Morphology	Color (dry/moist)
					Stickiness	Plasticity	Dry				
A	0–2 (2)	aw	gr–pl	none	ss	ps	so	0	SiL	es none	5YR6/4d 5YR3/4m
Bk1	2–16 (14)	as	1gr–msbk	none	so	ps	so	0	L	es I	5YR6/4d 5YR3/4m
Bk2	16–34 (18)	as	2csbk	vffpo	s	p	sh	0	SiC	ev I–	2.5YR6/4d 2.5YR4/4m
C1	34–82 (48)	as	m	none				0		I–	
C2	82–90 (8)	as	m	none				0		I–	
C3	90–148 (58)	as	m	none				0		I	
C4	126–139 (13)	as	m	none				0		none	
C5	148–179 (31)	as	m	none				0		none	
C6	179–195 (16)	aw	sg	none				0	SL	es none	5YR6/4d 5YR4/4m
C7	195–244 (49)		m	none				0	SiC	none	2.5YR5/4d 2.5YR4/4m
C8	244–264 (20)		m	none				0		none	
C9	264–300 (36)		m	none				0		I–	
C10	300–350+ (50)		m	none	vs	vp	eh	0	C		5YR6/4d 5YR3.5/4m

Profile No. LCR4 **Described by** Jeanne Klawon, Ralph Klinger **Date** 5/5/02 **Slope** 0° **Aspect** E

Map Unit 2 **Parent material** sandy alluvium

Location left bank, upstream from LCR1 and downstream from LCR2 **UTM Coords** 12S 0562096, 3866581

Quadrangle Joseph City, AZ **Township/Range**____ **Section**____ **Elevation**____

Horizon	Depth (Thickness) cm	Boundaries	Structure	Clay Films	Consistence			Gravel %	Texture	CaCO3 Effervescense Morphology	Color (dry/moist)
					Stickiness	Plasticity	Dry				
C1	0–13 (13)	as	sg	none	so	po	lo	0	LS	e none	7.5YR6/3d 7.5YR4/3m
O?	13–15 (2)	cs									
C2	15–28 (13)	aw	sg	none	so	po	lo	0	S	e none	7.5YR5.5/3d 7.5 YR4/3m
C3	28–61 (33)	as	sg	none	so	po	lo	0	LS	e none	7.5YR6/3d 7.5YR4/3m
C4	61–87 (26)	aw	sg	none	so	po	lo	0	LS	e– none	7.5YR6/3d 7.5YR4/3m
C5	87–96 (9)	as	sg	none	ss	ps	lo	0	L	es none	7.5YR6/3d 7.5YR4/3m
C6	96–115 (19)	as	sg	none	ss	po	lo	0	SL–L	es none	5YR6/3d 5YR4/3m
C7	115–122 (7)	as	sg	none	ss	ps	lo	0	SiCL	es none	5YR5/3d 5YR4/3m
C8	122–130 (8)		sg	none	ss	po	lo	0	SL	ev none	5YR6/3d 5YR4/3m

Profile No. LCR5 **Described by** Ralph Klinger, Jeanne Klawon **Date** 5/7/02 **Slope** 1° **Aspect** N

Map Unit 4/R **Parent material** alluvium, Moenkopi Fm.

Location soil pit on left bank downstream from diversion at Cholla Lake **UTM Coords** 12S 0564932, 3863633

Quadrangle Joseph City, AZ **Township/Range** ______ **Section** ______ **Elevation** ______

Horizon	Depth (Thickness) cm	Boundaries	Structure	Clay Films	Consistence			Gravel %	Texture	CaCO3 Effervescense Morphology	Color (dry/moist)
					Stickiness	Plasticity	Dry				
Av	0–4 (4)	cw	2–3fgr–pl	none	s	p	sh	0	L	es none	2.5YR5/4d 5YR4/4m
A	4–12 (8)	aw	3mpl	none	vs	p	sh	0	SiCL	es none	5YR6/3.5d 2.5YR5/4m
Bk	12–27 (15)	cw	2csbk	none	so	po	sh	0	SL	es I+	2.5YR4/4d 2.5YR3/4m
C1	27–52 (25)	as	2vcsbk	none	s	p	so	0	L	es I–	2.5–5YR6/4d 2.5YR4/4m
C2	52–94 (42)	aw	sg	none	so	po	lo	10		none	
Rr	94–102 (8)	as						75		none	
R	120+										

Profile No. LCR6 **Described by** Ralph Klinger, Jeanne Klawon **Date** 5/7/02 **Slope**_____ **Aspect** ____

Map Unit 4 **Parent material** silty and sandy alluvium, eolian sand

Location soil pit west of LCR5 near old diversion dam at Cholla Lake **UTM Coords** 12S 0564765, 3863756

Quadrangle Joseph City, AZ **Township/Range**_______ **Section**______ **Elevation**________

Horizon	Depth (Thickness) cm	Boundaries	Structure	Clay Films	Consistence			Gravel %	Texture	CaCO3 Effervescense Morphology	Color (dry/moist)
					Stickiness	Plasticity	Dry				
A	0–5 (5)	aw	1fgr–pl	none	so	po	lo	0	fLS	es none	2.5YR4/4d 2.5YR3/4m
Bw	5–27 (22)	cw	2csbk	none	so	po	sh	0	fLS	es none	2.5YR4/6d 2.5YR3/4m
2Bk1	27–45 (18)	aw–i	1msbk	none	s	p	so	0	vfSiL	es I–	5YR6/3d 5YR4/4m
2Bk2	45–84 (39)	aw	m	none				0		I–	
2C1	84–141 (57)	aw		none				0		none	
2C2	141–160+ (19)			none				0		none	

Profile No. LCR7 **Described by** Ralph Klinger, Jeanne Klawon **Date** 5/7/02 **Slope** 0° **Aspect** E

Map Unit 3 **Parent material** sandy alluvium

Location soil pit downstream of LCR6 and Cholla Lake **UTM Coords** 12S 0564586, 3863939

Quadrangle Joseph City **Township/Range** ____ **Section** ____ **Elevation** ____

Horizon	Depth (Thickness) cm	Boundaries	Structure	Clay Films	Consistence			Gravel %	Texture	CaCO3 Effervescense Morphology	Color (dry/moist)
					Stickiness	Plasticity	Dry				
A	0–8 (8)	as	2fgr–pl	none	ss	ps	lo	0	SL	es none	2.5 YR5/4d 2.5YR4/4m
B	8–26 (18)	aw	3csbk	none	s	p	so	0	L	ev I	2.5YR6/4d 2.5YR4.5/4
C	26–44 (18)	as	m	none	so	po	so–sh	0	LS	ev I–	5YR6/4d 5YR5/4m
2C	44–106 (62)	aw	sg	none				0			
3C	106–140+ (34)		sg	none				0			

Profile No. LCR8 **Described by** Jeanne Klawon, Ralph Klinger **Date** 5/8/02 **Slope** 0° **Aspect** W

Map Unit 3a **Parent material** fine–grained alluvium

Location pit in left bank downstream from Obed Bridge **UTM Coords** 12S 0559651, 3866993

Quadrangle Joseph City, AZ **Township/Range** ____ **Section** ____ **Elevation** ____

Horizon	Depth (Thickness) cm	Boundaries	Structure	Clay Films	Consistence Stickiness	Consistence Plasticity	Consistence Dry	Gravel %	Texture	CaCO3 Effervescense Morphology	Color (dry/moist)
A	0–4 (4)	aw	1fgr–pl	none	s	p	so–lo	0	fSiL	e none	2.5YR5/4d 2.5YR4/3m
2Bk	4–8 (4)	aw	1msbk	2dpf	s	p	sh	0	CL	e I	5YR5/3d 5YR4/3m
3Bk	8–20 (12)	aw	2m–csbk	none	so	ps	so	0	fSL	e I	2.5YR5/4d 2.5YR4/3m
4Bk	20–32 (12)	cs	1mabk	none	vs	vp	h	0	C	es I	5YR5/3d 5YR4/3m
Ck	32–120 (88)		m–sg	none	so	po	lo	0	LS–S	I–	

Profile No. LCR9 **Described by** Ralph Klinger, Jeanne Klawon **Date** 5/8/02 **Slope** 0° **Aspect** W

Map Unit 3b **Parent material** sandy alluvium

Location pit in left bank downstream from Obed bridge on APS access road **UTM Coords** 12S 0559802, 3866796

Quadrangle Joseph City, AZ **Township/Range**____ **Section**____ **Elevation**____

Horizon	Depth (Thickness) cm	Boundaries	Structure	Clay Films	Consistence			Gravel %	Texture	CaCO3 Effervescense Morphology	Color (dry/moist)
					Stickiness	Plasticity	Dry				
A	0–1 (1)	as	3cpl	none	s	p	sh	0	SiL	es none	2.5YR5/4d 2.5YR4/4m
Bk	1–14 (13)	aw	2fgr–msbk	none	vs	vp	so	0	CL	es I–	2.5YR5/4d 2.5YR4/4m
Bk2	14–31 (17)	cs	1–2msbk–sg	none	so	po	lo–so	0	fS	e I	5YR6/3d 5YR4/3m
C	31–43 (12)	as	sg	none				0		none	
C2	43–62 (19)	as	m	none				0		none	
C3	62–140+ (78)		sg	none				0		none	

Profile No. LCR10 **Described by** Ralph Klinger, Jeanne Klawon **Date** 5/8/02 **Slope** 0–1° **Aspect** N

Map Unit 4 **Parent material** fine–grained alluvium

Location roughly 50 m east of unit 3 riser **UTM Coords** 12S 0559915, 3866721

Quadrangle Joseph City **Township/Range** ____ **Section** ____ **Elevation** ____

Horizon	Depth (Thickness) cm	Boundaries	Structure	Clay Films	Consistence			Gravel %	Texture	CaCO3 Effervescense Morphology	Color (dry/moist)
					Stickiness	Plasticity	Dry				
A	0–6 (6)	aw	2fgr	none	s	p	lo–so	0	SCL	e none	2.5YR5/4d 2.4YR4/4m
Bk1	6–24 (18)	aw	1–2mgr–f–msbk	1dpf	vs	vp	sh–h	0	C	e I–	2.5YR5/4d 2.5YR4/4m
Bk2	24–49 (25)	as	2msbk	3ppf	vs	vp	h	0	SiC	e I	2.5YR5/4d 2.5YR4/4m
2Bk	49–57 (8)	as	1–2f–msbk	1fpo	vs	vp	h	0	SiC	es I–	5YR6/4d 5YR4/4m
3Bk1	57–77 (20)	aw	2m–csbk	3ppf	vs	vo	vh	0	C	es I	2.5YR5/4d 5YR4/4m
3Bk2	77–110 (33)	aw	3m–cabk	2ppf	vs	vp	vh	0	SiC	es I+	2.5YR5/4d 5YR4/4m
C	110–165 (55)		m		so	po	lo–so	0	vfLS–S	I+	

Profile No. LCR11 **Described by** Ralph Klinger, Jeanne Klawon **Date** 5/8/02 **Slope** 2° **Aspect** W

Map Unit 4 **Parent material** fine–grained alluvium

Location pit in left bank downstream of Obed bridge on APS access road **UTM Coords** 12S 0560073, 3866590

Quadrangle Joseph City **Township/Range** ____ **Section** ____ **Elevation** ____

Horizon	Depth (Thickness) cm	Boundaries	Structure	Clay Films	Consistence			Gravel %	Texture	CaCO3 Effervescense Morphology	Color (dry/moist)
					Stickiness	Plasticity	Dry				
Av	0–1 (1)	as	1cpl	none	ss	ps	sh	0	L	es none	2.5–5YR5/4d 2.5YR4/4m
Bk1	1–29 (28)	cw	3csbk	2dcp, 3ppf	vs	vp	h	0	C	es I	2.5YR5/4d 2.5YR4/4m
Bk2	29–54 (25)	cw	2m–csbk	2dco, 3ppf	vs	vp	h–vh	0	C	es I	2.5YR5/4d 2.5YR4/4m
Bk3	54–68 (14)	ds	1msbk	v1fpf	vs	vp	lo–so	0	SiCL	es I–	2.5YR6/3d 2.5YR4/4m
Bk4	68–95 (27)	as	1msbk	2dpf	vs	vp	sh	0	SiCL	e I–	2.5YR6/4d 2.5YR4/4m
2C	95–112 (17)	aw	1msbk	none	ss	ps	so	0	SiL	es none	2.5YR6/4d 2.5YR4/4m
2C2	112–158 (37)	aw	m	1–2dpf	vs	vp	sh	0	SiCL	e none	2.5YR5/4d 2.5YR4/4m
2C3	158–180+ (22)		sg	none	so	po	lo	0	S	none none	5YR6/3d 5YR5/3m

Profile No. LCR12 **Described by** Ralph Klinger, Jeanne Klawon **Date** 5/9/02 **Slope** 0° **Aspect** E

Map Unit 4 **Parent material** fine–grained alluvium

Location pit downstream of Clear Creek Dam and south of canal **UTM Coords** 12S 0533136, 3870927

Quadrangle Clear Creek Reservoir, AZ **Township/Range**____ **Section**____ **Elevation**____

Horizon	Depth (Thickness) cm	Boundaries	Structure	Clay Films	Consistence: Stickiness	Consistence: Plasticity	Consistence: Dry	Gravel %	Texture	CaCO3 Effervescense Morphology	Color (dry/moist)
O	+10 (10)		sg	none	so	po	lo	0	LS	e none	7.5YR5/4d 7.5YR3/2m
C1	0–29 (29)	aw	sg–m	none	so	po	lo	0	LS	e none	7.5YR6/3d 7.5YR4/4
C2	29–57 (28)	aw	m	none	vs	vp	h–vh	0	SiC	e–es none	7.5YR3/2m
C3	57–76 (19)	aw	m	none	vs	vp	h–vh	0	SiC	none none	5YR5/4d 5YR4/4m
C4	76–87 (11)	aw	m	none	vs	vp	h–vh	0	SiC	none none	5YR5/4d 5YR4/4m
C5	87–98 (11)	aw	m	none	vs	vp	h–vh	0	C	none none	
C6	98–115 (17)	aw	m	none	so	po	lo	0	LS	e none	7.5YR5/4d 7.5YR4/4m
C7	115–135 (20)	aw	m	none	s	p	sh	0	CL	e none	7.5YR4/3m
C8	135–145+ (10)		sg	none	so	po	lo	0	SL	es none	5YR6/4d 5YR4/3.5m

Notes:

Site has vegetated coppice dunes on surface.

Profile No. LCR13 **Described by** Ralph Klinger, Jeanne Klawon **Date** 5/9/02 **Slope** 0° **Aspect** W

Map Unit 4 **Parent material** fine–grained alluvium

Location pit north of I–40 and east of AZ87 **UTM Coords** 12S 0532194, 3874549

Quadrangle Winslow, AZ **Township/Range** T19N/R16E **Section** 28,SW1/4 **Elevation** 4853 ft

Horizon	Depth (Thickness) cm	Boundaries	Structure	Clay Films	Consistence Stickiness	Consistence Plasticity	Consistence Dry	Gravel %	Texture	CaCO3 Effervescense Morphology	Color (dry/moist)
	0–3 (3)	aw	2fpl–msbk	none	s	p	so	0	fL	es none	5YR5/4d 5YR3/3m
	3–7 (4)	aw	2fsbk	none	s	p	sh	0	Si	es I	5YR5/3d 5YR4/4m
	7–18 (11)	as	m	none	so	po	lo	0	fSL	es none	5YR5/4d 2.5YR4/4m
	18–24 (6)	cs	m	none	so	po	lo	0	LS	e none	5YR5/4d 5YR4/4m
	24–35 (11)	aw	m	none	so	po	lo	0	fSL	e none	5YR5/4d 5YR4/4m
	35–56 (21)	as	m	none	ss	ps	so	0	L	es none	5YR4/2d 5YR3/2m
	56–64 (8)	as	sg	none	so	po	lo	0	LS	e none	5YR6/3d 5YR4/3m
	64–89 (25)	cw	m	none	s	p	sh	0	L	es I–	5YR6/3d 5YR4/3m
	89–150 (61)		m	none	s	p	so–sh	0	SiCL	es I–	5YR6/3d 5YR4/3m

Profile No. LCR14 **Described by** Ralph Klinger, Jeanne Klawon **Date** 5/9/02 **Slope** 1° **Aspect** W

Map Unit 2 **Parent material** fine–grained alluvium and eolian sand

Location exposure in right bank downstream of Jackrabbit **UTM Coords** 12S 0551277, 3869312

Quadrangle Apache Butte, AZ **Township/Range** ____ **Section** ____ **Elevation** ____

Horizon	Depth (Thickness) cm	Boundaries	Structure	Clay Films	Consistence			Gravel %	Texture	CaCO3 Effervescense Morphology	Color (dry/moist)
					Stickiness	Plasticity	Dry				
C	0–12 (12)	aw	sg	none	so	po	lo	0	LS	e none	5YR6/2d 5YR4/3m
2C	12–42 (30)	ai	2msbk	none	s	p	sh	0	L	e I–	5YR5/3d 5YR4/3
2C2	42–62 (20)	as	m	none	so	po	so–sh	0	LS	e none	5YR6/3d 5YR4/3m
2C3	62–90 (28)	aw	sg	none			lo	0		e none	
2C4	90–130 (40)		m	none			lo	0		e none	

Profile No. LCR15 **Described by** Ralph Klinger, Jeanne Klawon **Date** 5/9/02 **Slope** 0° **Aspect** S

Map Unit 4 **Parent material** fine–grained alluvium and eolian sand

Location exposure in right bank near Jackrabbit, AZ **UTM Coords** 12S 0550863, 3869437

Quadrangle Apache Butte **Township/Range** **Section** **Elevation**

Horizon	Depth (Thickness) cm	Boundaries	Structure	Clay Films	Consistence			Gravel %	Texture	CaCO3 Effervescense Morphology	Color (dry/moist)
					Stickiness	Plasticity	Dry				
C	0–19 (19)	as	sg	none	so	po	lo–so	0	vf–fSL	e none	
2Bk	19–117 (98)	cs	3msbk	2dpf,po,co	vs	vp	h	0	SiC	es I	
2Bk2	117–150 (33)	as	3f–msbk	2dpf,po,co	vs	vp	h	0	SiC	es I–	
2C	150–170+ (20)		sg	none	so	po	lo	0	fLS	es none	

Notes:

All colors and textures estimated on the basis of previous descriptions.

APPENDIX B

PALEOBOTANICAL AND MACROFOSSIL ANALYSES

EXAMINATION OF BULK SOIL AND DETRITAL CHARCOAL FOR RADIOCARBON DATABLE MATERIAL FROM ALONG THE LITTLE COLORADO RIVER, ARIZONA

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Prepared For

Bureau of Reclamation

Reclamation Service Center

Denver, Colorado

July 2001

INTRODUCTION

Detrital charcoal samples from stream terrace deposits along the Little Colorado River, Arizona, were floated to recover organic fragments suitable for radiocarbon analysis. These samples were collected from natural exposures or soil pits as part of the Little Colorado River Sediment Transport Study. Botanic components and detrital charcoal were identified, and potentially datable material was separated.

METHODS

The charcoal samples were present in varying amounts of soil. The majority of the samples were water–screened through a 0.25 mm screen to separate the charcoal from the soil. Three of the larger samples were floated using a modification of the procedures outlined by Matthews (1979). The sample was added to approximately 3 gallons of water. The sample was stirred until a strong vortex formed, which was allowed to slow before pouring the light fraction through a 150 micron mesh sieve. Additional water was added and the process repeated until all visible macrofloral material was removed from the sample (a minimum of 5 times). The material which remained in the bottom (heavy fraction) was poured through a 0.5 mm mesh screen. The floated portions were allowed to dry.

The water–screened and floated samples were weighed, then passed through a series of graduated screens (US Standard Sieves with 4 mm, 2 mm, 1 mm, 0.5 mm and 0.25 mm openings to separate charcoal debris and to initially sort the remains. The contents of each screen were then examined. Charcoal pieces ranging in size from 2 mm to 0.25 mm in diameter were broken to expose a fresh cross–section and examined under a binocular microscope at a magnification of 70x. The remaining material in the 4 mm, 2 mm, 1 mm, 0.5 mm, and 0.25 mm sieves was scanned under a binocular stereo microscope at a magnification of 10x, with some identifications requiring magnifications of up to 70x. The material which passed through the 0.25 mm screen was not examined. Remains were recorded as charred and/or uncharred, whole and/or fragments.

Macrofloral remains, including charcoal, were identified using manuals (Core *et al.* 1976; Martin and Barkley 1973; Panshin and Zeeuw 1980; Petrides and Petrides 1992) and by comparison with modern and archaeological references. The term "seed" is used to represent seeds, achenes, caryopses, and other disseminules. Because charcoal and possibly other botanic remains were to be sent for radiocarbon analysis, clean laboratory conditions were used during flotation and identification to avoid contamination. All instruments were washed between samples, and samples were protected from contact with modern carbon.

DISCUSSION

A total of 27 charcoal samples were collected from natural exposures or soil pits on stream terrace deposits adjacent to the Little Colorado River between Holbrook and Winslow in northeastern Arizona. The terrace deposits are formed predominantly of sand, but are locally interstratified with pebbly sand and clay beds. Woody vegetation on the stream terraces historically included Cottonwood (*Populus*) and willow (*Salix*), but currently is dominated by Tamarisk (*Tamarix*).

Sample PR1–1 was collected from a depth of 29–42 cm (Table 1). This sample consisted of seven fragments of *Juniperus* charcoal weighing 0.132 g and one piece of *Quercus* charcoal weighing 0.015 g, reflecting juniper and oak wood that burned (Table 2, Table 3). Both charcoal types can be submitted for radiocarbon analysis. The minimum requirement of charcoal for standard AMS radiocarbon analysis reported by Beta Analytic, Inc. is 5 mg or 0.005 g; however, Beta now offers an AMS–MS dating technique for very small sample sizes. It may be possible to date charcoal weighing 1 mg or 0.001 g.

Sample LCR1–1 from a depth of 160–170 cm contained six fragments of *Juniperus* charcoal weighing 0.003 g and a piece of *Pinus* charcoal weighing less than 0.001 g. Several fragments of conifer charcoal not identified to genus and one piece of unidentified hardwood charcoal also were present.

Charcoal in sample LCR1–2 from a depth of 140–155 cm was dominated by several small fragments of *Juniperus* charcoal weighing 0.076 g. Other charcoal types present in the sample include 0.015 g of *Atriplex*, 0.026 g of Chenopodiaceae, 0.048 g of *Pinus*, and 0.008 g of Salicaceae. The sample also contained unidentified charcoal, a few uncharred rootlets from modern plants, and a few snail shells.

The few, small pieces of conifer charcoal in sample LC1–3 from a depth of 341 cm weighed less than 0.001 g. No wood charcoal fragments were present in samples LCR1–6 (441 cm) and LCR2–1 (114 cm); however, a charred *Juniperus* leaf fragment weighing 0.004 g was present in sample LCR1–6 that can be submitted for radiocarbon analysis, possibly the new AMS–MS technique.

Sample LCR2–2 was taken from a depth of 152–159 cm. This sample contained several pieces of conifer charcoal weighing 0.005 g and fewer pieces of unidentified hardwood charcoal weighing 0.003 g. The sample yielded several fragments of a black, coal–like material weighing 0.079 g. This material was hard, smooth, solid, shiny, and somewhat flaky. A few uncharred seeds and rootlets from modern plants and two insect chitin fragments also were present.

The few pieces of charcoal in sample LCR3C–1 from a depth of 362 cm were too small for identification and weighed less than 0.001 g. Sample LCR3C–2 from a depth of 140 cm, however, contained a variety of charcoal types including *Artemisia* weighing less than 0.001 g, *Atriplex* weighing 0.007 g, conifer charcoal weighing 0.006 g, *Juniperus* weighing 0.006 g, *Pinus* weighing 0.004 g, and *Quercus*, Salicaceae and unidentified charcoal each weighing less than 0.001 g. Recovery of one charred insect fecal pellet might indicate that some of the burned wood contained insects. Four small fragments of PET fruity tissue weighing less than 0.001 g probably represent fleshy fruit or berry tissue that burned, or succulent plant tissue such as cactus pads. The term PET (processed edible tissue) was originated by Nancy Stenholm (1993) and refers to softer tissue types, such as starchy parenchymoid or fruity epithelioid tissues. The sample also contained a few snail shells.

Sample LCR3C–3 from a depth of 95 cm contained two small pieces of Salicaceae charcoal weighing less than 0.001 g, as well as several small fragments of unidentified hardwood charcoal weighing 0.002 g. A piece of conifer charcoal weighing less than 0.001 g and several small fragments of unidentified hardwood charcoal weighing 0.001 g were present in sample LCR3C–4 from a depth of 165 cm.

Samples LCR3E–1 and LCR3E–2 were both collected at a depth of 130 cm. Sample LCR3E–1 contained a piece of vitrified conifer charcoal weighing 0.004 g. Vitrified material has a shiny, glassy appearance due to fusion by heat. It is possible that vitrified charcoal represents burning "green", fresh wood with a higher sap content. This sample also contained several fragments of the black, coal–like material weighing 0.075 g. Three pieces of *Pinus* charcoal weighing 0.011 g were present in sample LCR3E–2 that can be submitted for AMS radiocarbon analysis.

Sample LCR3F–1 was recovered from a depth of 193 cm. This sample yielded only a small amount of sand and no charcoal or other organic fragments.

Several small fragments of conifer charcoal weighing less than 0.001 g were present in sample LCR4–1 from a depth of 53 cm. A small piece of conifer charcoal weighing 0.002 g was present in sample LCR4–2 from a depth of 81 cm. This sample also yielded several fragments of black, coal–like material, as well as a few uncharred rootlets from modern plants, two insect chitin fragments, and two snail shell fragments.

Charcoal fragments in samples LCR4–3 (82 cm) and LCR4–4 (109 cm) were very small, weighing less than 0.001 g. Sample LCR4–3 contained conifer charcoal, unidentified hardwood, and charcoal too small for identification. A few uncharred rootlets and an insect chitin fragment complete the record. Conifer charcoal and charcoal too small for identification were present in sample LCR4–4, as well as two insect chitin fragments and a few uncharred seeds and rootlets from modern plants.

Sample LCR8–1 was collected at a depth of 55–57 cm. This sample contained a charred *Chenopodium* seed weighing less than 0.001 g, as well as uncharred *Chenopodium* and *Sphaeralcea* seeds. Charcoal types present in the sample include less than 0.001 g of conifer charcoal, 0.002 g of vitrified conifer charcoal, less than 0.001 g of *Juniperus* charcoal, 0.004 g of *Pinus* charcoal, less than 0.001 g of unidentified hardwood charcoal, and 0.013 g of unidentifiable vitrified charcoal. Two charred *Pinus* bark scale fragments weighing less than 0.001 g reflect pine logs/branches that burned. Several fragments of coal–like material weighing 0.206 g and a few snail shells also were present.

One charred *Abies/Pseudotsuga* needle fragment weighing less than 0.001 g was present in sample LCR8–2 from a depth of 42–44 cm. The sample contained pieces of conifer charcoal too small to identify to genus weighing 0.003 g, *Pinus* charcoal weighing 0.004 g, and *Pinus* charcoal with slightly rounded edges weighing 0.005 g. The *Pinus* charcoal identification was confirmed by the presence of Pinoid cross–field pitting. A few fragments of coal–like material, an insect chitin fragment, and an uncharred *Chenopodium* seed and a few rootlets from modern plants complete the record.

Charred remains in sample LCR12–1 from a depth of 98–115 cm include *Pinus* charcoal weighing 0.008 g, three *Pinus* bark scale fragments weighing 0.002 g, four pieces of unidentified vitrified tissue weighing 0.005 g, and unidentified charcoal weighing 0.005 g. The sample also contained a few snail shell fragments and an uncharred *Portulaca* seed and a few rootlets from modern plants.

Sample LCR12–2 from a depth of 115–125 cm contained seven fragments of *Pinus* charcoal weighing 0.010 g that can be submitted for AMS radiocarbon analysis. A few rootlets from modern plants and a few snail shell fragments also were present.

Sample LCR14–1 was recovered from a depth of 82–85 cm. This sample contained a variety of botanic remains, both charred and uncharred. Charred remains include an *Atriplex* fruit weighing 0.003 g, a *Chenopodium* seed fragment weighing less than 0.001 g, and unidentified seed fragments weighing less than 0.001 g. A charred unidentified seed with adhering PET fruity tissue weighing 0.001 g represents a fleshy fruit/berry that burned. Several charcoal types were present in this sample, dominated by *Pinus* weighing 0.023 g. Other charcoal types include *Artemisia* weighing 0.003 g, *Atriplex* weighing 0.005 g, conifer charcoal too small to identify to genus weighing 0.006 g, *Juniperus* with rounded edges weighing 0.003 g, *Pinus* with rounded edges weighing 0.015 g, *Fraxinus* weighing 0.011 g, *Quercus* weighing 0.004 g, unidentified hardwood charcoal weighing 0.006 g, and unidentified charcoal weighing 0.082 g. Many of the charcoal fragments exhibited an orangish coating on the outside, like an orangish sand, but the inner vessel walls did not appear to be coated with the same material. Recovery of a few charred insect fecal pellets suggests that some of the burned wood contained insects. An abundance of coal–like material also was present in the sample. One *Chara* oogonia fragment was present, representing stonewort, a green algae that grows best in hard water (high pH), often forming dense mats on the bottom of ponds. Stoneworts usually have a garlic–like odor and some species are covered by a brittle, limey crust. *Chara* is often found in still, nutrient–poor water (Reid 1987:36; Schoch *et al.* 1988:49). A few rodent fecal pellets, insect chitin fragments, and worm casts were present, indicating some subsurface disturbance from rodent, insect, and earthworm activity. Several types of uncharred seeds represent modern plants at the site, probably introduced through bioturbation. The sample also contained an uncharred *Papaver somniferum* seed, indicating introduction of non–native, historic/modern material into this area. *Papaver somniferum* (common poppy, opium poppy) is a native of the Mediterranean region that has been cultivated for the drug opium and for its seeds. The small, kidney–shaped seeds are used mostly to season breads and sweets, and an oil extracted from the seeds can be used as a substitute for olive oil (Hedrick 1972:407; McGee 1984213). An uncharred bone fragment, an ostracode carapace (shell) fragment, and a few snail shells also were recovered. Ostracodes are small, bivalved crustaceans widely distributed in fresh and saline water, normally under well oxygenated conditions in lakes, ponds, springs, and streams (Palacios–Fest *et al.* 1994:145).

Charcoal fragments in sample LCR14–2 from a depth of 110 cm were very small and consisted of conifer and unidentified hardwood charcoal weighing less than 0.001 g. The sample also contained uncharred *Chenopodium* seed fragments, an uncharred *Taraxacum* seed, and a few uncharred rootlets from modern plants. Several fragments of the coal–like material also were present.

One charred *Salsola* seed was present in sample LCR14–3 from a depth of 89 cm. *Salsola* is reported to have been introduced into the United States in 1873 or 1874 in a shipment of flax seed (Martin 1972:43). Charred Russian thistle seeds have been recovered from prehistoric archaeological samples in Wyoming, Colorado, Nebraska, and Utah, however, and might suggest that a Russian thistle existed in the United States before the historic introduction (Cummings and Puseman 1992; Puseman 1993; Roper 1996). The charcoal record consists of conifer charcoal weighing 0.007 g, unidentified hardwood charcoal weighing 0.002 g, and charcoal too small for identification weighing 0.001 g. A few uncharred seeds and rootlets represent modern plants in the area. The sample also contained fragments of coal–like material, an insect chitin fragment, snail shells, and a few worm casts.

Sample LCR14–4 was recovered from a depth of 47 cm and yielded pieces of conifer charcoal weighing 0.003 g, unidentified hardwood charcoal weighing 0.001 g, and two fragments of uncharred unidentified hardwood wood weighing 0.001 g. Two uncharred *Chenopodium* seed fragments and a few rootlets represent modern plants. Fragments of coal–like material and four insect chitin fragments complete the record.

Charcoal present in sample LCR14–5 from a depth of 27 cm includes conifer weighing 0.005 g, *Pinus* weighing 0.003 g, unidentified hardwood charcoal weighing 0.002 g, and charcoal too small for identification weighing less than 0.001 g. The sample also contained uncharred conifer and unidentified wood, as well as an uncharred *Chenopodium* seed fragment and a few uncharred rootlets from modern plants. Non–floral remains include coal–like material, two snail shell fragments, and a few worm casts.

SUMMARY AND CONCLUSIONS

Examination of charcoal samples from Little Colorado River Sediment Transport Study resulted in recovery of charcoal and other charred botanic remains that can be submitted for radiocarbon analysis. The majority of the samples were small, often resulting in minute amounts of recovered charcoal. Larger sample sizes might have resulted in larger amounts of charcoal for radiocarbon analysis.

TABLE 1
PROVENIENCE DATA FOR SAMPLES FROM ALONG THE LITTLE COLORADO RIVER, ARIZONA

Sample No.	Depth (cm)	Description	Analysis
PR1–1	29–42	Charcoal	Charcoal ID for radiocarbon analysis
LCR1–1	160–170	Charcoal in sediment	Charcoal ID for radiocarbon analysis
LCR1–2	140–155	Charcoal in sediment	Charcoal ID for radiocarbon analysis
LCR1–3	341	Charcoal in sediment	Charcoal ID for radiocarbon analysis
LCR1–6	441	Charcoal in sediment	Charcoal ID for radiocarbon analysis
LCR2–1	114	Charcoal in sediment	Charcoal ID for radiocarbon analysis
LCR2–2	152–159	Charcoal in sediment	Float/Charcoal ID for radiocarbon analysis
LCR3C–1	362	Charcoal in sediment	Charcoal ID for radiocarbon analysis
LCR3C–2	140	Charcoal in sediment	Charcoal ID for radiocarbon analysis
LCR3C–3	95	Charcoal in sediment	Charcoal ID for radiocarbon analysis
LCR3C–4	165	Charcoal in sediment	Charcoal ID for radiocarbon analysis
LCR3E–1	130	Charcoal in sediment	Charcoal ID for radiocarbon analysis
LCR3E–2	130	Charcoal in sediment	Charcoal ID for radiocarbon analysis
LCR3F–1	193	Charcoal in sediment	Charcoal ID for radiocarbon analysis
LCR4–1	53	Charcoal in sediment	Charcoal ID for radiocarbon analysis
LCR4–2	81	Charcoal in sediment	Charcoal ID for radiocarbon analysis
LCR4–3	82	Charcoal in sediment	Charcoal ID for radiocarbon analysis
LCR4–4	109	Charcoal in sediment	Charcoal ID for radiocarbon analysis
LCR8–1	55–57	Charcoal in sediment	Charcoal ID for radiocarbon analysis
LCR8–2	42–44	Charcoal in sediment	Charcoal ID for radiocarbon analysis

Sample No.	Depth (cm)	Description	Analysis
LCR12–1	98–115	Charcoal in sediment	Float/Charcoal ID for radiocarbon analysis
LCR12–2	115–125	Charcoal in sediment	Float/Charcoal ID for radiocarbon analysis
LCR14–1	82–85	Charcoal in sediment	Charcoal ID for radiocarbon analysis
LCR14–2	110	Charcoal in sediment	Charcoal ID for radiocarbon analysis
LCR14–3	89	Charcoal in sediment	Charcoal ID for radiocarbon analysis
LCR14–4	47	Charcoal in sediment	Charcoal ID for radiocarbon analysis
LCR14–5	27	Charcoal in sediment	Charcoal ID for radiocarbon analysis

TABLE 2
MACROFLORAL REMAINS FROM ALONG THE LITTLE COLORADO RIVER, ARIZONA

Sample No.	Identification	Part	Charred		Uncharred		Weights/ Comments
PR1–1	CHARCOAL/WOOD:						
29–42 cm	Juniperus	Charcoal		7			0.132 g
	Quercus	Charcoal		1			0.015 g
LCR1–1	Volume Floated						20 ml
160–170	Floated Sample Weight						0.70g
cm	FLORAL REMAINS:						
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	Conifer	Charcoal		21			0.003g
	Juniperus	Charcoal		6			0.003g
	Pinus	Charcoal		1			<0.001g
	Unidentified hardwood	Charcoal		1			<0.001g
	NON–FLORAL REMAINS:						
	Sand					X	Scant
LCR1–2	Volume Floated						300 ml
140–155	Floated Sample Weight						4.81g
cm	FLORAL REMAINS:						
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	Chenopodiaceae	Charcoal		8			0.026g
	Atriplex	Charcoal		5			0.015g
	Juniperus	Charcoal		12			0.076g
	Pinus	Charcoal		8			0.048g
	Salicaceae	Charcoal		2			0.008g
	Unidentified $\geq$ 1 mm	Charcoal		X			0.436g
	NON–FLORAL REMAINS:						
	Sand					X	Few
	Snail shell				X	X	Few
LCR1–3	Volume Floated						<5 ml
341 cm	Floated Sample Weight						0.06g
	FLORAL REMAINS:						
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	Conifer	Charcoal		4			<0.001g
LCR1–6	Volume Floated						5 ml
441 cm	Floated Sample Weight						0.207g
	FLORAL REMAINS:						
	Juniperus	Leaf		1			0.004g
	Rootlets					X	Few
	NON–FLORAL REMAINS:						
	Sand					X	Few
LCR2–1	Volume Floated						5 ml
114 cm	Floated Sample Weight						0.39g
	FLORAL REMAINS:						
	Rootlets					X	Few
	NON–FLORAL REMAINS:						
	Sand					X	Few
LCR2–2	Volume Floated						1.00 L
152–159	Floated Sample Weight						5.56 g
cm	FLORAL REMAINS:						
	Chenopodium	Seed				1	
	Poaceae	Floret			1		
	Scirpus	Seed			4	2	
	Rootlets					X	Few

Sample No.	Identification	Part	Charred		Uncharred		Weights/ Comments
	CHARCOAL/WOOD:						
	Conifer	Charcoal		10			0.005g
	Unidentified hardwood	Charcoal		5			0.003g
	NON–FLORAL REMAINS:						
	Coal–like material $\geq$ 1 mm					X	0.079g
	Insect	Chitin				2	
	Sand					X	
LCR3C–1	Volume Floated						<5 ml
362 cm	Floated Sample Weight						0.059g
	CHARCOAL/WOOD:						
	Unidentifiable–small	Charcoal		4			<0.001g
	NON–FLORAL REMAINS:						
	Sand					X	Scant
LCR3C–2	Volume Floated						75 ml
140 cm	Floated Sample Weight						0.604g
	FLORAL REMAINS:						
	PET Fruity	Tissue		4			<0.001g
	CHARCOAL/WOOD:						
	Total charcoal $\geq$ 0.5mm						0.075g
	Artemisia	Charcoal		3			<0.001g
	Atriplex	Charcoal		6			0.007g
	Conifer	Charcoal		3.5			0.006g
	Juniperus	Charcoal		9			0.006g
	Pinus	Charcoal		16			0.004g
	Quercus	Charcoal		1			<0.001g
	Salicaceae	Charcoal		3			<0.001g
	Unidentified hardwood	Charcoal		1			<0.001g
	NON–FLORAL REMAINS:						
	Insect fecal pellet		1				<0.001g
	Sand					X	Few
	Snail shell					X	Few
LCR3C–3	Volume Floated						5 ml
95 cm	Floated Sample Weight						0.104g
	CHARCOAL/WOOD:						
	Salicaceae	Charcoal		2			<0.001g
	Unidentified hardwood	Charcoal		X			0.002g
	NON–FLORAL REMAINS:						
	Sand					X	Few
LCR3C–4	Volume Floated						<5ml
165 cm	Floated Sample Weight						0.010g
	CHARCOAL/WOOD:						
	Total charcoal $\geq$ 0.25 mm						0.005g
	Conifer	Charcoal		1			<0.001g
	Unidentified hardwood	Charcoal		X			0.001g
	NON–FLORAL REMAINS:						
	Sand					X	Few
LCR3E–1	Volume Floated						<5 ml
130 cm	Floated Sample Weight						0.76g
	CHARCOAL/WOOD:						
	Conifer–vitrified	Charcoal		1			0.004g
	NON–FLORAL REMAINS:						
	Coal–like material $\geq$ 1mm						0.075g
	Sand						Few
LCR3E–2	Volume Floated						<5 ml
130 cm	Floated Sample Weight						0.068g
	CHARCOAL/WOOD:						
	Pinus	Charcoal		3			0.011g

Sample No.	Identification	Part	Charred		Uncharred		Weights/ Comments
	NON–FLORAL REMAINS:						
	Sand					X	Few
LCR3F–1	Volume Floated						15 ml
193 cm	Floated Sample Weight						0.038g
	NON–FLORAL REMAINS:						
	Sand					X	Few
LCR4–1	Volume Floated						5 ml
53 cm	Floated Sample Weight						0.045g
	CHARCOAL/WOOD:						
	Conifer	Charcoal		50			<0.001g
	NON–FLORAL REMAINS:						
	Sand					X	Few
LCR4–2	Volume Floated						25 ml
81 cm	Floated Sample Weight						0.63g
	FLORAL REMAINS:						
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	Conifer – rounded	Charcoal		1			0.002g
	NON–FLORAL REMAINS:						
	Coal–like material ≥ 1mm					X	0.039g
	Insect	Chitin				2	
	Sand					X	Few
	Snail shell					2	
LCR4–3	Volume Floated						35 ml
82 cm	Floated Sample Weight						0.19g
	FLORAL REMAINS:						
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	Conifer	Charcoal		3			<0.001g
	Unidentified hardwood	Charcoal		1			<0.001g
	Unidentifiable – small	Charcoal		18			<0.001g
	NON–FLORAL REMAINS:						
	Insect	Chitin				1	
	Sand					X	Few
LCR4–4	Volume Floated						5 ml
109 cm	Floated Sample Weight						0.33g
	FLORAL REMAINS:						
	Atriplex					1	
	Portulaca					1	
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	Conifer	Charcoal		1			<0.001g
	Unidentifiable–small	Charcoal		3			<0.001g
	NON–FLORAL REMAINS:						
	Insect	Chitin				2	
	Sand					X	Few
LCR8–1	Volume Floated						200 ml
55–57 cm	Floated Sample Weight						93.57g
	FLORAL REMAINS:						
	Chenopodium	Seed		1			<0.001 g
	Chenopodium	Seed			1	2	
	Pinus	Bark scale		2			<0.001 g
	Sphaeralcea	Seed			1		
LCR8–1	CHARCOAL/WOOD:						
55–57 cm	Conifer	Charcoal		3			<0.001g
	Conifer – vitrified	Charcoal		4			0.002 g
	Juniperus	Charcoal		1			<0.001 g

Sample No.	Identification	Part	Charred		Uncharred		Weights/ Comments
	Pinus	Charcoal		3			0.004 g
	Unidentified hardwood	Charcoal		2			<0.001 g
	Unidentifiable – vitrified	Charcoal		X			0.013 g
	NON–FLORAL REMAINS:						
	Coal–like material ≥ 1 mm					X	0.206g
	Sand					X	Few
	Snail shell					X	Few
LCR8–2	Volume Floated						15 ml
42–44 cm	Floated Sample Weight						0.34g
	FLORAL REMAINS:						
	Abies/Pseudotsuga	Needle		1			<0.001g
	Chenopodium	Seed				1	
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	Conifer–small	Charcoal		20			0.003g
	Pinus	Charcoal		8			0.004g
	Pinus – slightly rounded	Charcoal		2			0.005g
	NON–FLORAL REMAINS:						
	Coal–like material					X	Few
	Insect	Chitin				1	
	Sand					X	Few
LCR12–1	Volume Floated						1.0 L
98–115 cm	Floated Sample Weight						13.85g
	FLORAL REMAINS:						
	Pinus	Bark scale		3			0.002g
	Vitrified tissue			4			0.005g
	Portulaca	Seed			1		
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	Pinus	Charcoal		31			0.008g
	Unidentified ≥ 0.5mm	Charcoal		X			0.005g
LCR12–1	NON–FLORAL REMAINS:						
98–115 cm	Sand					X	Few
	Snail shell					X	Few
LCR12–2	Volume Floated						600 ml
115–125	Floated Sample Weight						13.15g
cm	FLORAL REMAINS:						
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	Pinus	Charcoal		7			0.010g
	NON–FLORAL REMAINS:						
	Sand					X	Few
	Snail shell					X	Few
	NON–FLORAL REMAINS:						
	Bone					1	
	Coal–like material					X	Abundant
	Insect fecal pellet		X				Few
	Insect	Chitin				4	
	Ostracode carapace					1	
	Rodent fecal pellet				X	X	Few
	Snail shell				2	X	Few
	Worm casts				X		Few
LCR14–1	Volume Floated						50 ml
82–85 cm	Floated Sample Weight						14.479g
	FLORAL REMAINS:						
	Atriplex	Fruit	1				0.003g
	Chenopodium	Seed		1			< 0.001g

Sample No.	Identification	Part	Charred		Uncharred		Weights/ Comments
	Unidentified	Seed		4			< 0.001g
	Unidentified seed with adhering PET fruity tissue			1			0.001g
	Amaranthus	Seed			7	7	
	Atriplex	Seed			14		
	Chara	Oogonia				1	
	Chenopodium	Seed			78	38	
	Cleome	Seed				1	
	Echinocereus	Seed			1	2	
	Eleocharis	Seed			1		
	Euphorbia	Seed				5	
	Helianthus	Seed				1	
	Papaver somniferum	Seed			1		
	Portulaca	Seed			8		
	Scirpus	Seed			1	2	
	Solanum	Seed			1		
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	Artemisia	Charcoal		2			0.003g
	Atriplex	Charcoal		3			0.005g
	Conifer	Charcoal		8			0.006g
	Juniperus – rounded	Charcoal		2			0.003g
	Pinus	Charcoal		25			0.023g
	Pinus	Charcoal		14			0.015g
	Fraxinus	Charcoal		5			0.011g
	Quercus	Charcoal		2			0.004g
	Unidentified hardwood	Charcoal		4			0.005g
	Unidentified $\geq$ 2 mm	Charcoal		X			0.082g
LCR14–1	NON–FLORAL REMAINS:						
82–85 cm	Bone					1	
	Coal–like material					X	Abundant
	Insect fecal pellet		X				Few
	Insect	Chitin				4	
	Ostracode carapace					1	
	Rodent fecal pellet				X	X	
	Snail shell				2	X	
	Worm casts				X		Few
LCR14–2	Volume Floated						50 ml
110 cm	Floated Sample Weight						5.920g
	FLORAL REMAINS:						
	Chenopodium	Seed				3	
	Taraxacum	Seed			1		
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	Conifer	Charcoal		10			<0.001g
	Unidentified hardwood	Charcoal		1			<0.001g
	NON–FLORAL REMAINS:						
	Coal–like material $\geq$ 2mm					X	0.142g
	Sand					X	
LCR14–3	Volume Floated						45 ml
89 cm	Floated Sample Weight						3.51g
	FLORAL REMAINS:						
	Salsola	Seed		1			
	Chenopodium	Seed			7	6	
	Euphorbia	Seed				1	
	Portulaca	Seed			1		
	Verbena	Seed			1		

Sample No.	Identification	Part	Charred		Uncharred		Weights/ Comments
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	Conifer	Charcoal		19			0.007g
	Unidentified hardwood	Charcoal		7			0.002g
	Unidentifiable–small	Charcoal		X			0.001g
LCR14–3	NON–FLORAL REMAINS:						
89 cm	Coal–like material ≥ 2mm					X	0.433g
	Insect	Chitin				1	
	Sand					X	
	Snail shell ≥ 0.5mm					18*	
	Worm casts				X		Few
LCR14–4	Volume Floated						50 ml
47 cm	Floated Sample Weight						5.66g
	FLORAL REMAINS:						
	Chenopodium	Seed				2	
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	Conifer	Charcoal		6			0.003g
	Unidentified hardwood	Charcoal		3			0.001g
	Unidentified hardwood	Wood				2	0.001g
	NON–FLORAL REMAINS:						
	Coal–like material ≥ 1mm					X	0.022g
	Insect	Chitin				4	
	Sand					X	
LCR14–5	Volume Floated						25 ml
27 cm	Floated Sample Weight						9.25g
	FLORAL REMAINS:						
	Chenopodium	Seed				1	
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	Conifer	Charcoal		18			0.005g
	Pinus	Charcoal		2			0.003g
	Unidentified hardwood	Charcoal		1			0.002g
	Unidentifiable–small	Charcoal		X			<0.001g
	Conifer	Wood				7	0.009g
	Unidentified	Wood				X	0.001g
LCR14–5	NON–FLORAL REMAINS:						
27 cm	Coal–like material ≥ 1mm					X	0.009g
	Sand						
	Snail shell					2	
	Worm casts				X	X	Few

W = Whole

F = Fragment

X = Presence noted in sample

g = grams

* = Estimated frequency

TABLE 3
INDEX OF MACROFLORAL REMAINS RECOVERED FROM ALONG THE LITTLE COLORADO RIVER, ARIZONA

Scientific Name	Common Name
FLORAL REMAINS:	
Abies/Pseudotsuga	Fir/Douglas–fir
Chara	Stonewort (a green algae)
Cleome	Beeweed
Amaranthus	Pigweed, Amaranth
Chenopodium	Goosefoot
Salsola	Russian thistle
Scirpus	Bulrush, Threesquares
Echinocereus	Hedgehog cactus, Strawberry cactus
Eleocharis	Spikerush
Euphorbia	Spurge
Helianthus	Sunflower
Juniperus	Juniper
Papaver somniferum	Common poppy, opium poppy
Pinus	Pine
Poaceae	Grass family
Portulaca	Purslane
Solanum	Nightshade
Sphaeralcea	Globemallow
Taraxcum	Dandelion
Verbena	Verbena
PET fruity tissue	Fruity epithelioid tissues; resemble sugar–laden fruit or berry tissue without the seeds, or succulent plant tissue such as cactus pads

CHARCOAL/WOOD:	
Artemisia	Sagebrush
Chenopodiaceae	Goosefoot family
Atriplex	Saltbush
Conifer	Cone-bearing, gymnospermous trees and shrubs, mostly evergreens, including the pine, spruce, fir, juniper, cedar, yew, and cypress
Juniperus	Juniper
Pinus	Pine
Quercus	Oak
Salicaceae	Willow Family
NON-FLORAL REMAINS:	
Ostracode	Small, bivalved crustacean of fresh and salt water, normally under well oxygenated conditions

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Identification of snail shells collected from the Little Colorado River sediments

Letter Report

by

Emmett Evanoff

Museum of Natural History

University of Colorado

Boulder, Colorado

Prepared For

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August 2002

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Dear Jeanne:

I have examined the snail shells from the Little Colorado River sediments, and they are all land snails. All of the samples contain some sort of succineid. The only identifiable taxon was *Succinea* spp., that is a land snail that cannot be identified from its shell below the level of genus. Living *Succinea* spp. lives in moist habitats not far from standing waters, though I have seen the shells of *Succinea* in dry habitats far from rivers or other standing water. The second most abundant snail represented in these collections is *Pupoides hordaceus.* This snail is very widespread in the Colorado Plateau and lives in a wide range of habitats, ranging from moist areas near standing water to very dry habitats on uplands. *Pupilla muscorum* is also a widespread land snail, occurring throughout the temperate regions of North America. P. *muscorum* also has a wide range in habitats, though it typically does not occur in the very dry habitats P. *hordaceus* can exist. *Gasirocopta cristata* is much more restricted in its distribution, both geographically (limited to the southwestern states ranging from Texas and Oklahoma to Arizona) and environmentally. G. *cristata* is typically found in moist wooded habitats on flood plains and canyon bottoms, though it has been reported to occur in dry grassy areas. Finally, *Vallonia* spp. is very widespread throughout North America and in the western U.S. It can live in a variety of habitats ranging from moist areas near standing water to very dry habitats on uplands. Taken together, these snails probably are reflecting moist, well vegetated habitats not far from standing water. None of these snails are deep burrowers during times of drought, when they typically burrow down to the base of the leaf litter in soils. All of these snails are known to live in and adjacent to the modern Colorado Plateau and to occur in Pleistocene deposits in the region. Therefore, none are age specific beyond the designation of Quaternary.

Sincerely,

Emmett Evanoff

Taxonomic List of the Mollusks Collected in the Little Colorado River Project

Phylum Mollusca
Class Gastropoda
Subclass Pulmonata
Order Geophila
Family Succineidae
Genus *Succinea* Draparnaud, 1801
Succinea spp.
Family Pupillidae
Genus *Pupoides* Pfeiffer, 1854
Pupoides hordaceus (Gabb), 1866
Genus *Pupilla* Leach (in Fleming), 1828
Pupilla muscorum (Linneaus), 1758
Genus Gastrocopta Wollaston, 1878
Gastrocopta cristata (Pilsbry & Vanetta), 1900 Family Valloniidae
Genus *Vallonia* Risso, 1826
Vallonia spp.

Taxonomic List by Site for the Little Colorado River Project:

LCR1–2, 140–155 cm

Gastrocopta cristata (8), *Pupoides hordaceus* (7), *Pupilla muscorum* (3), *Succinea* spp. (2), *Vallonia* spp. (1)

LCR1–4, 341 cm, 5/4/02, REK/JEK

Shell fragments of a succineid.

LCR1–5, 441 cm, 5/4/02, REK/JEK

Very fragmented shells, probably of a succineid.

LCR3E–3, @135 cm, 5/6/02, REK/JEK

Fragments of a succineid; Juvenile whorls of *Pupoides hordaceus* (1).

LCR3E–4, @ 142 cm, 5/6/02, REK/JEK

Succinea spp. (1)

APPENDIX C

SUMMARY OF BED MATERIAL SAMPLES

HEC RAS Station No.	Location Description	d_{16} (mm)	d_{50} (mm)	d_{84} (mm)	d_g [S(d_{84}*d_{16})]
	Leroux Wash – u/s of Route 77 bridge	0.144	0.261	0.506	0.270
	Leroux Wash – u/s of Route 77 bridge	0.152	0.385	1.324	0.448
	Leroux Wash – u/s of Route 77 bridge – bank approx 3 feet high	0.081	0.152	0.252	0.143
	Leroux Wash – u/s of Route 77 bridge	0.146	0.319	1.223	0.423
	Puerco R., Railroad bridge u/s of railroad crossing	0.074	0.144	0.243	0.134
	Puerco R, Railroad bridge u/s of railroad crossing	NA	0.077	0.135	NA
	Puerco R, Railroad bridge u/s of railroad crossing	NA	0.081	0.158	NA
	Puerco R, Railroad bridge u/s of railroad crossing	NA	NA	0.244	NA
	Little CO, u/s of Little Co and Silver Creek confluence – high above channel, terrace	0.177	0.328	0.469	0.288
	Silver Creek, d/s of Woodruff Dam	NA	NA	NA	NA
	Little CO, near pipe crossing, 10–12 mi u/s of Holbrook	NA	0.160	0.367	NA
	Little CO, d/s of Penzance Dam	NA	0.094	0.298	NA
4630	Little CO, d/s of Penzance Dam	NA	0.162	0.260	NA
	Little CO, d/s of Penzance Dam	0.094	0.201	0.358	0.183
	Joseph City Wash	0.165	0.293	0.485	0.283
3710	Little CO, d/s of Joseph City Wash, top, main	0.167	0.273	0.425	0.266
	Little CO, d/s of Joseph City Wash, top, bar	0.095	0.191	0.285	0.164
3790	Little CO, d/s of Obed bridge, top, main	0.086	0.189	0.261	0.149
	Cottonwood Wash, d/s of frontage road	0.124	0.212	0.323	0.200
	Little CO u/s I–40		0.089	0.145	
1180	Little CO u/s I–40	0.169	0.259	0.374	0.252
	Little CO u/s I–40 – terrace	0.154	0.248	0.381	0.243
	Little CO u/s I–40 – bank	0.095	0.183	0.256	0.156
	Little CO, near Levee Failure, bank	NA	NA	NA	NA
960	Little CO, near State Park	NA	NA	NA	NA
	Little CO, near State Park – bedrock sample	NA	0.440	2.578	NA
	Little CO, between Holbrook and Woodruff, terrace	NA	0.082	0.187	NA
	Little CO, hwy 180 bridge	NA	NA	NA	NA
	Little CO, between Holbrook and Woodruff	NA	0.187	0.340	NA
4650	Little CO, above Penzance Dam	0.137	0.209	0.304	0.204
	Cottonwood Wash, above I–40 bridge	0.103	0.194	0.277	0.169
	Puerco River above Holbrook	0.081	0.128	0.227	0.135
5730	Little CO, between hwy 77 and Apache Railroad	NA	0.109	0.197	NA
	Little CO, above hwy 180 bridge	NA	0.083	0.183	NA
	Little CO, beneath hwy 180 bridge	NA	0.104	0.222	NA
	Little CO, d/s of Winslow 35 09.147', 110 40.943'	NA	NA	0.113	NA

	LCR, @ Highway 180 bridge, Bed Material u/s of bridge	NA	0.107	0.174	NA
	LCR u/s of Highway 180 Bridge	NA	0.097	0.204	NA
	LCR u/s of Railyard	0.123	0.196	0.273	0.183
	LCR u/s of Railyard	0.156	0.213	0.290	0.213
	Puerco River 600 yds u/s of Confluence w/ LCR	0.162	0.232	0.346	0.237
	LCR between Highway and Pipe Xing	0.126	0.202	0.287	0.190
6170	LCR d/s of Puerco confluence	0.107	0.186	0.270	0.170
	LCR opp. Exit 283	0.109	0.188	0.271	0.172
	Puerco River u/s LCR confluence, 200 yds	0.160	0.260	0.400	0.253
5910	LCR between Holbrook and Puerco–LCR confluence	0.155	0.215	0.302	0.216
	Leroux, opp. Truck Stop Exit 283	0.107	0.191	0.288	0.176
5830	LCR, between Puerco River and Holbrook Bridge	0.157	0.213	0.290	0.213
5260	LCR, @ mile 284	0.118	0.191	0.263	0.176
	Leroux Wash u/s of I–40	0.179	0.347	2.074	0.609
	LCR below R.R. bridge	0.146	0.243	0.386	0.238
200	Downstream of Winslow	0.109	0.186	0.265	0.170
600	Downstream of Winslow	0.083	0.116	0.188	0.125
670	Downstream of Winslow	0.097	0.168	0.248	0.155
920	Downstream of Winslow	0.157	0.209	0.280	0.209
1050	Downstream of Winslow	0.296	0.285	0.396	0.342
1170	Downstream of Winslow	0.096	0.172	0.274	0.162

Note: Only bed material taken from the main channel of the Little Colorado River was used in the sediment transport modeling.

APPENDIX D

INDEX MAP OF SHOWING CROSS SECTION LOCATIONS


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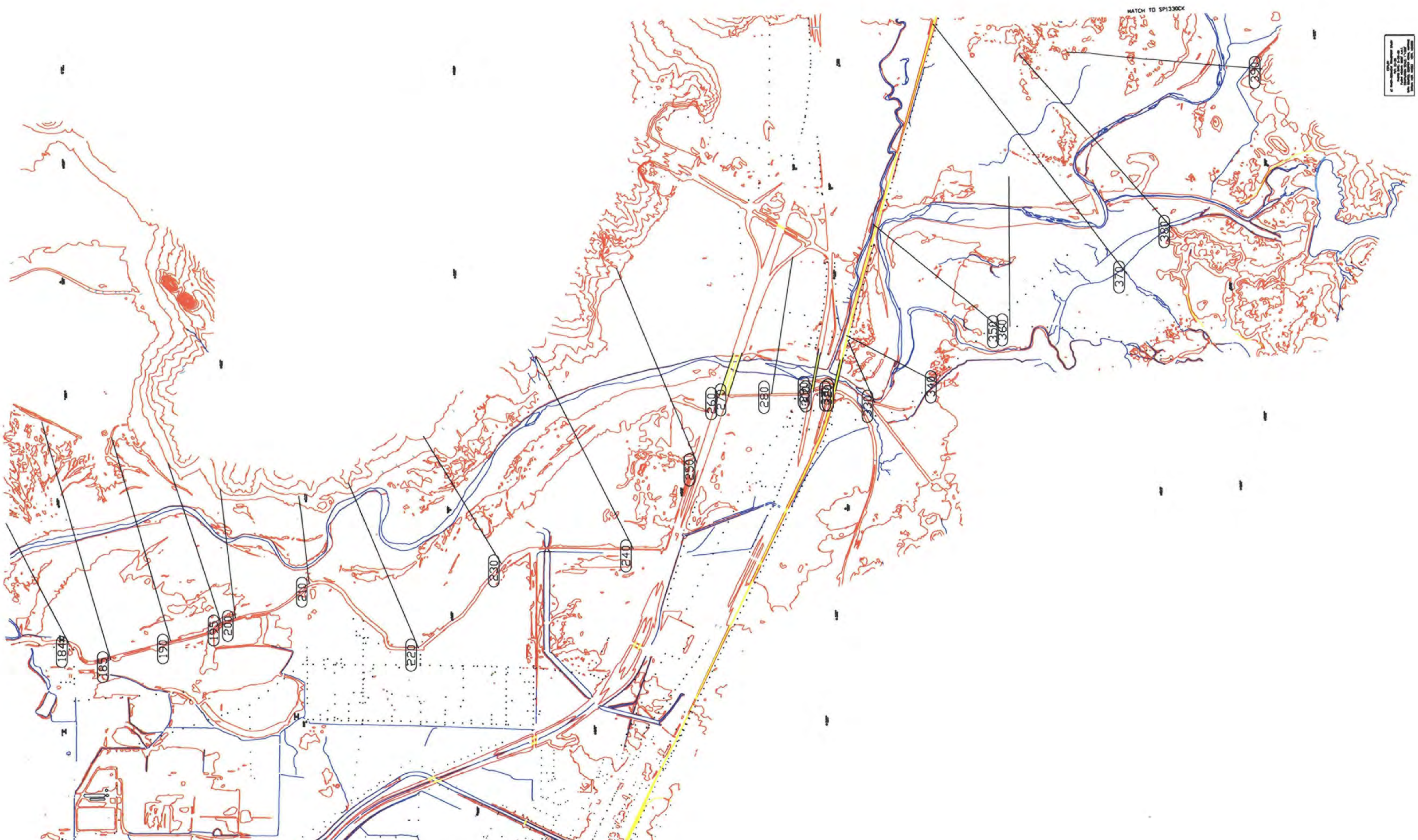
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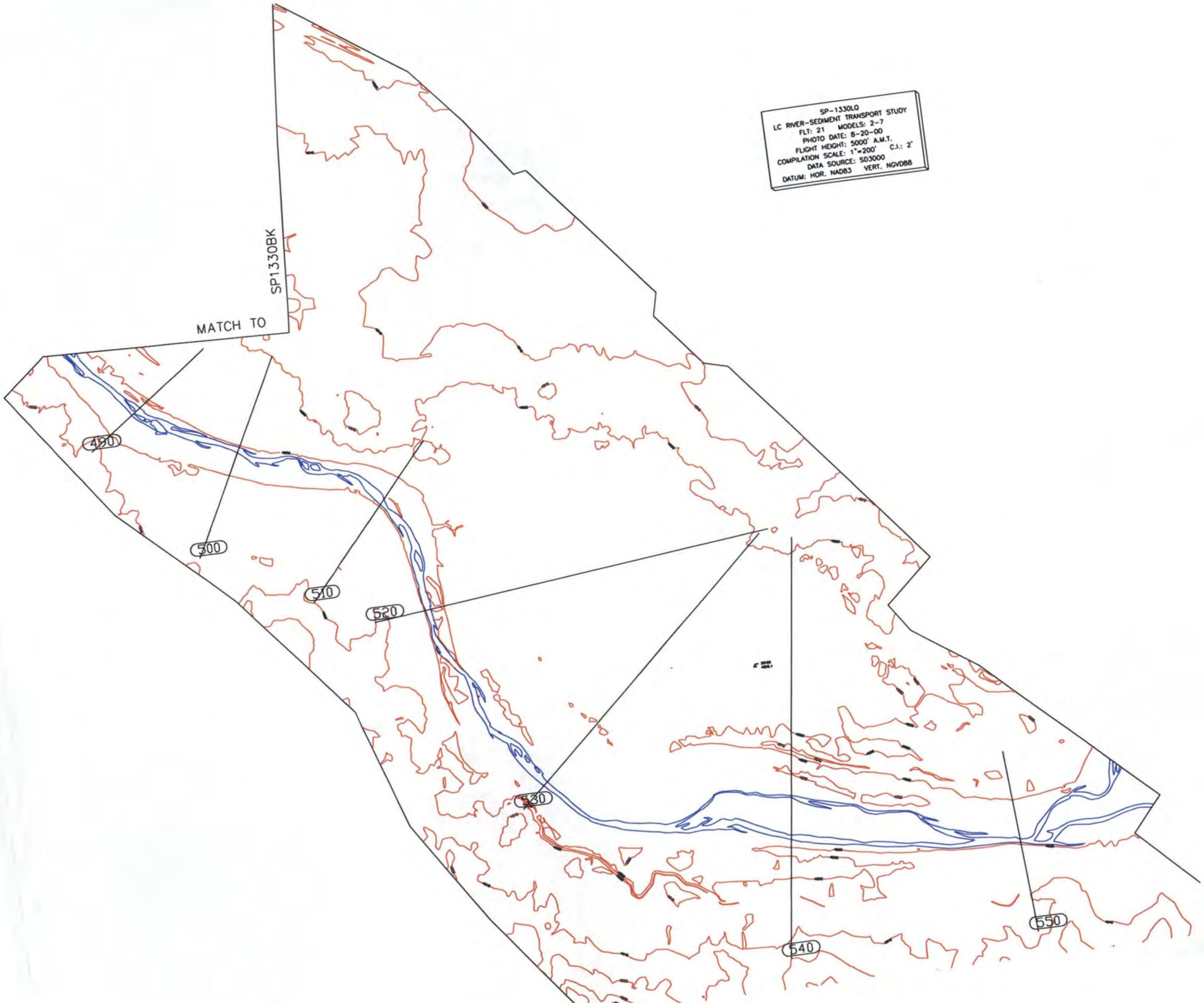

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FLIGHT HEIGHT: 5000' A.M.T.
COMPILATION SCALE: 1"=200' C.I.: 2'
DATA SOURCE: SD3000
DATUM: HOR. NAD83 VERT. NGVD88
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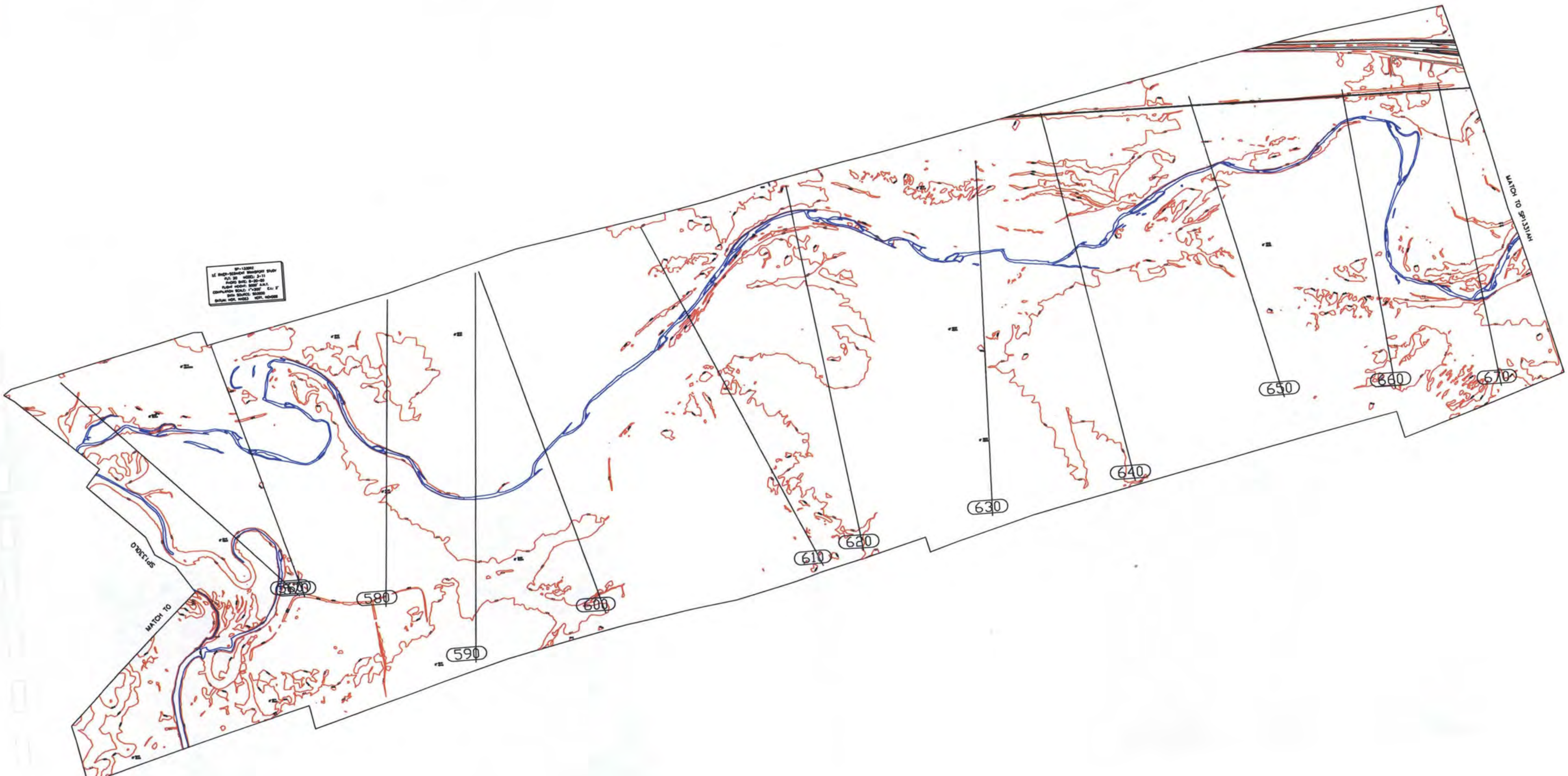

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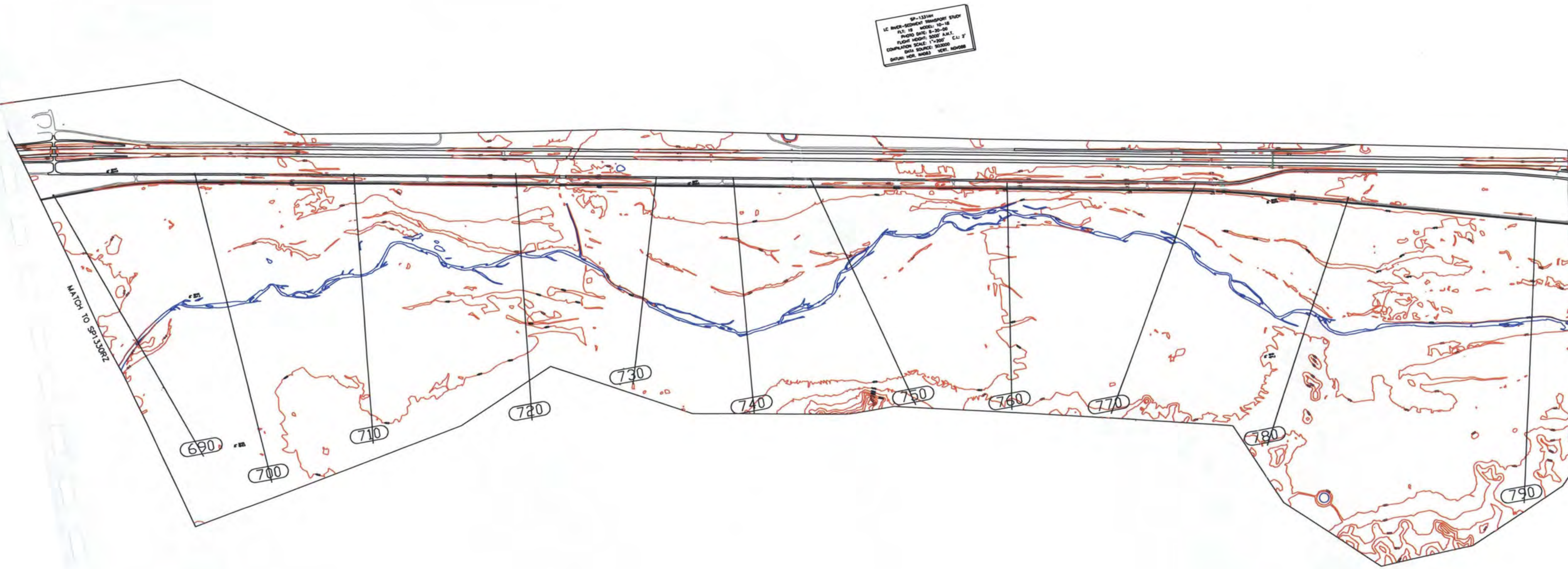
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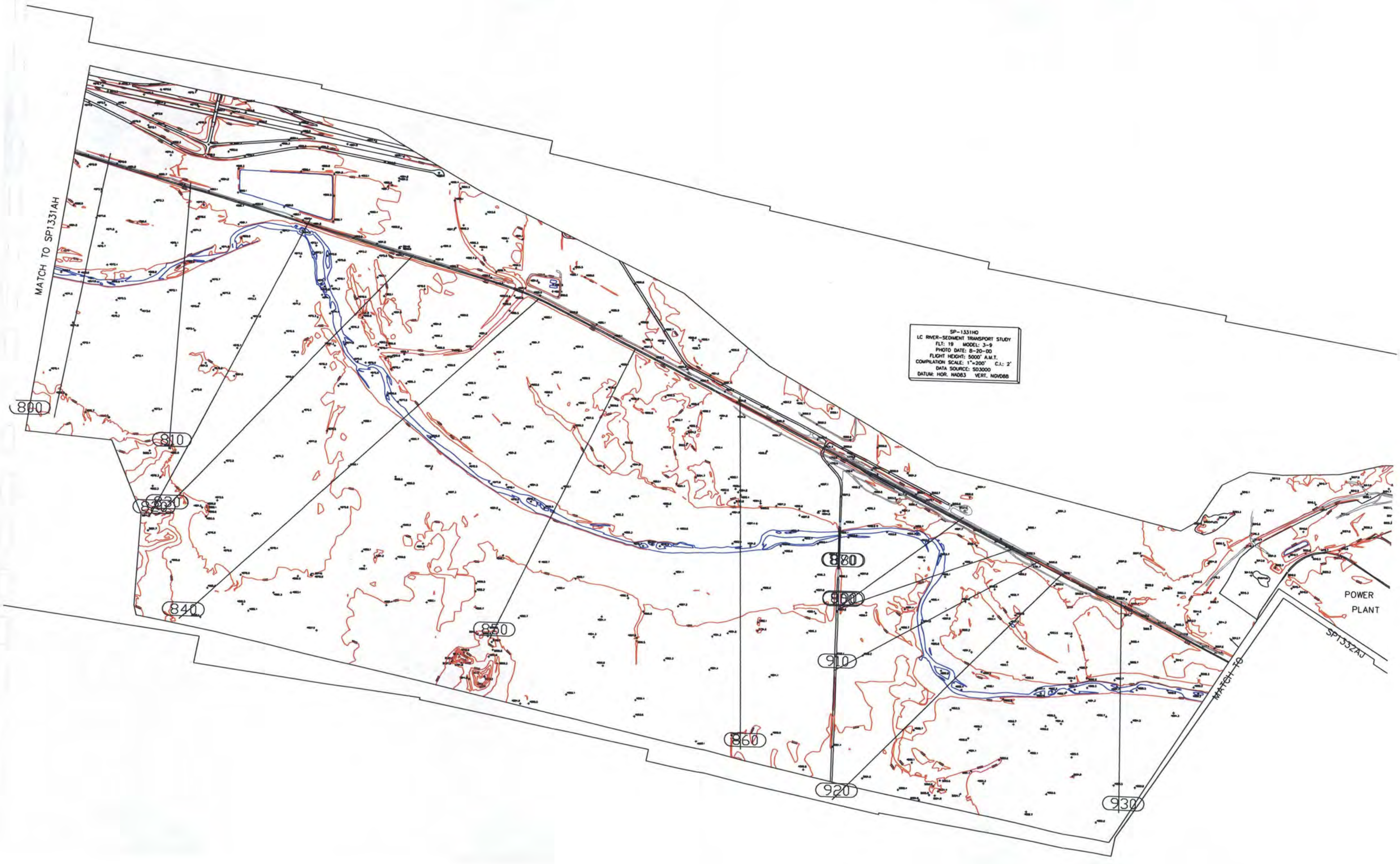
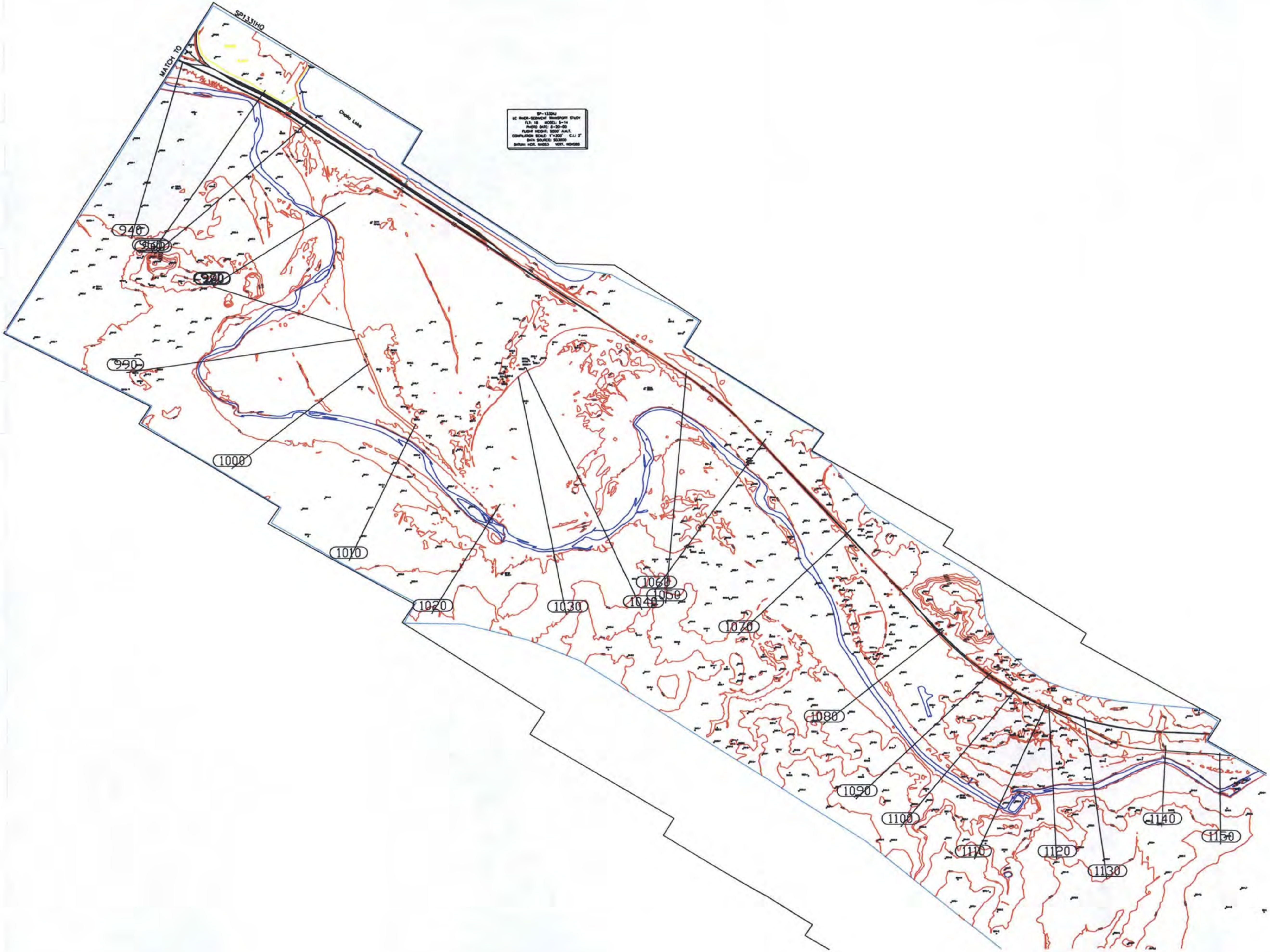
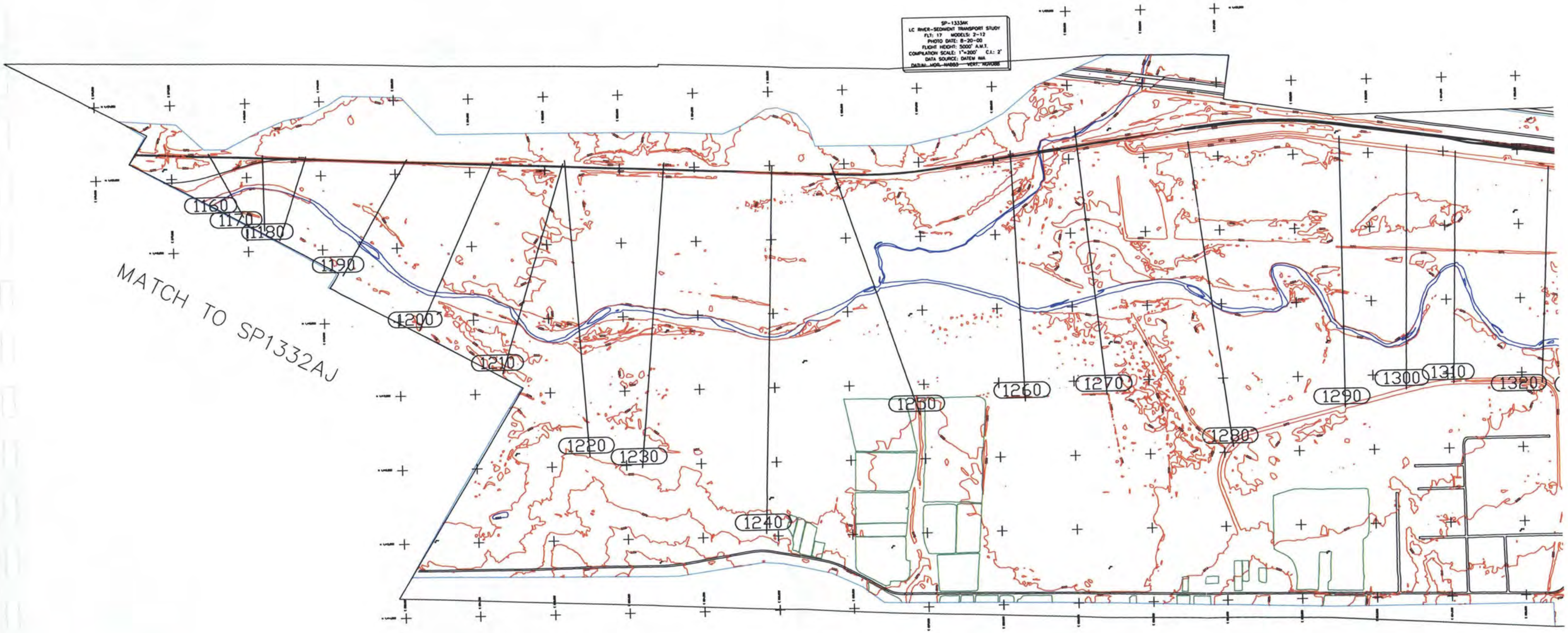
FLT: 18 MODEL: 10-18
FLIGHT HEIGHT: 5000' A.M.T.
COMPILATION SCALE: 1"=200' C.I.: 2'
DATUM: HOR. NAD83
MATCH TO SP1330RZ
MATCH TO SP1331HO
690
700
710
720
730
740
750
760
770
780
790

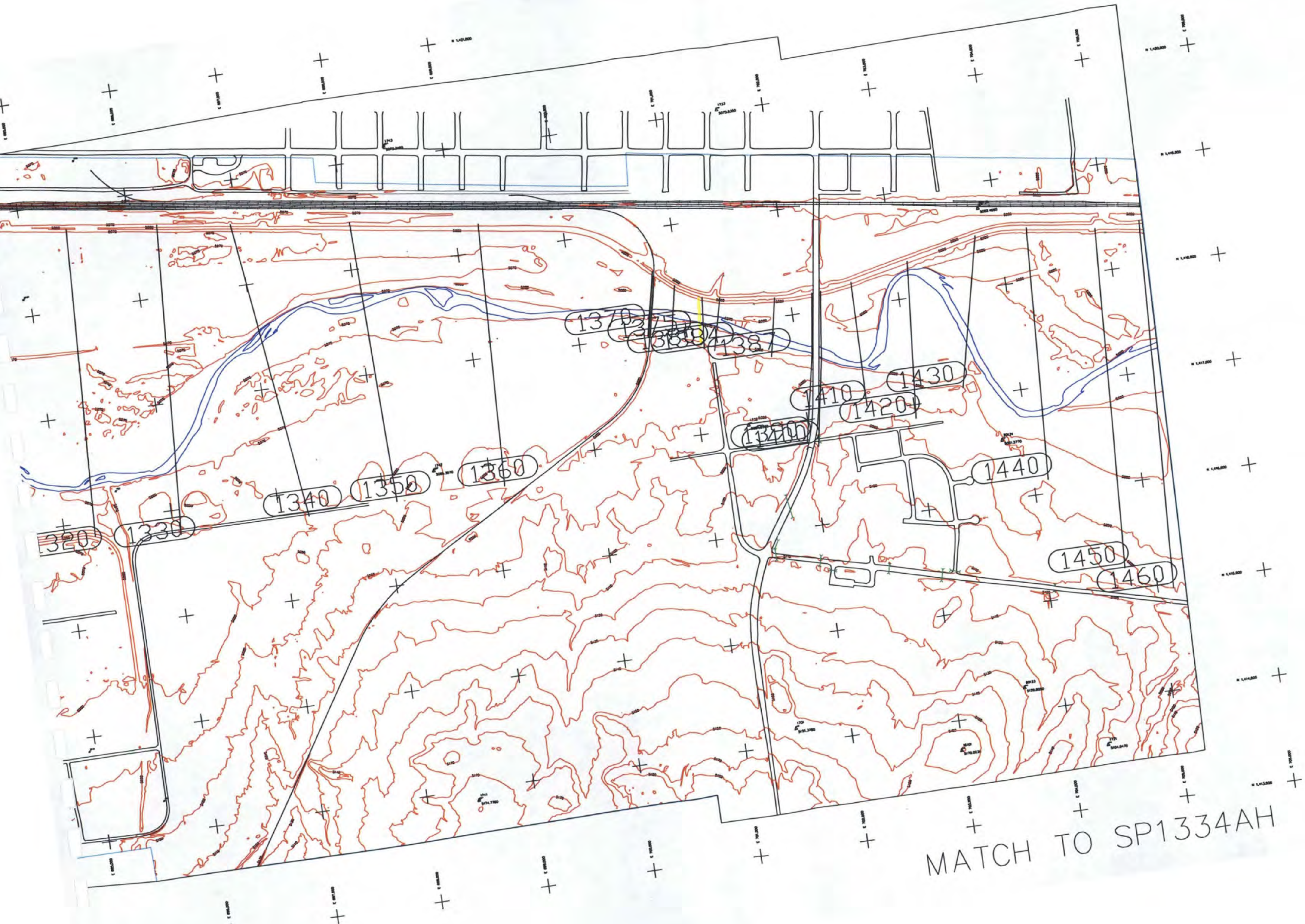


SP-1331HO
LC RIVER-SEDIMENT TRANSPORT STUDY
FLT: 19 MODEL: 3-9
PHOTO DATE: 8-20-00
FLIGHT HEIGHT: 5000' A.M.T.
COMPILATION SCALE: 1"=200' C.I.: 2'
DATA SOURCE: 503000
DATUM: HOR. NAD83 VERT. NGVD88
MATCH TO SP1331AH
MATCH TO SP1332AJ
POWER PLANT
800
810
830
840
850
860
880
900
910
920
930



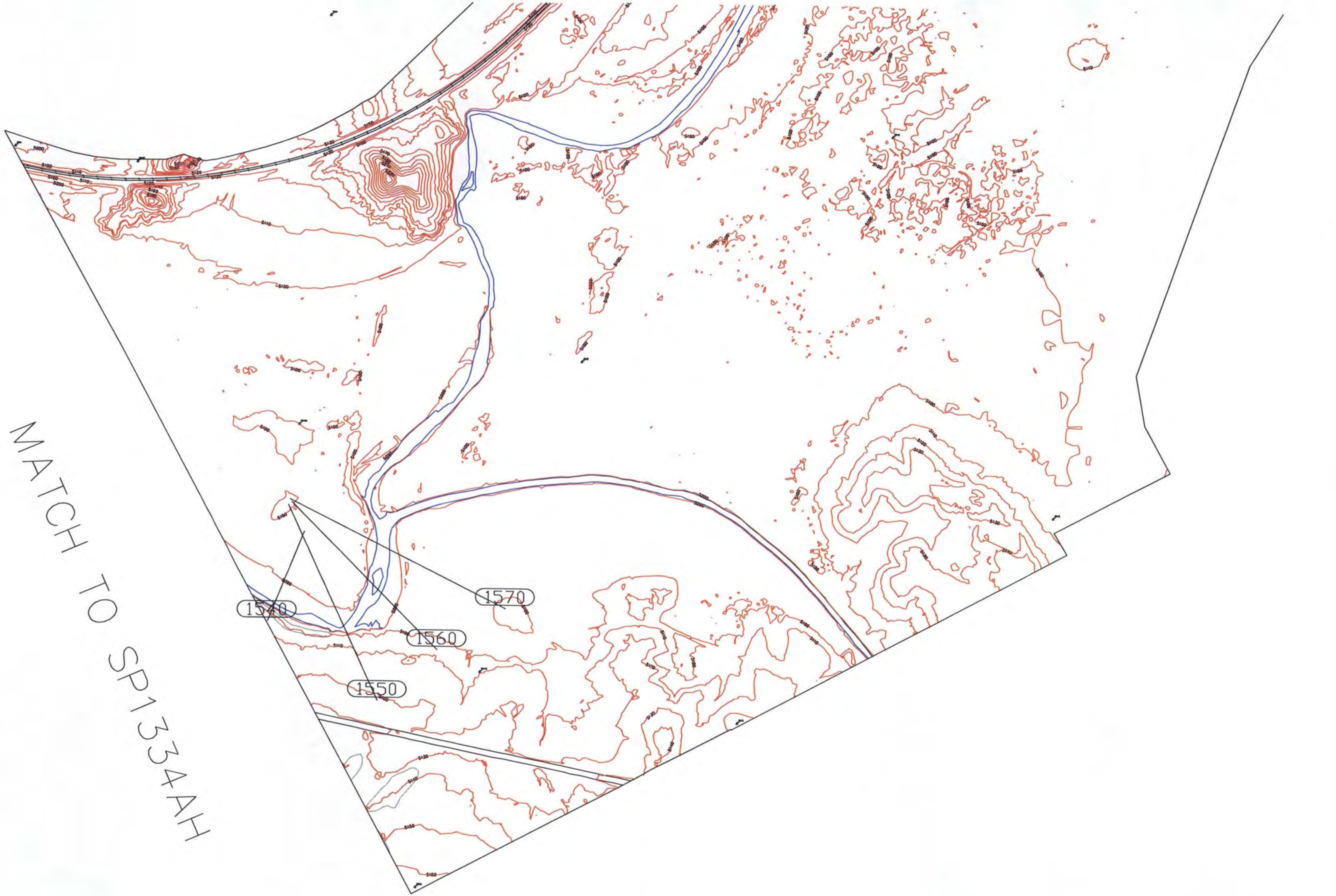
MATCH TO
SP1331HO
LC RIVER-SEDIMENT TRANSPORT STUDY
940
990
1000
1010
1020
1030
1040
1050
1060
1070
1080
1090
1100
1110
1120
1130
1140
1150


SP-1333AK
LC RIVER-SEDIMENT TRANSPORT STUDY
FLT: 17 MODELS: 2-12
PHOTO DATE: 8-20-00
FLIGHT HEIGHT: 5000' A.M.T.
COMPILATION SCALE: 1"=200' C.I.: 2'
DATA SOURCE: DATEM
DATUM: HOR. NAD83 VERT. NGVD88
MATCH TO SP1332AJ
1160
1170
1180
1190
1200
1210
1220
1230
1240
1250
1260
1270
1280
1290
1300
1310
1320



320
1330
1340
1350
1360
1370
1387
1410
1420
1430
1440
1450
1460
MATCH TO SP1334AH


1470
1480
1490
1500
1510
1520
1530


MATCH TO SP1334AH
1540
1550
1560
1570

APPENDIX E

INCIPIENT MOTION RESULTS

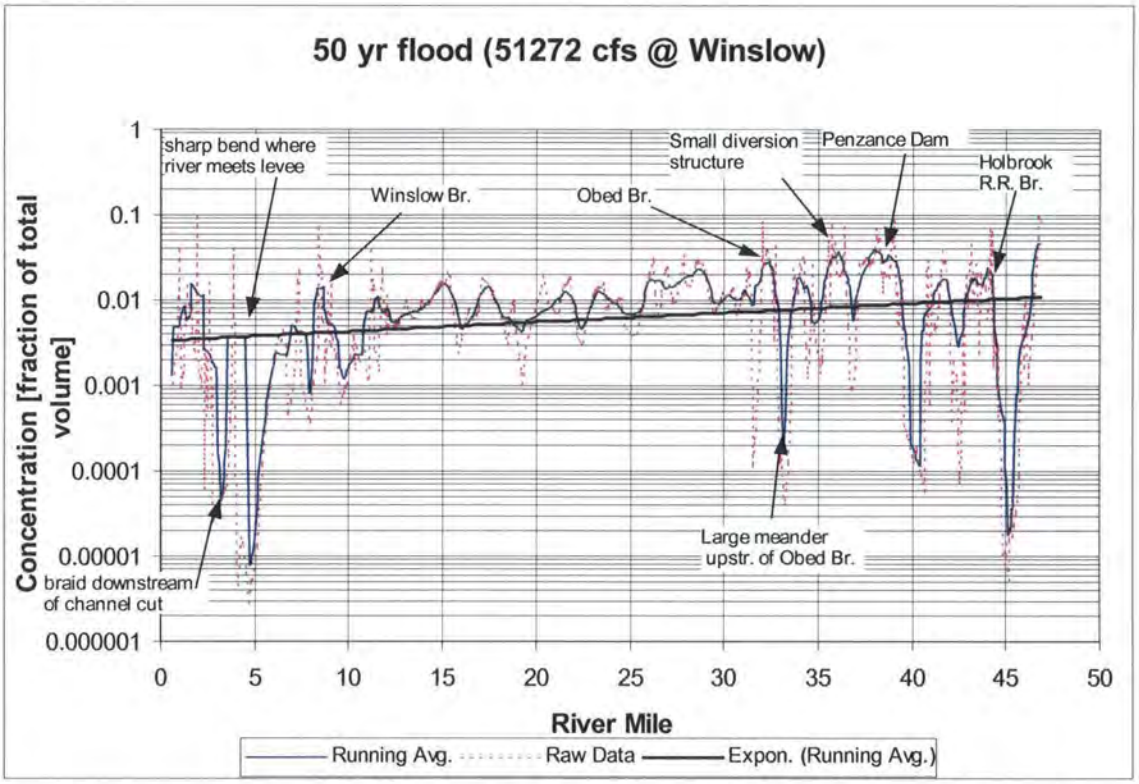


Figure E–1. Capacity of suspended sediment with discharges from peak flow analysis and the high flow hydraulic model.

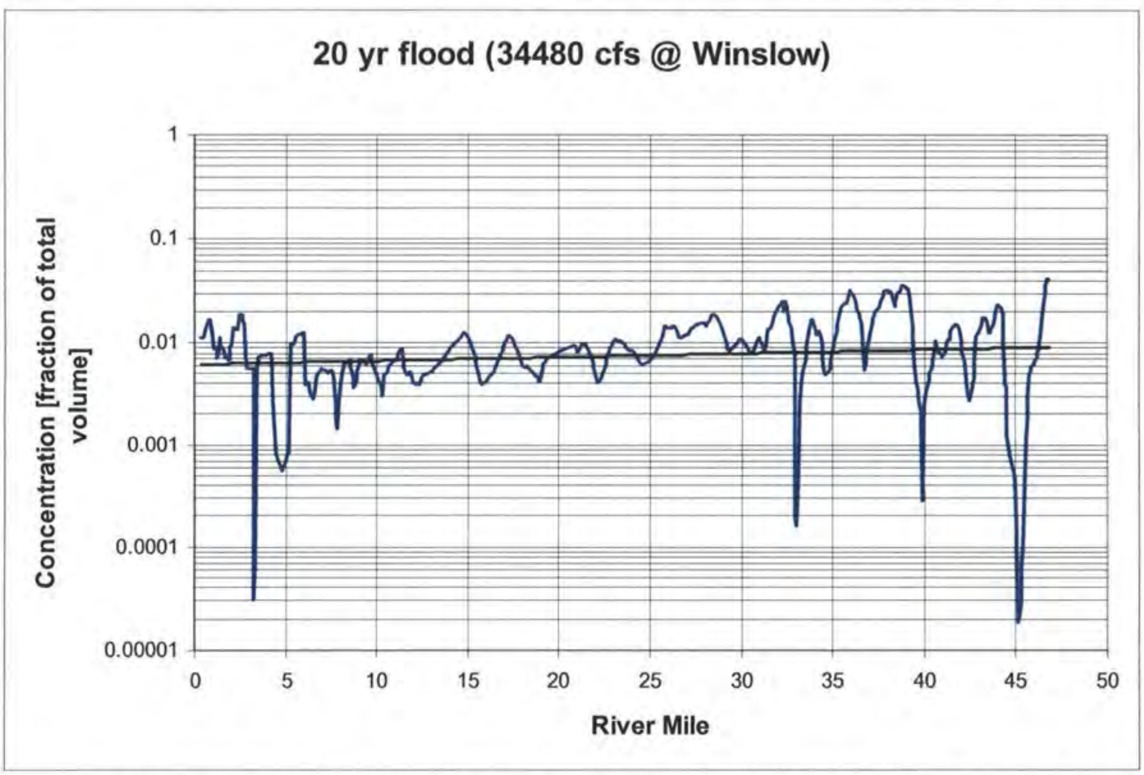


Figure E– 2. Capacity of suspended sediment with discharges from peak flow analysis and the high flow hydraulic model.

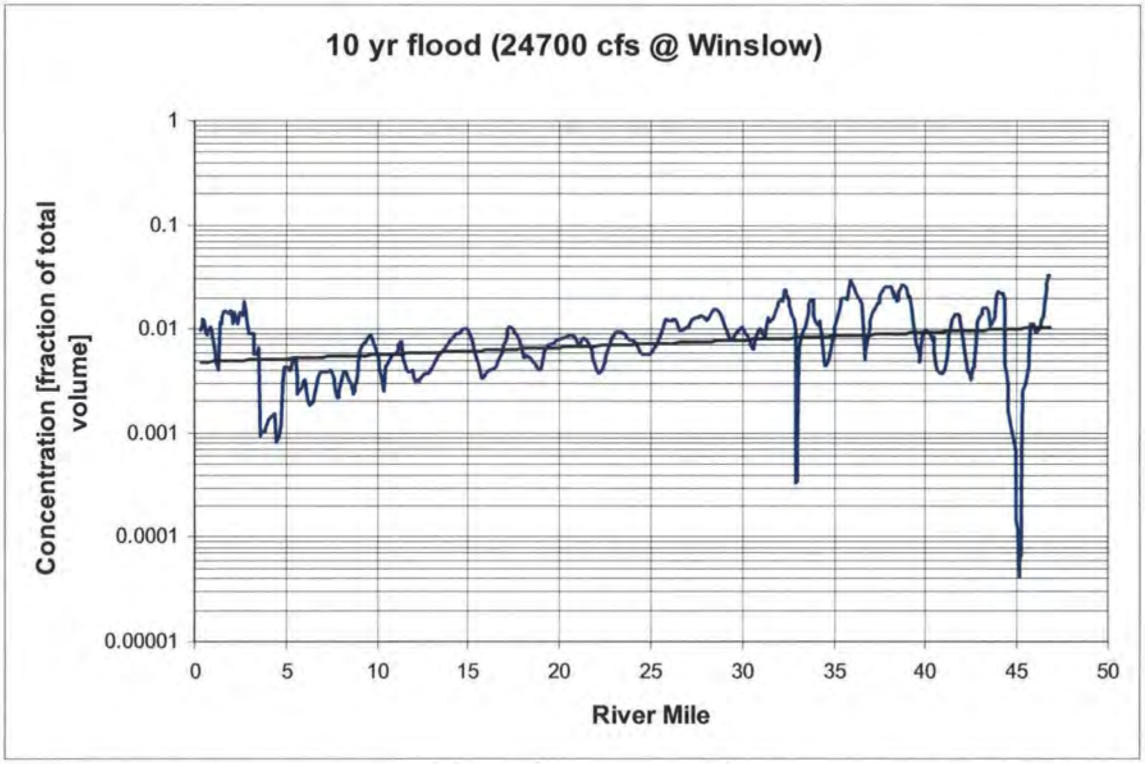


Figure E– 3. Capacity of suspended sediment with discharges from peak flow analysis and the high flow hydraulic model.

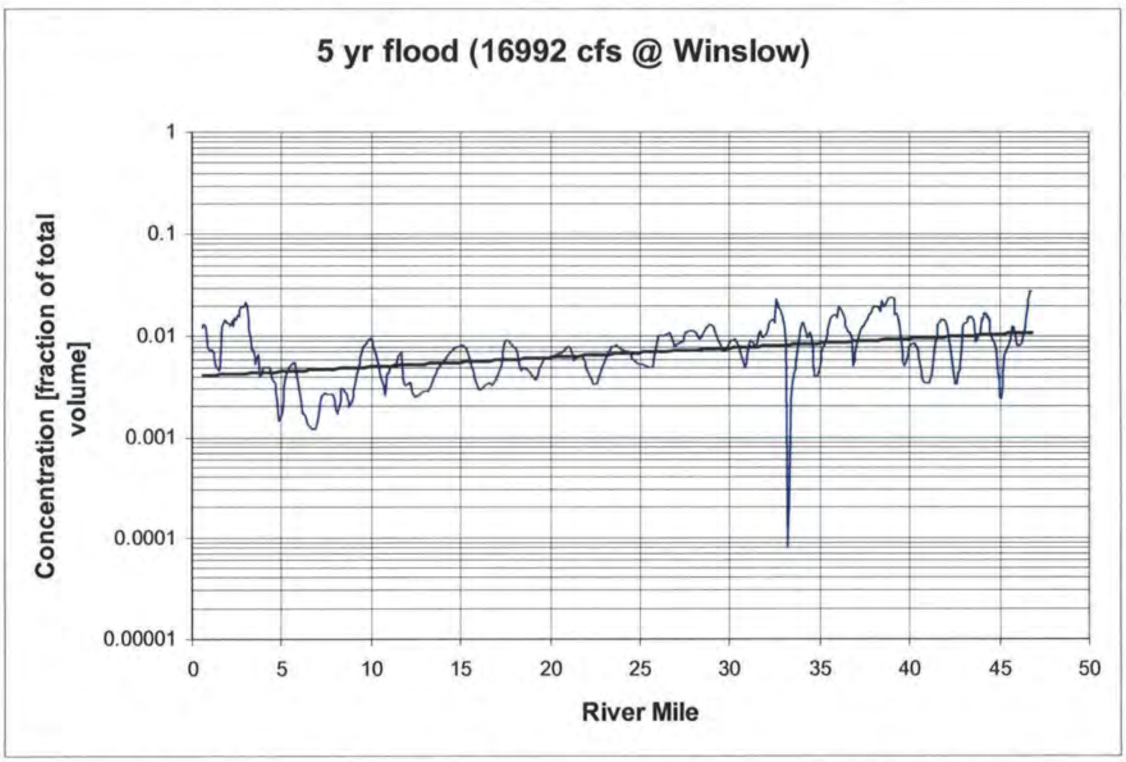


Figure E– 4. Capacity of suspended sediment with discharges from peak flow analysis and the high flow hydraulic model.

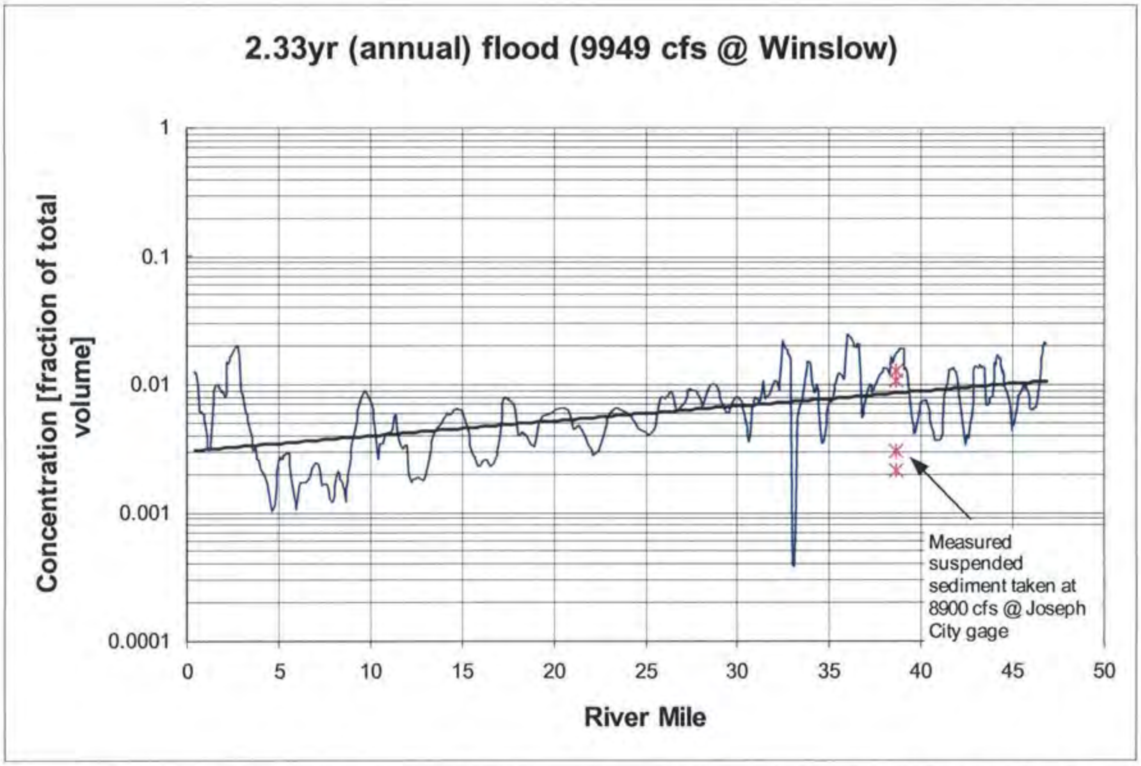


Figure E– 5. Capacity of suspended sediment with discharges from peak flow analysis and the high flow hydraulic model.

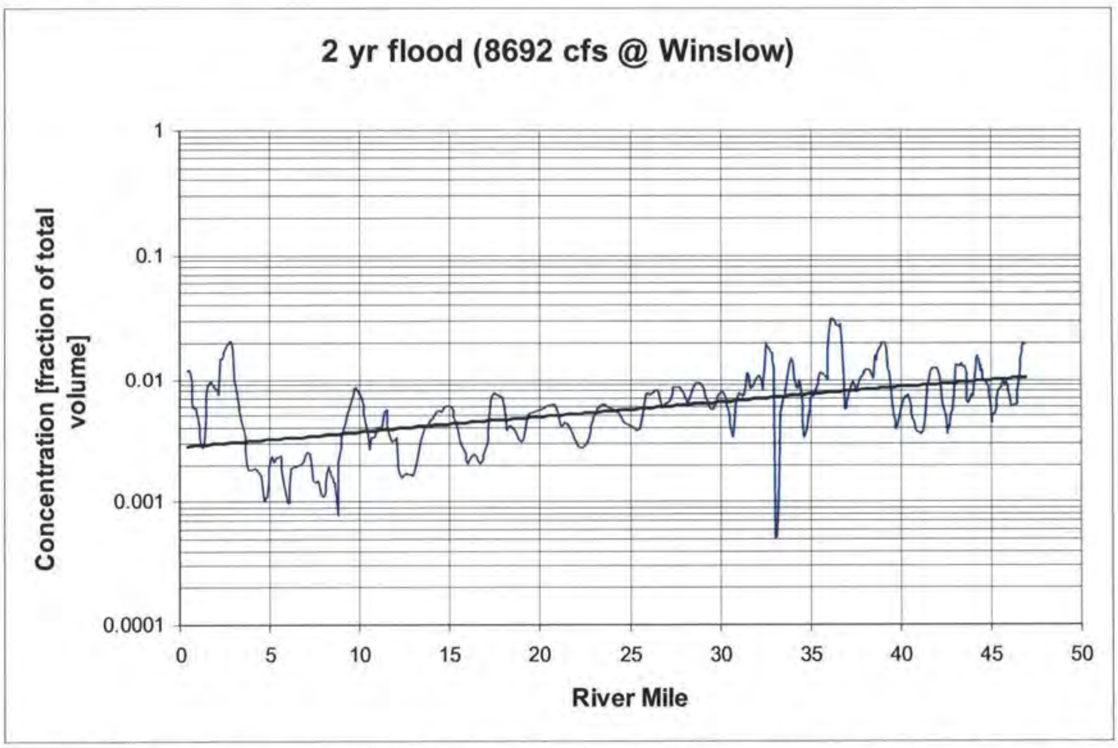


Figure E– 6. Capacity of suspended sediment with discharges from peak flow analysis and the high flow hydraulic model.

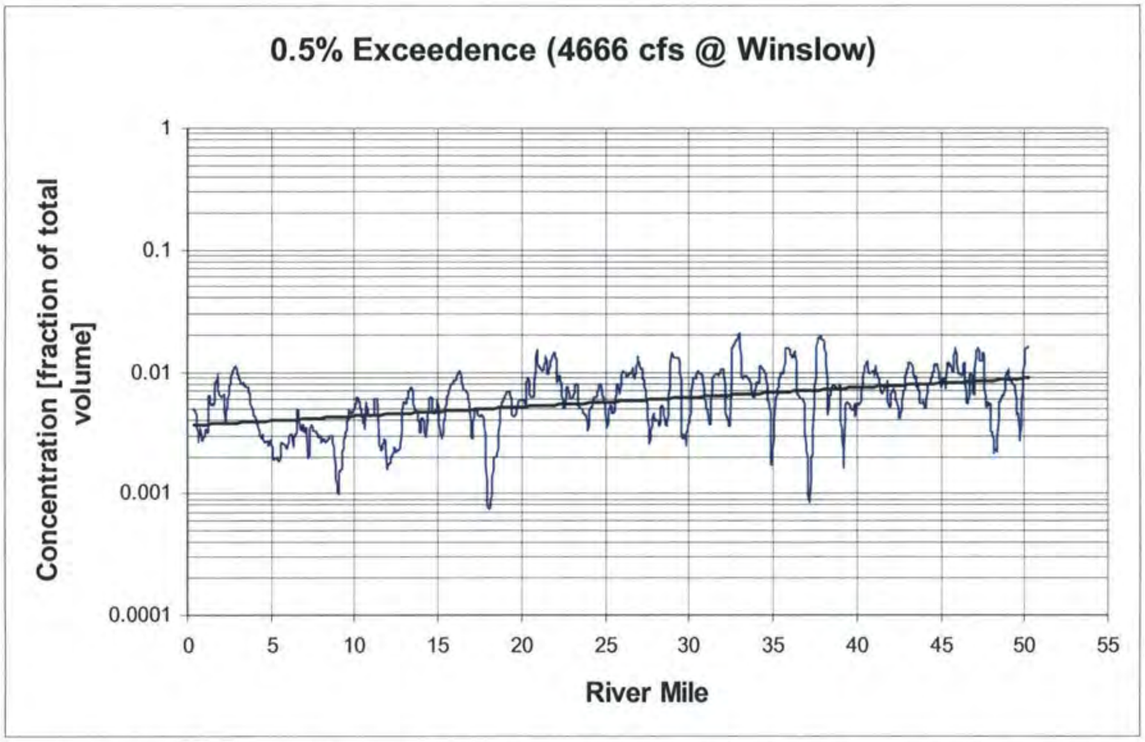


Figure E– 7. Capacity of suspended sediment with discharges from average daily flow analysis and low flow hydraulic model.

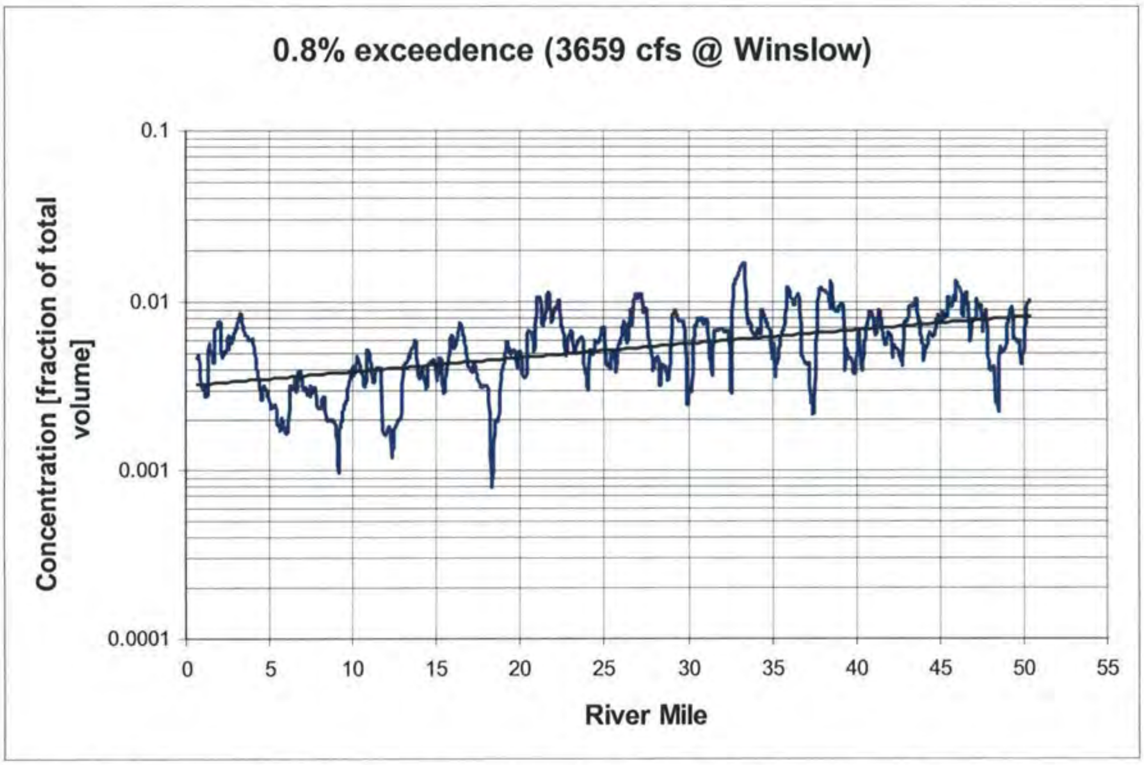


Figure E– 8. Capacity of suspended sediment with discharges from average daily flow analysis and low flow hydraulic model.

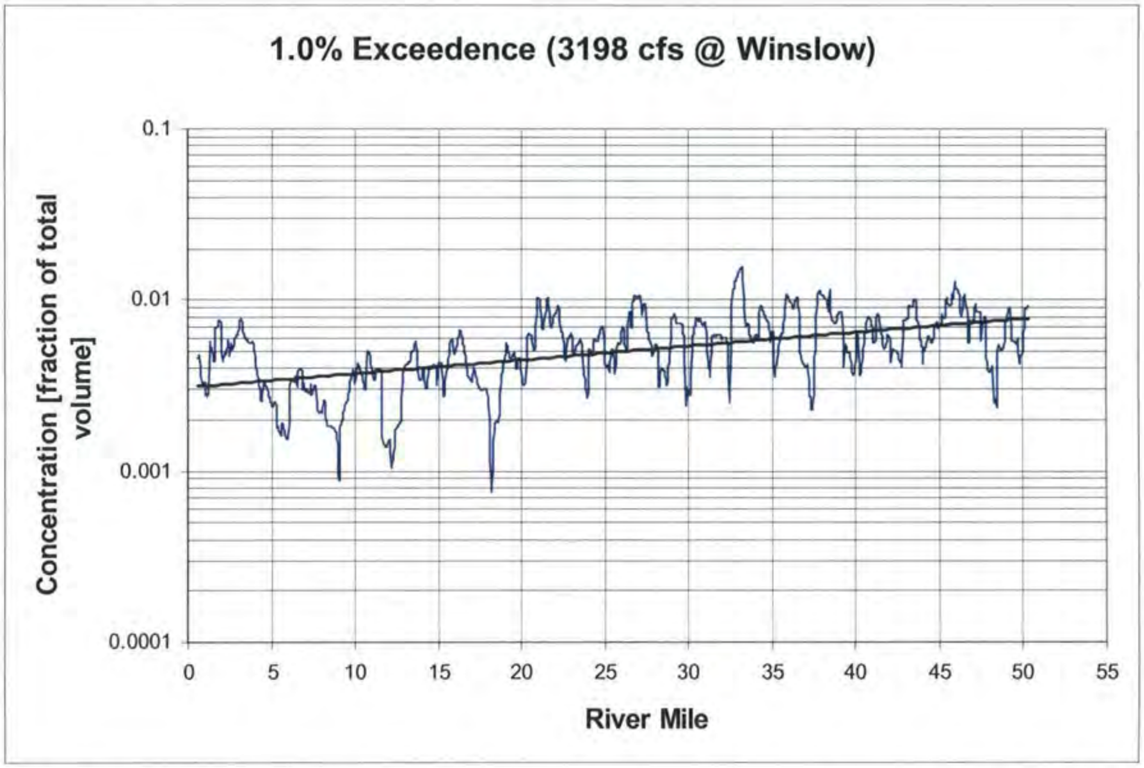


Figure E– 9. Capacity of suspended sediment with discharges from average daily flow analysis and low flow hydraulic model.

Figure E– 10. Capacity of suspended sediment with discharges from average daily flow analysis and low flow hydraulic model.

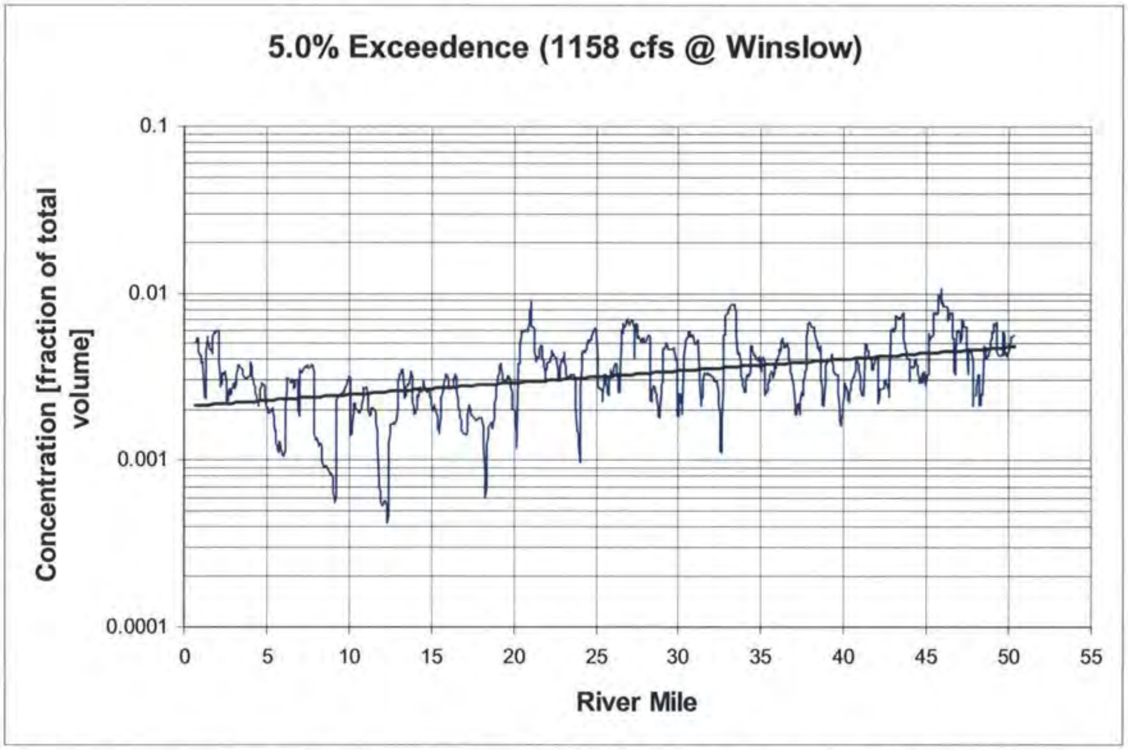


Figure E– 11. Capacity of suspended sediment with discharges from average daily flow analysis and low flow hydraulic model.

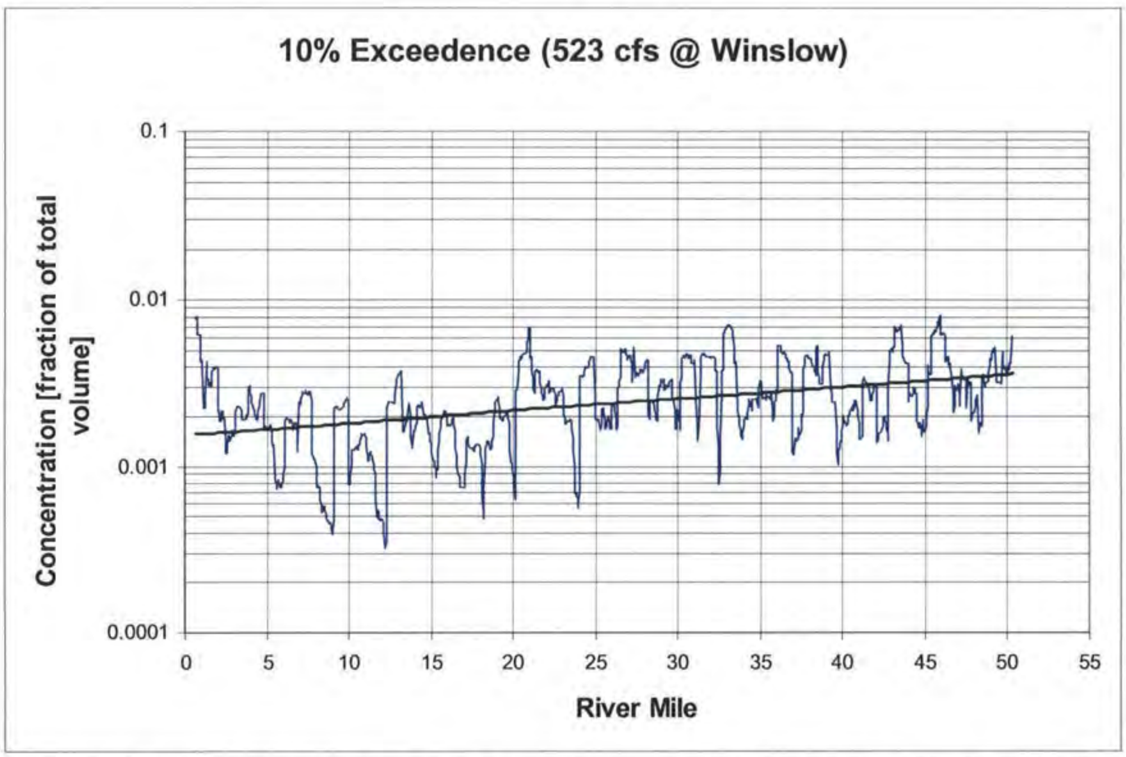


Figure E– 12. Capacity of suspended sediment with discharges from average daily flow analysis and low flow hydraulic model.

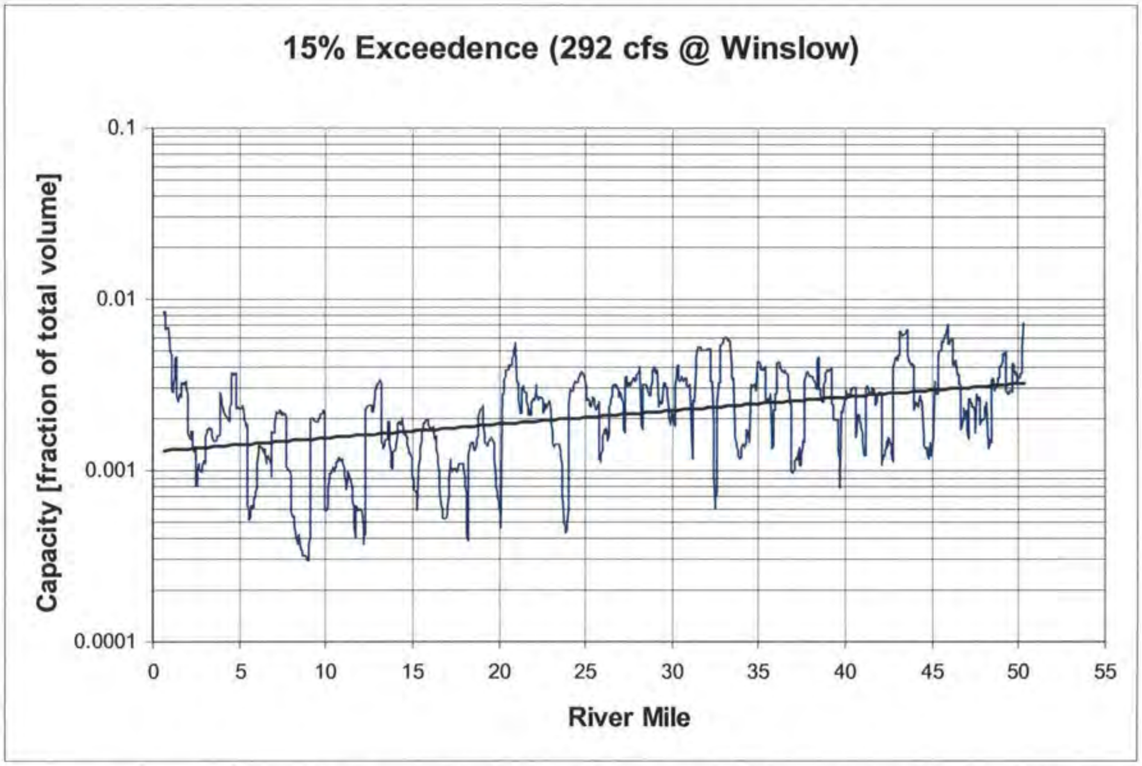


Figure E– 13. Capacity of suspended sediment with discharges from average daily flow analysis and low flow hydraulic model.

APPENDIX F

HYDROGRAPHS USED FOR HYDROLOGIC SCENARIOS

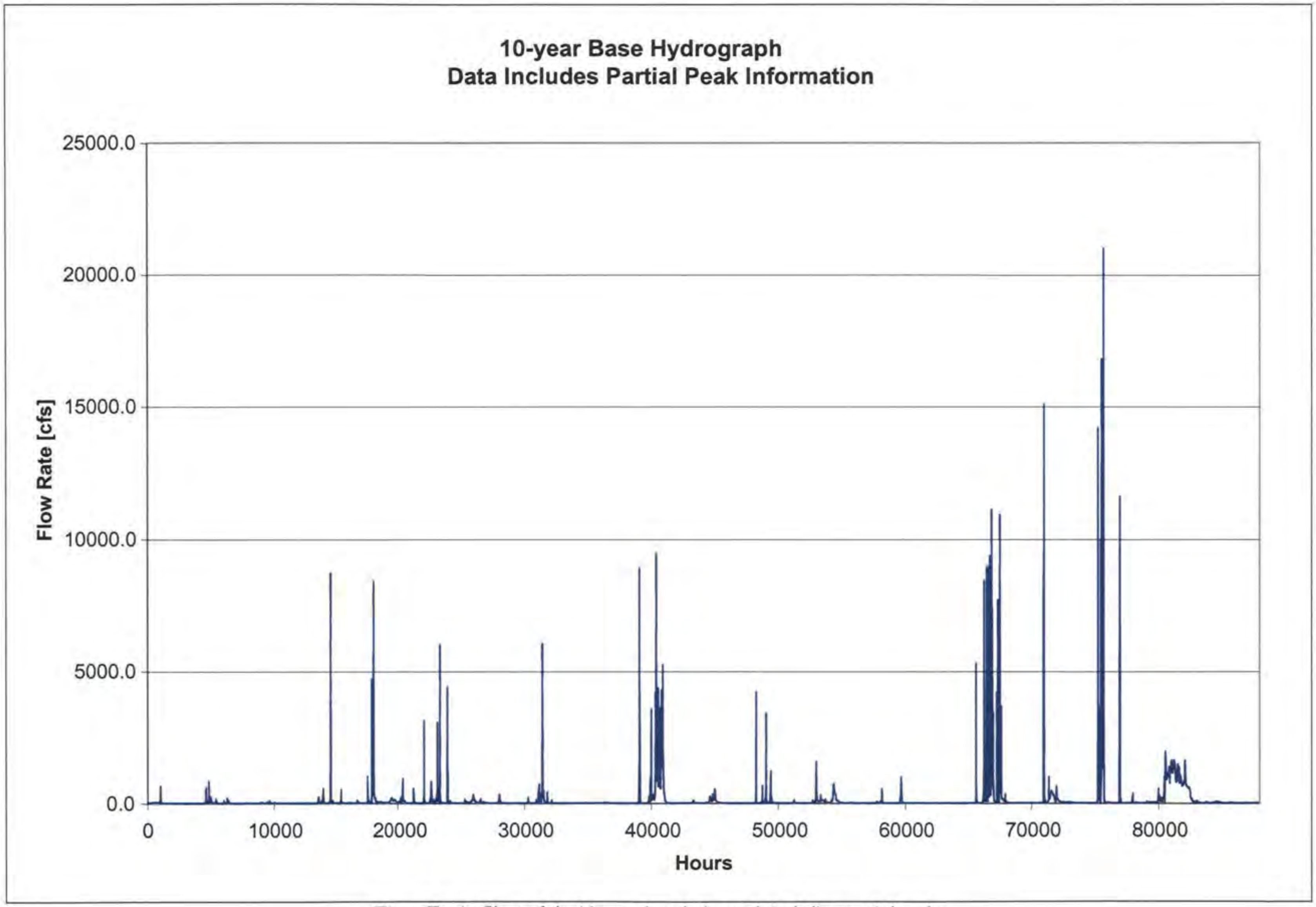


Figure F– 1. Chart of the 10–year base hydrograph including partial peaks.

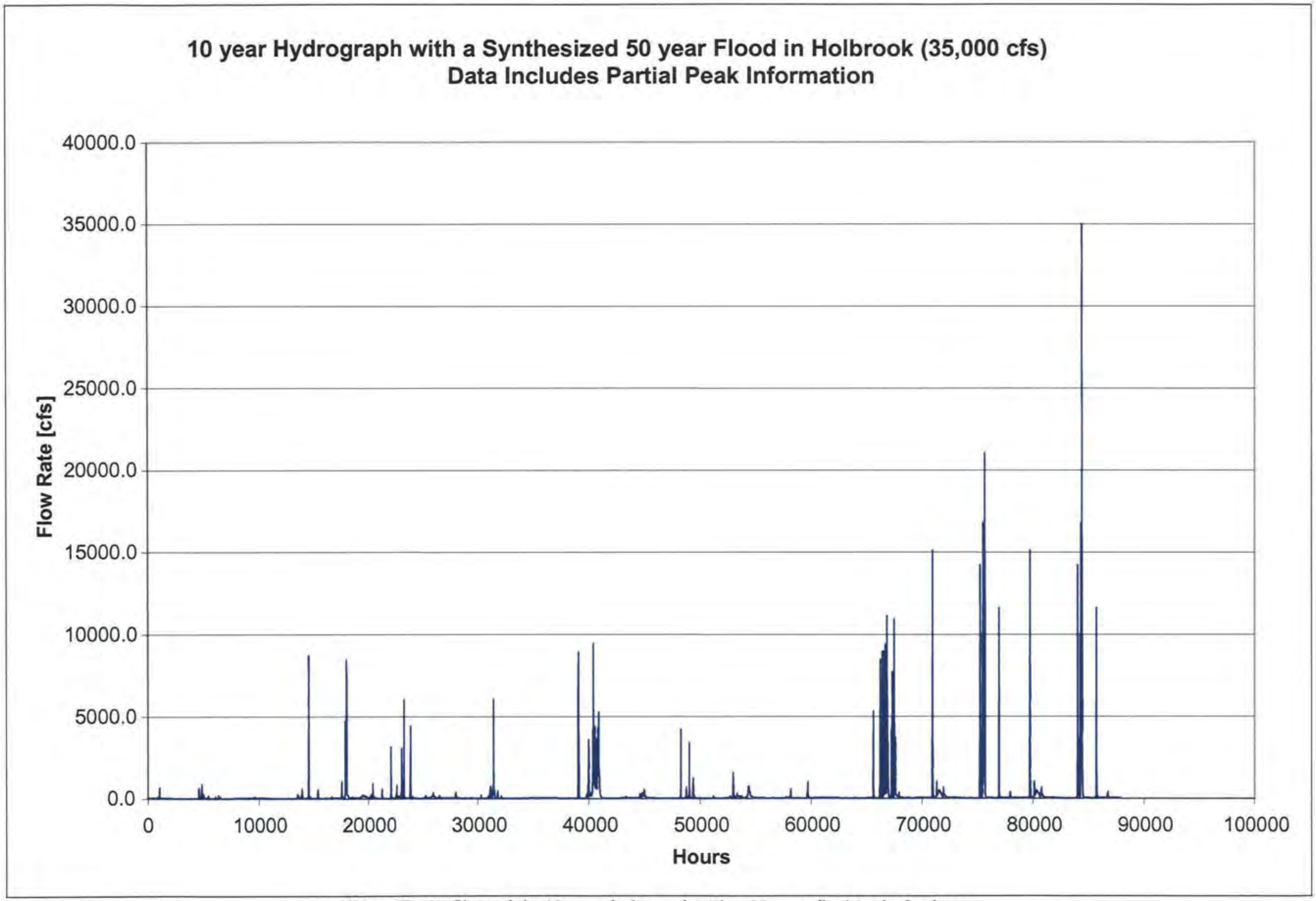


Figure F– 2. Chart of the 10–year hydrograph with a 50–year flood in the final year.

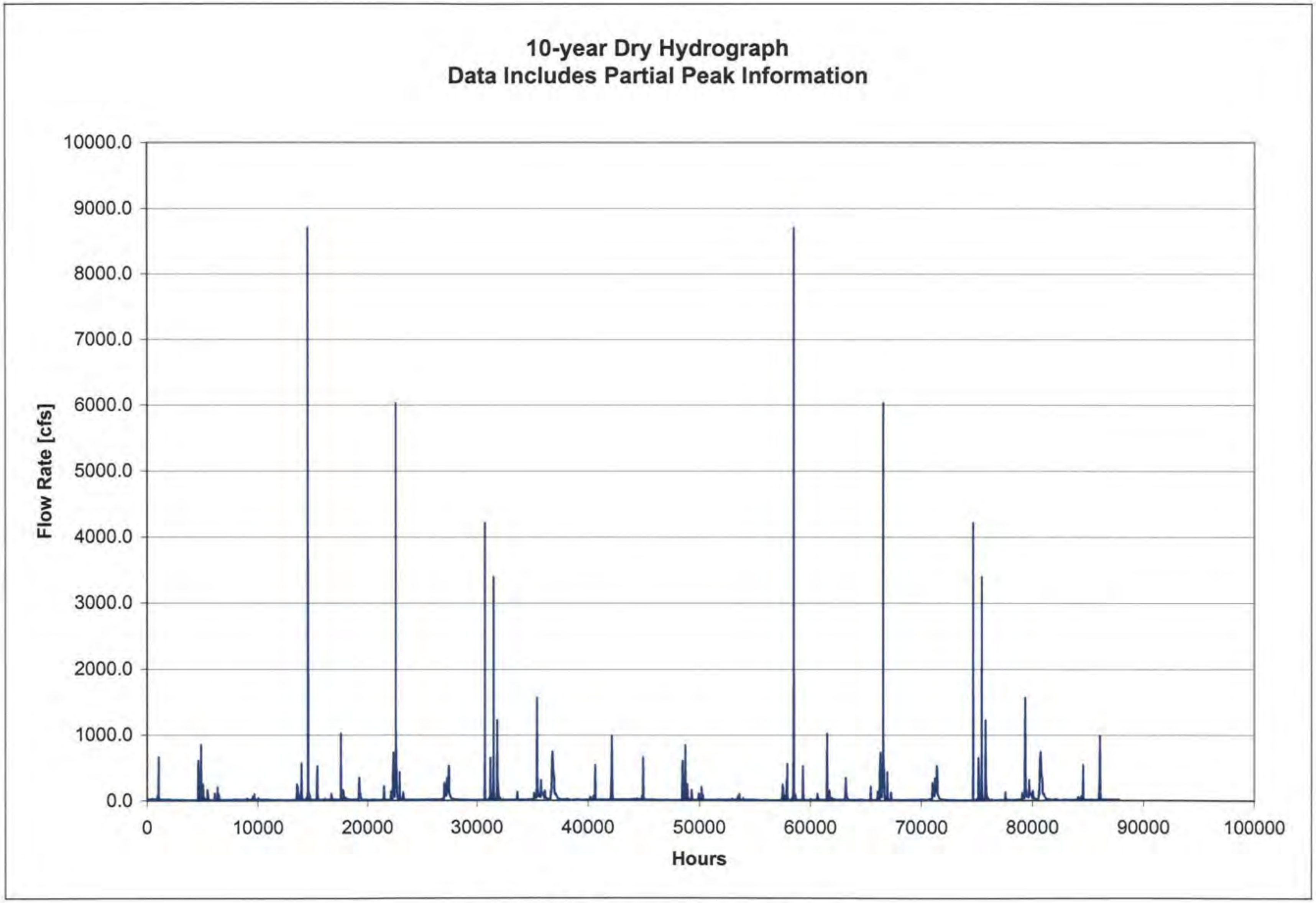


Figure F– 3. Chart of the 10–year dry hydrograph.

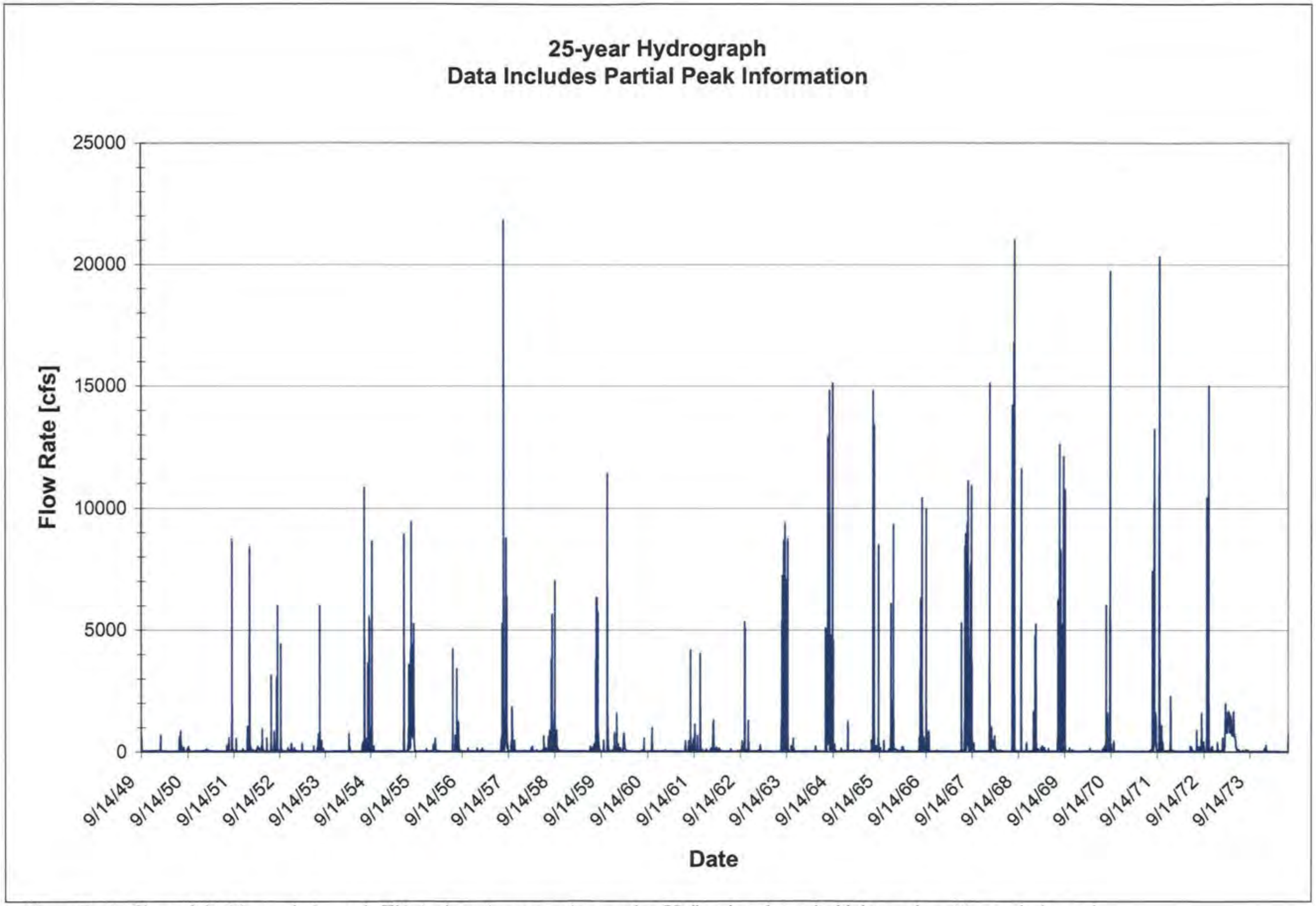


Figure F– 4. Chart of the 25–year hydrograph. This is the entire consecutive record at Holbrook and was doubled to make a 50–year hydrograph.

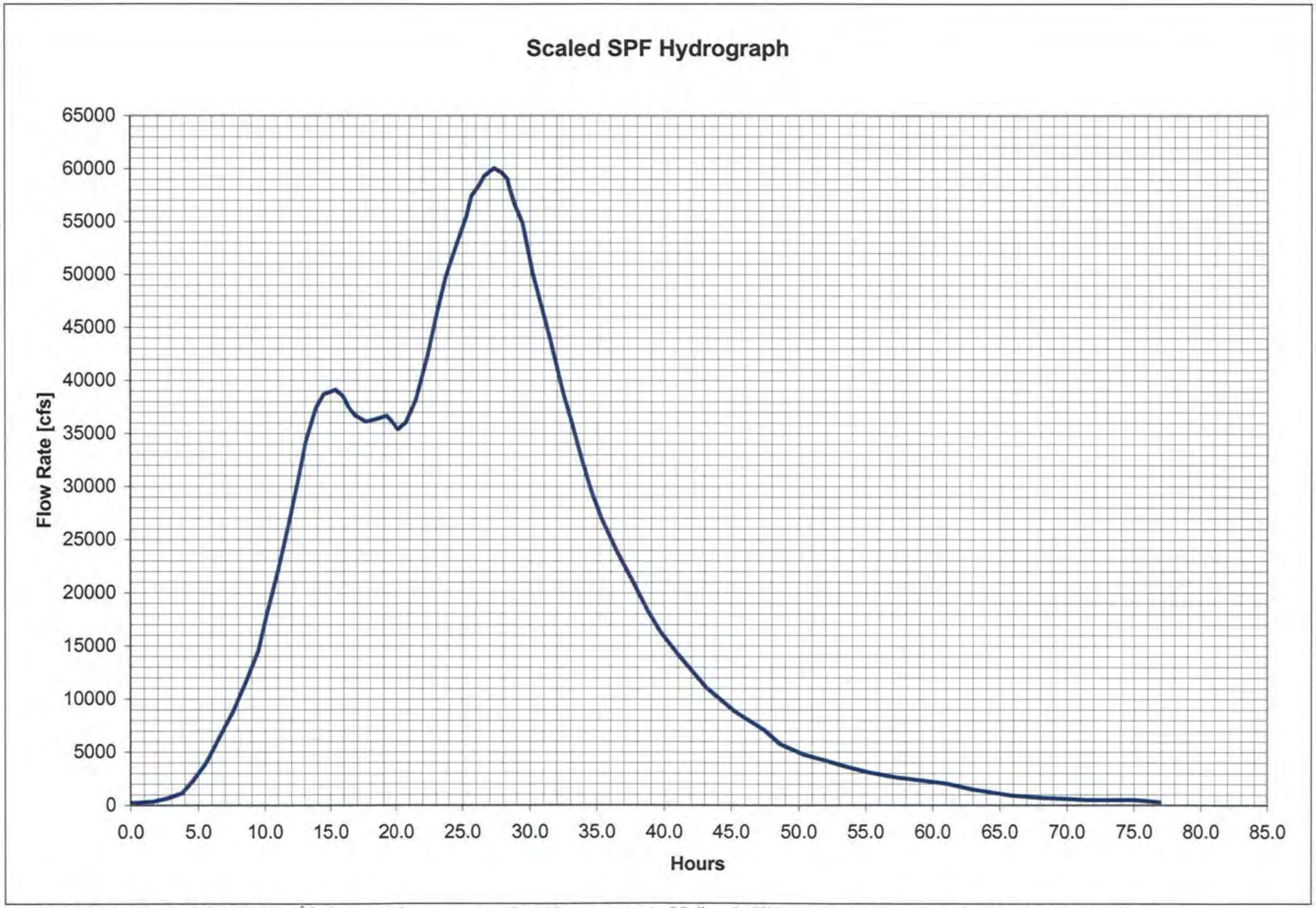


Figure F– 5. Chart of the 60,000 ft^3/s hydrograph representing the 100–year event in Holbrook. This was scaled down from the Standard Project Flood.

APPENDIX G

SEDIMENT MODEL RESULTS USING THE 10–YEAR BASE HYDROGRAPH

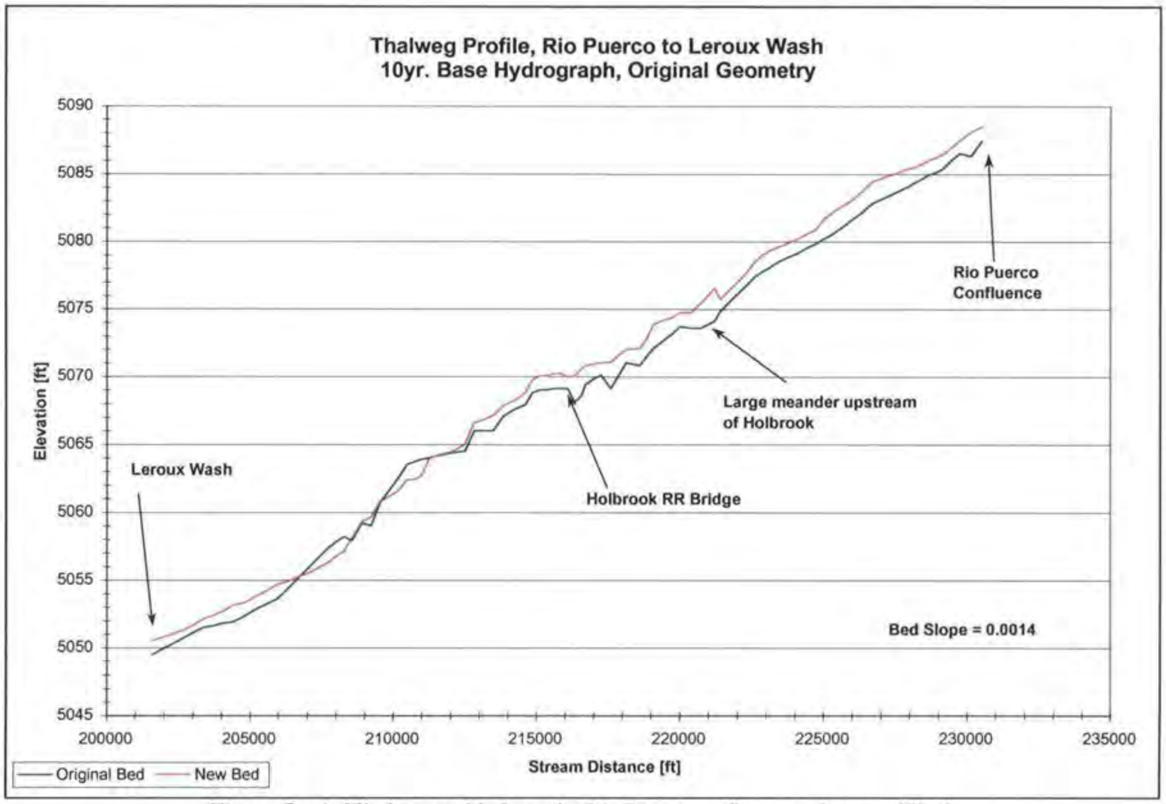


Figure G– 1. Thalweg profile from the Rio Puerco confluence to Leroux Wash.

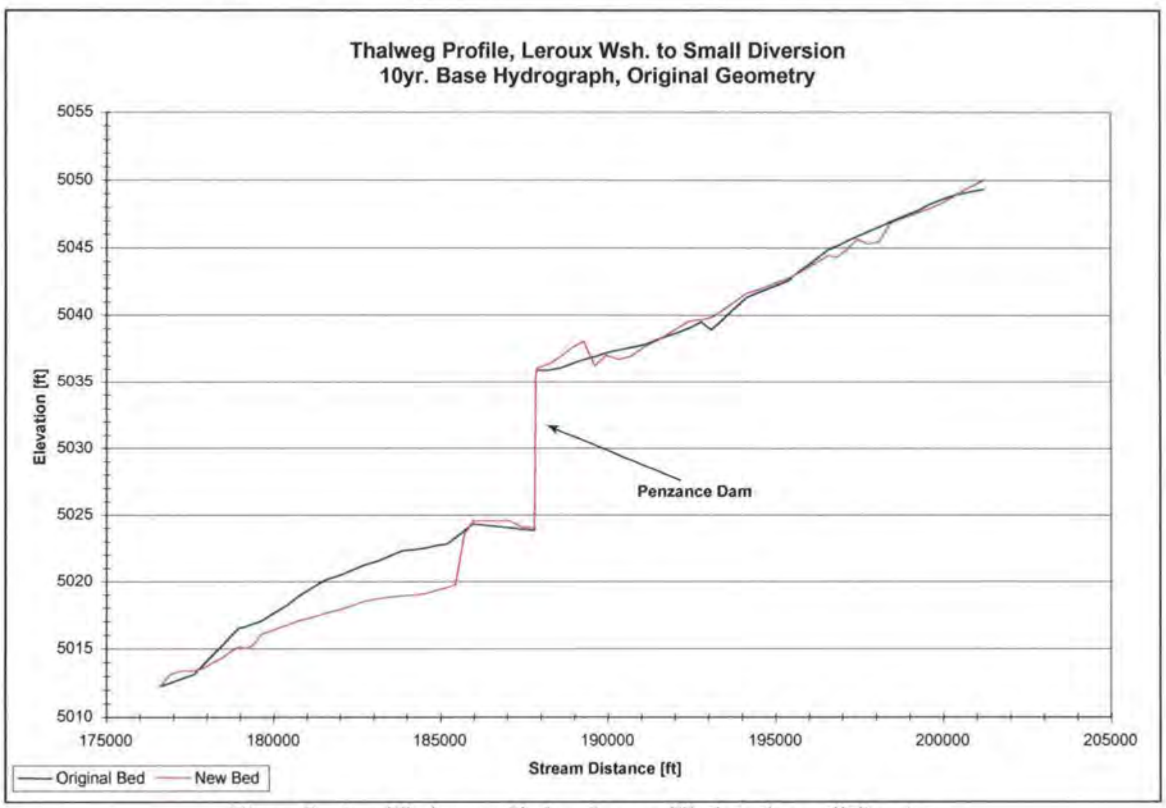


Figure G– 2. – Thalweg profile from Leroux Wash to the small diversion.

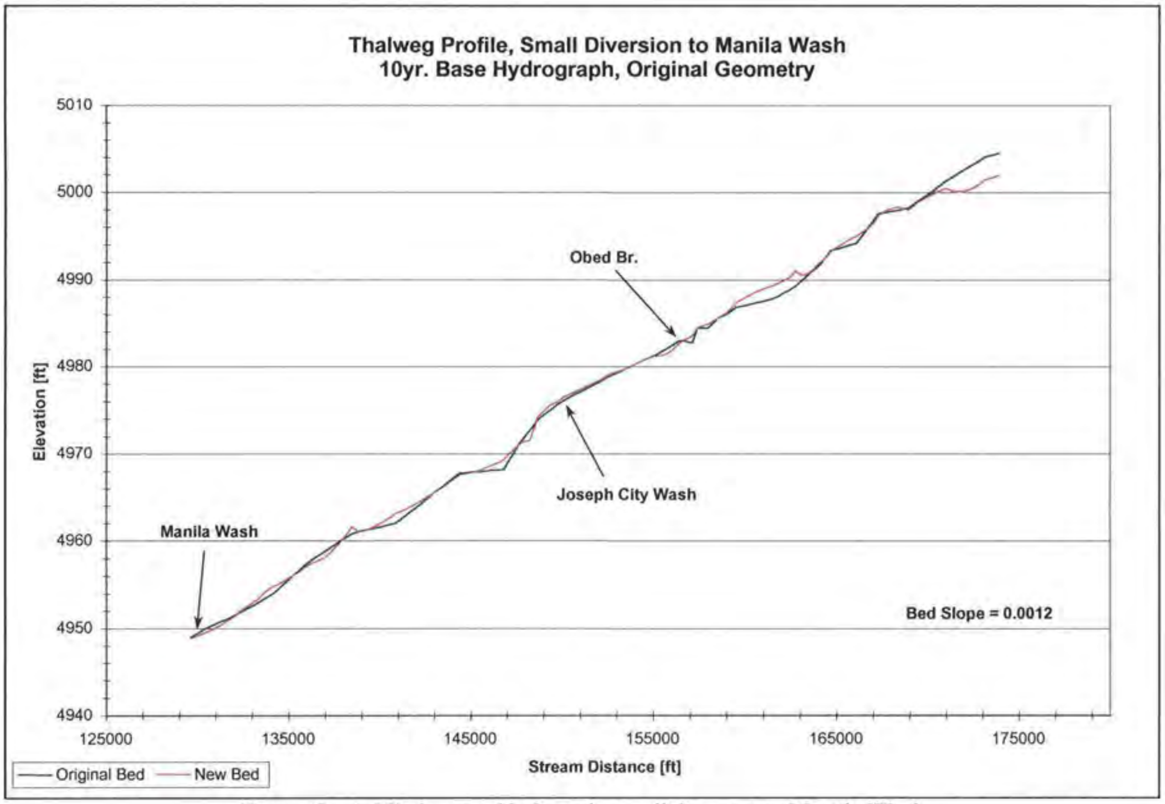


Figure G– 3. Thalweg profile from the small diversion to Manila Wash.

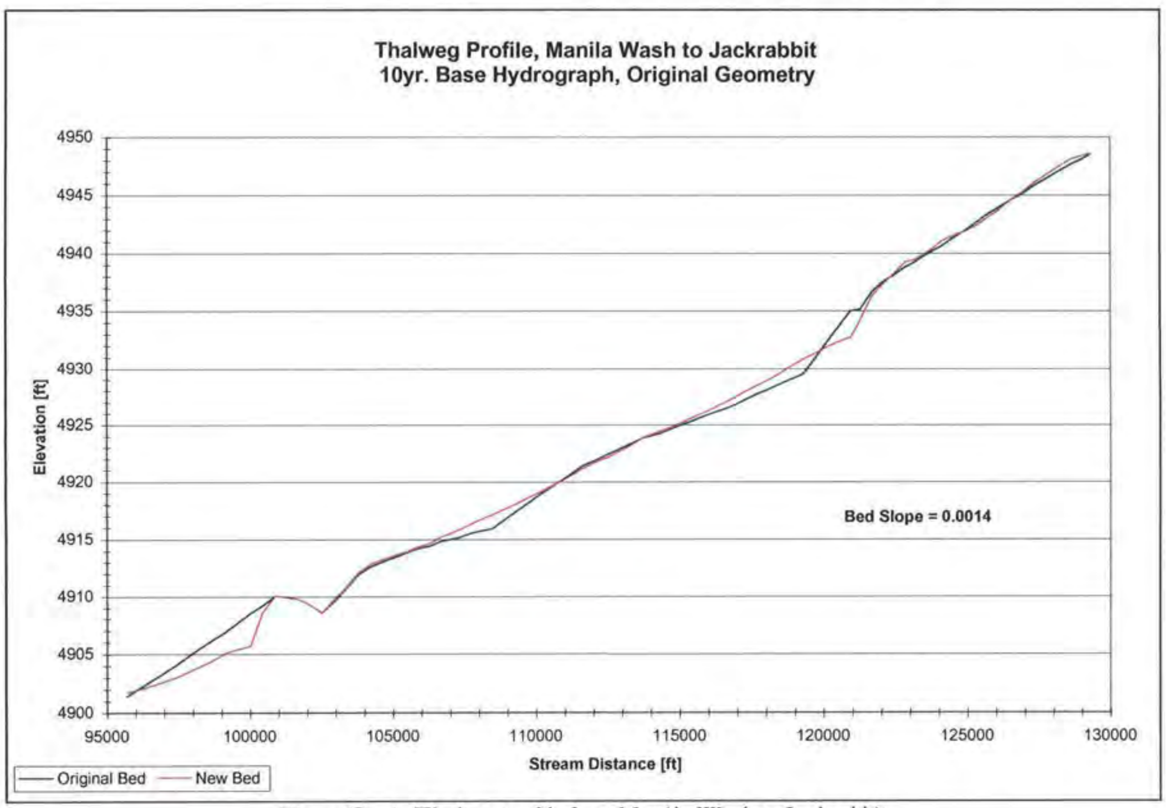


Figure G– 4. Thalweg profile from Manila Wash to Jackrabbit.

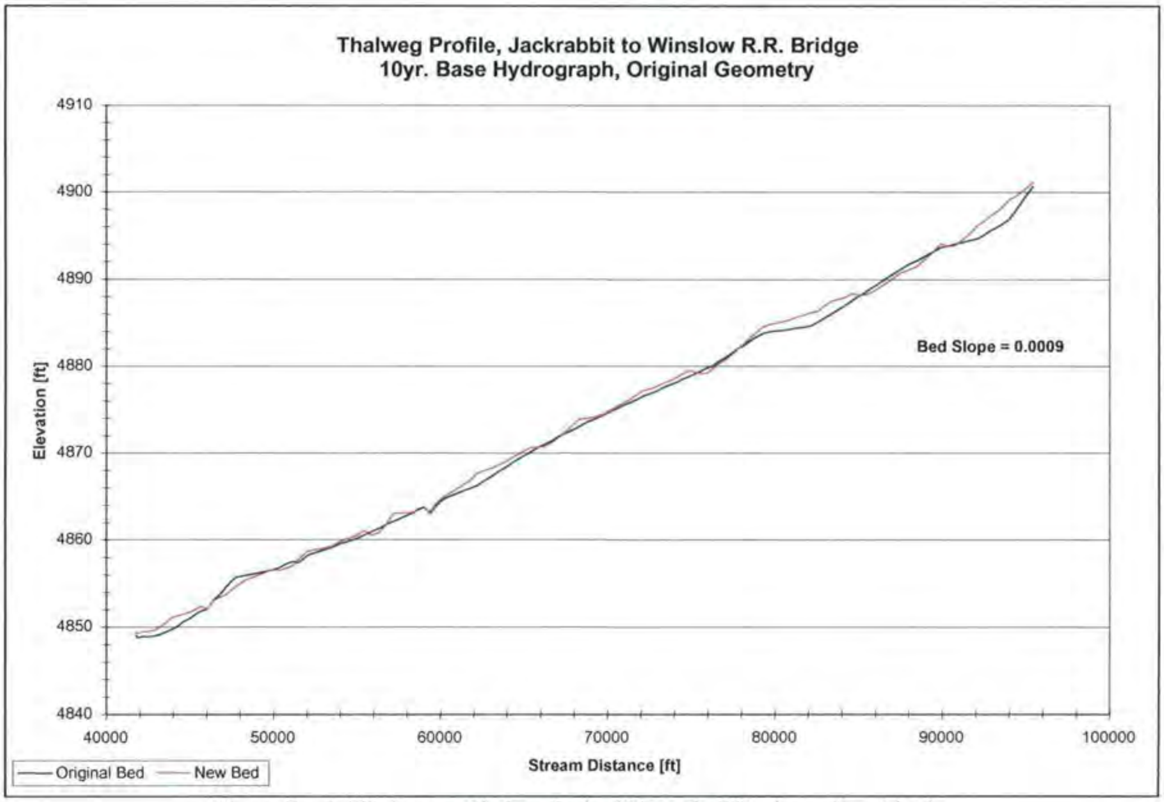


Figure G– 5. Thalweg profile from Jackrabbit to the Winslow railroad bridge.

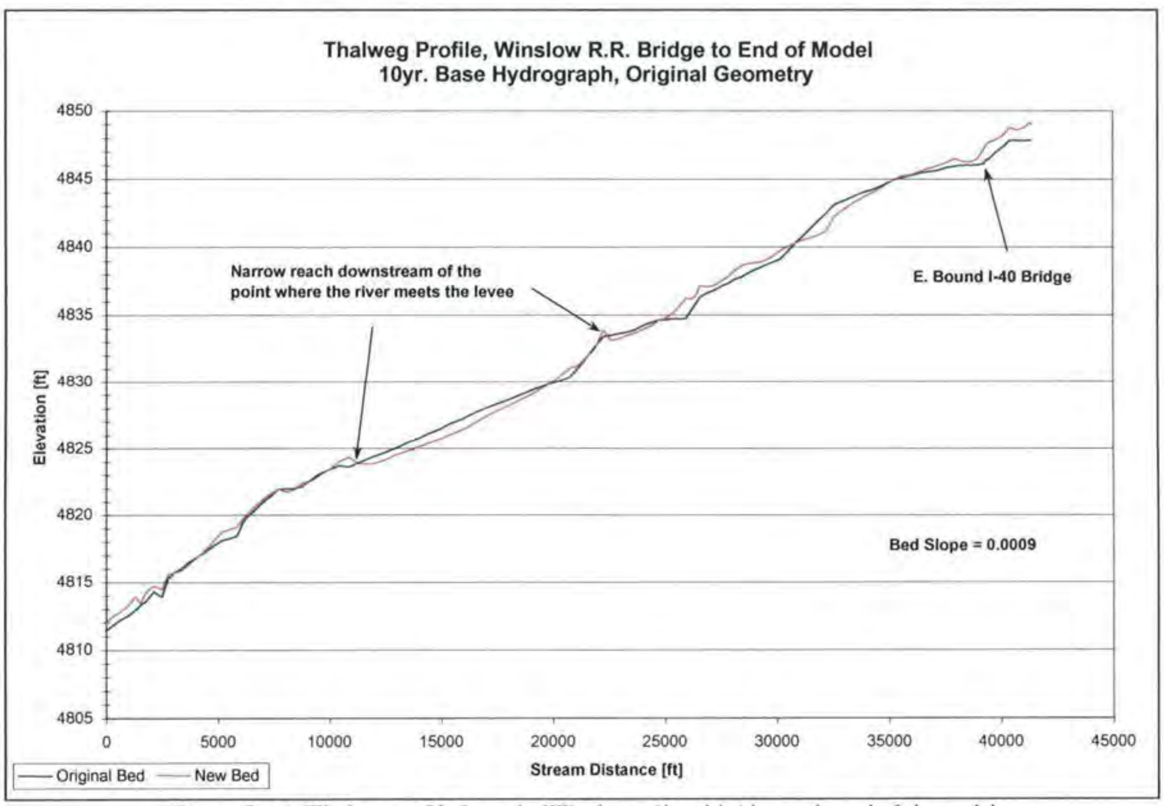


Figure G– 6. Thalweg profile from the Winslow railroad bridge to the end of the model.

APPENDIX H

TEMPORAL PROGRESSION OF MODELED AGGRADATION IN THE PUERCO RIVER TO HOLBROOK REACH USING THE 10-YEAR BASE HYDROGRAPH

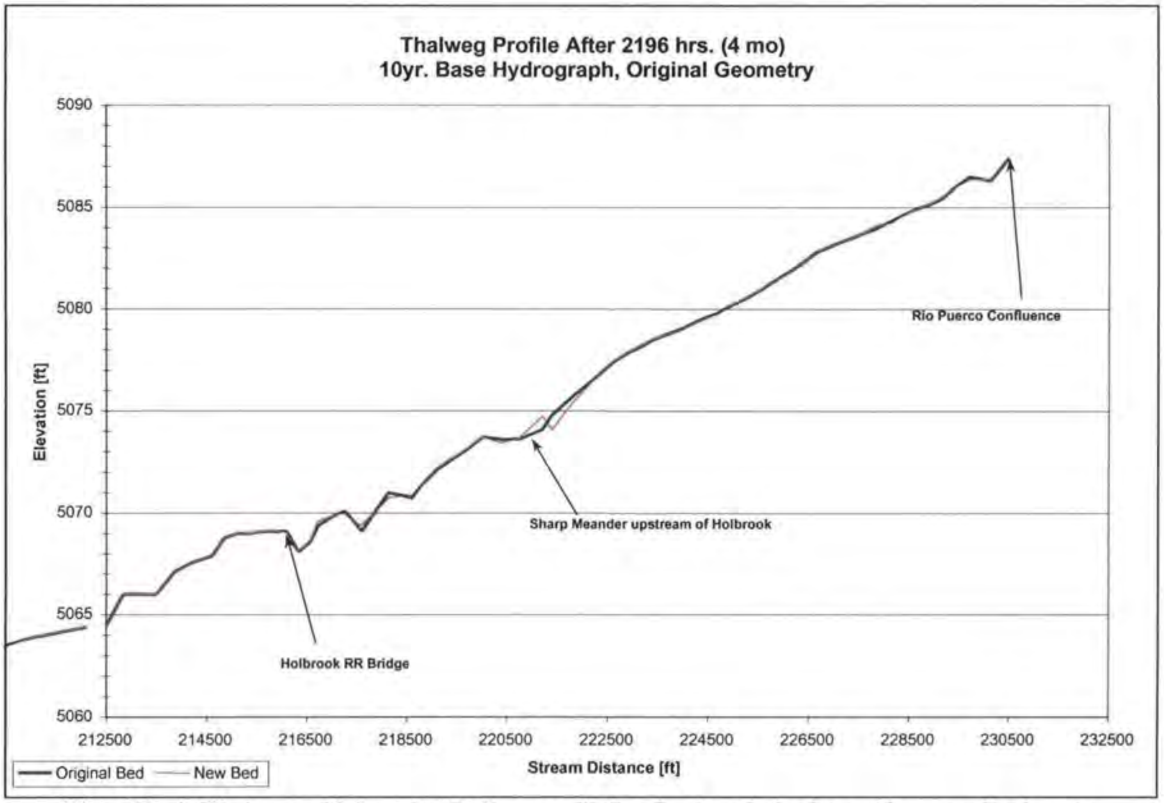


Figure H– 1. Thalweg profile from the Rio Puerco to Holbrook. Aggradation has not begun at this time step.

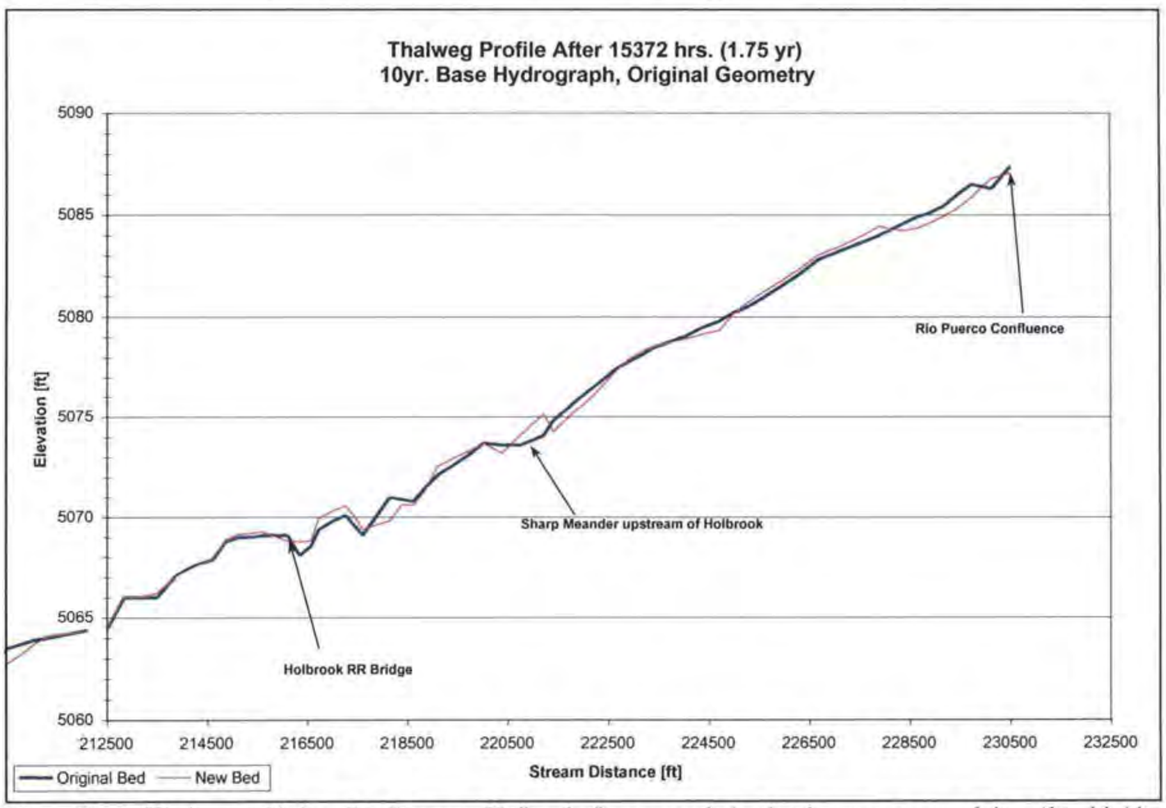


Figure H– 2. Thalweg profile from Rio Puerco to Holbrook. Some aggradation has begun upstream of the railroad bridge and in the meander upstream of Holbrook.

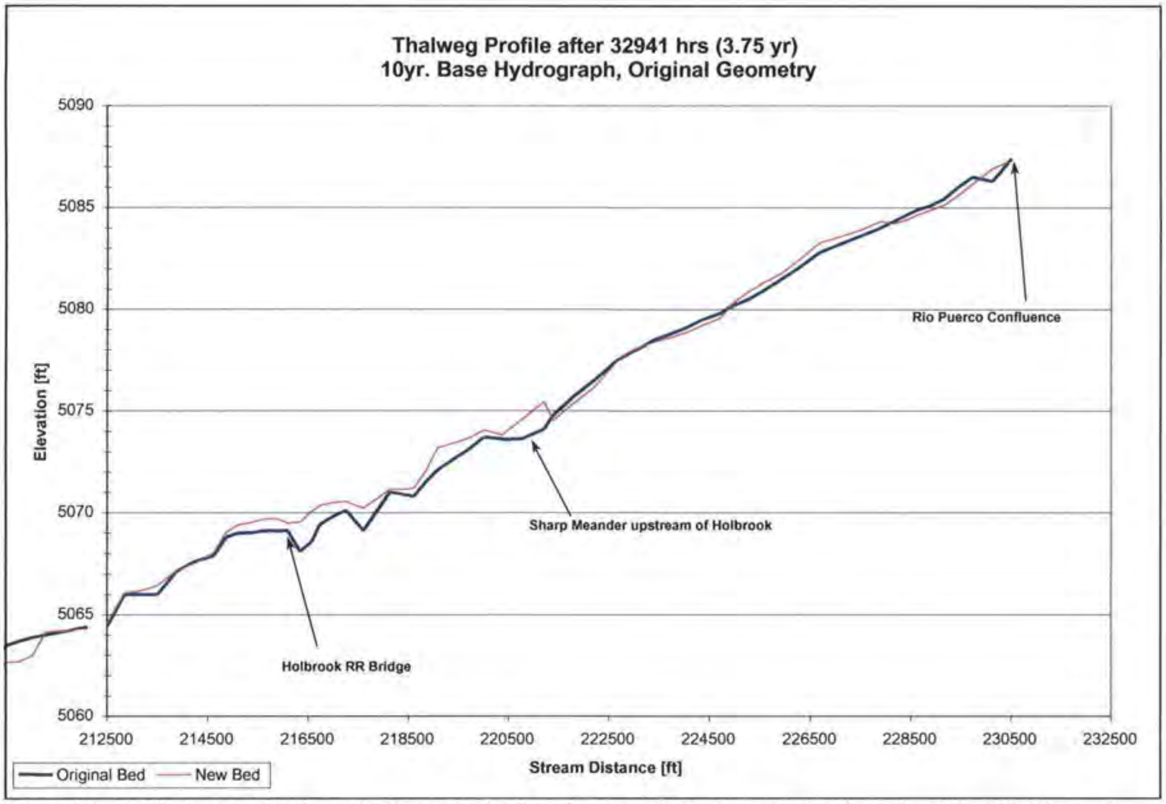


Figure H– 3. Thalweg profile from Rio Puerco to Holbrook. Aggradation is increasing from the railroad bridge to the meander upstream of Holbrook.

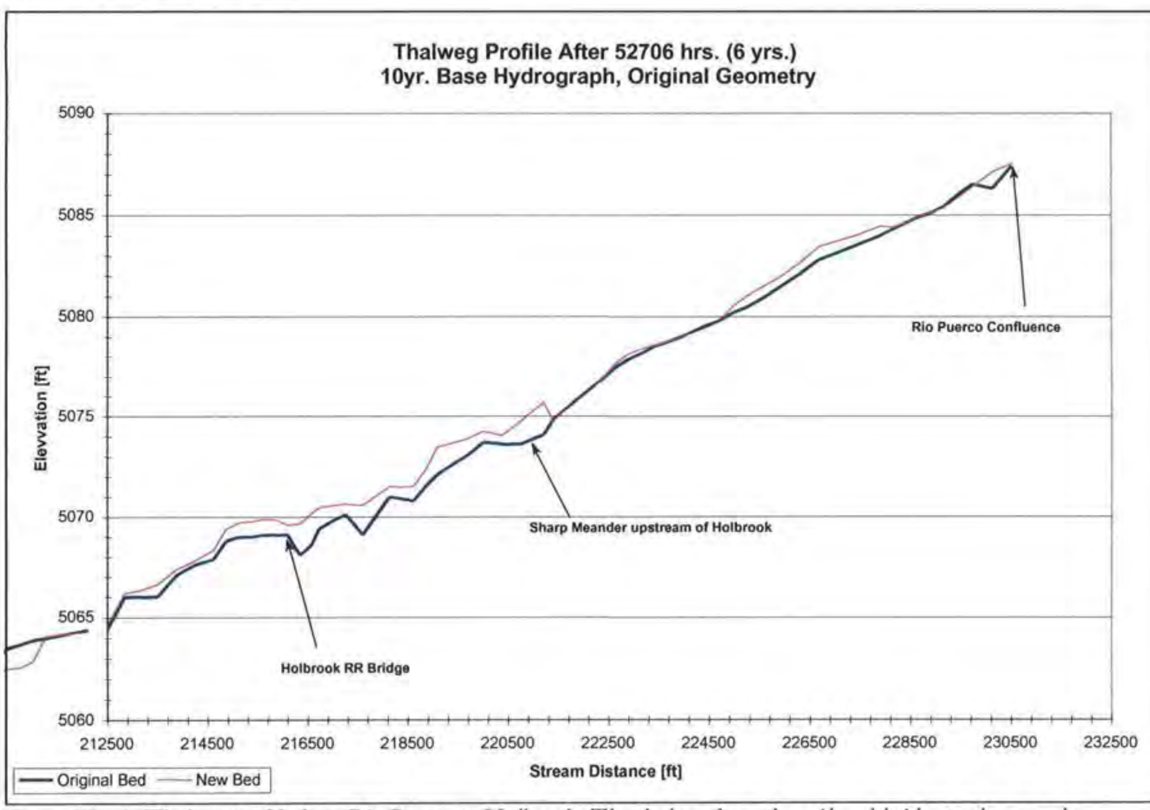


Figure H– 4. Thalweg profile from Rio Puerco to Holbrook. The thalweg from the railroad bridge to the meander continues to aggrade, very little activity upstream of the meander.

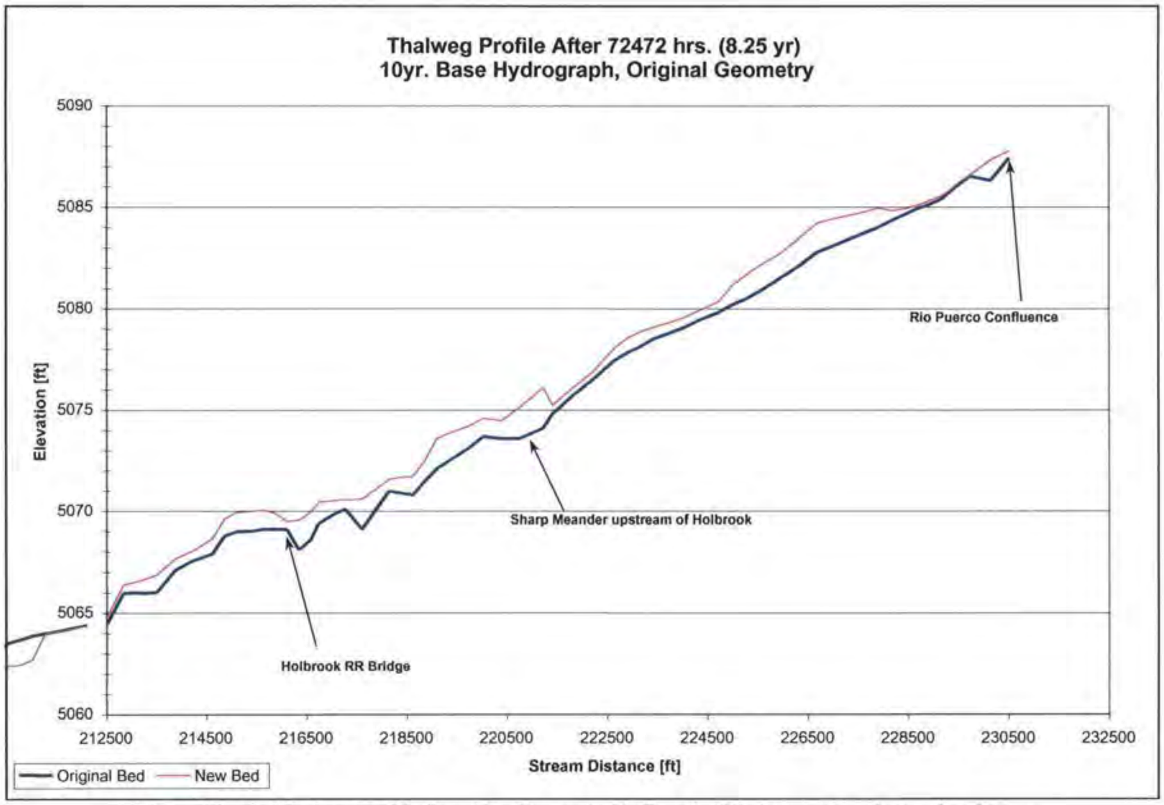


Figure H– 5. Thalweg profile from Rio Puerco to Holbrook. Upstream aggradation has begun.

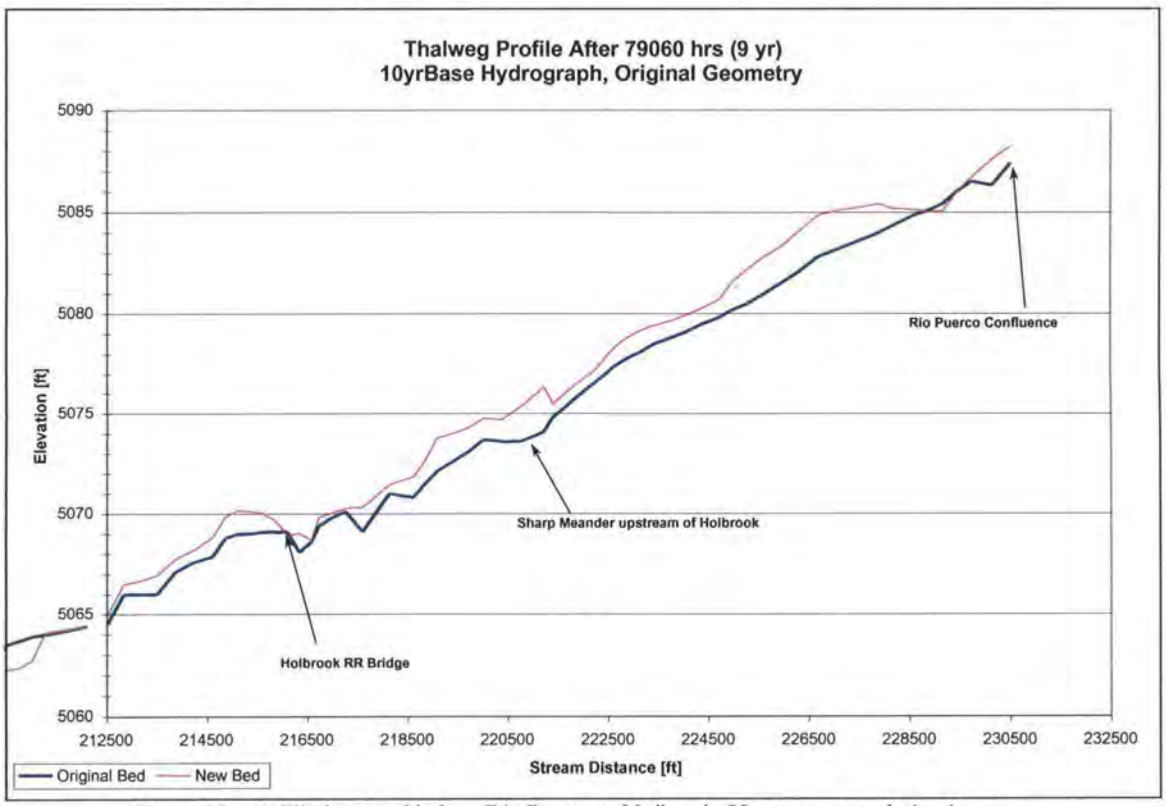


Figure H – 6. Thalweg profile from Rio Puerco to Holbrook. Upstream aggradation increases.

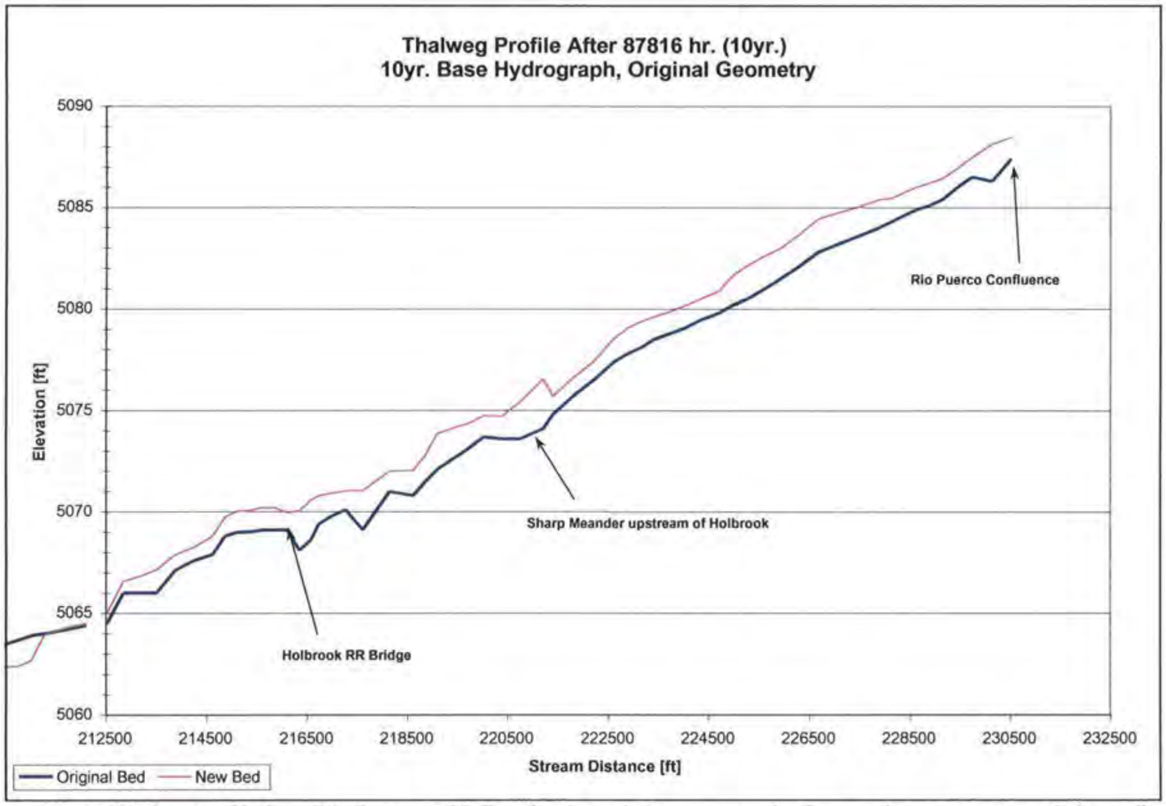


Figure H– 7. Thalweg profile from Rio Puerco to Holbrook. Aggradation amounts level out and progresses toward the confluence.

APPENDIX I

SEDIMENT MODEL RESULTS USING THE 10-YEAR BASE HYDROGRAPH WITH A SYNTHETIC 50-YEAR FLOOD

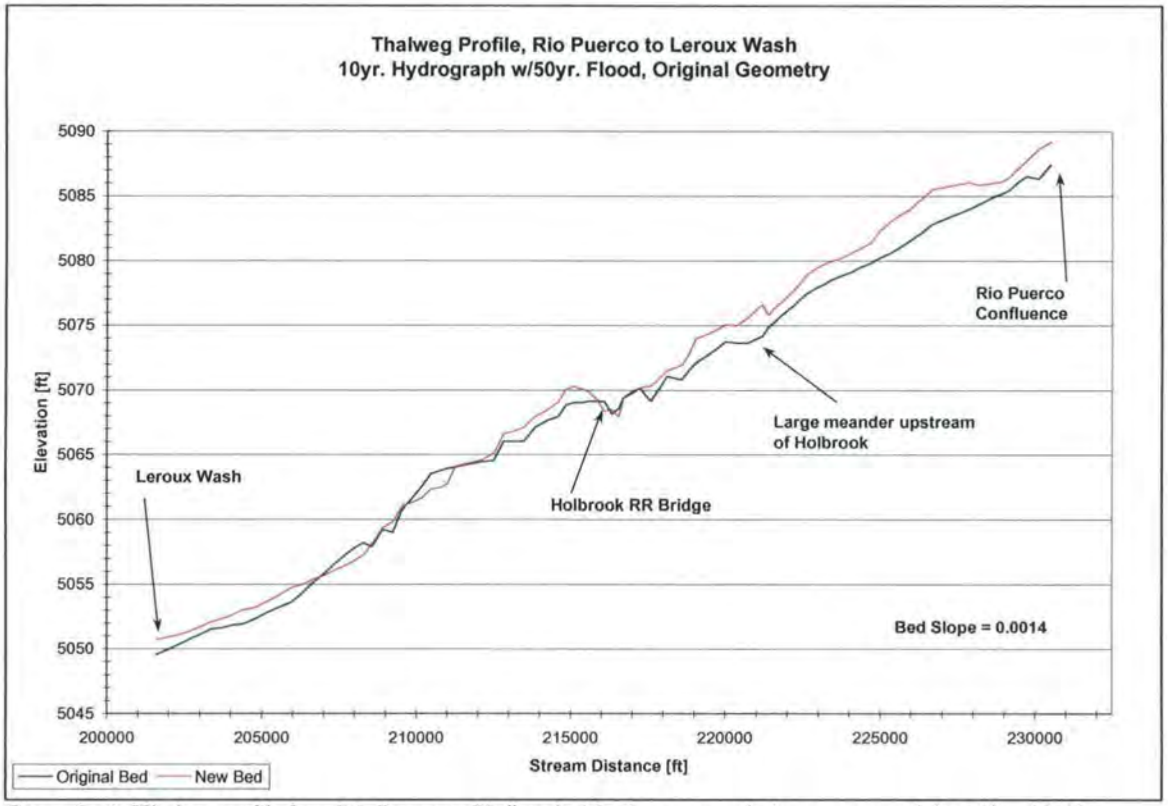


Figure I– 1. Thalweg profile from Rio Puerco to Holbrook. Maximum aggradation upstream of the railroad bridge increased by roughly one foot as compared to the 10–year base hydrograph.

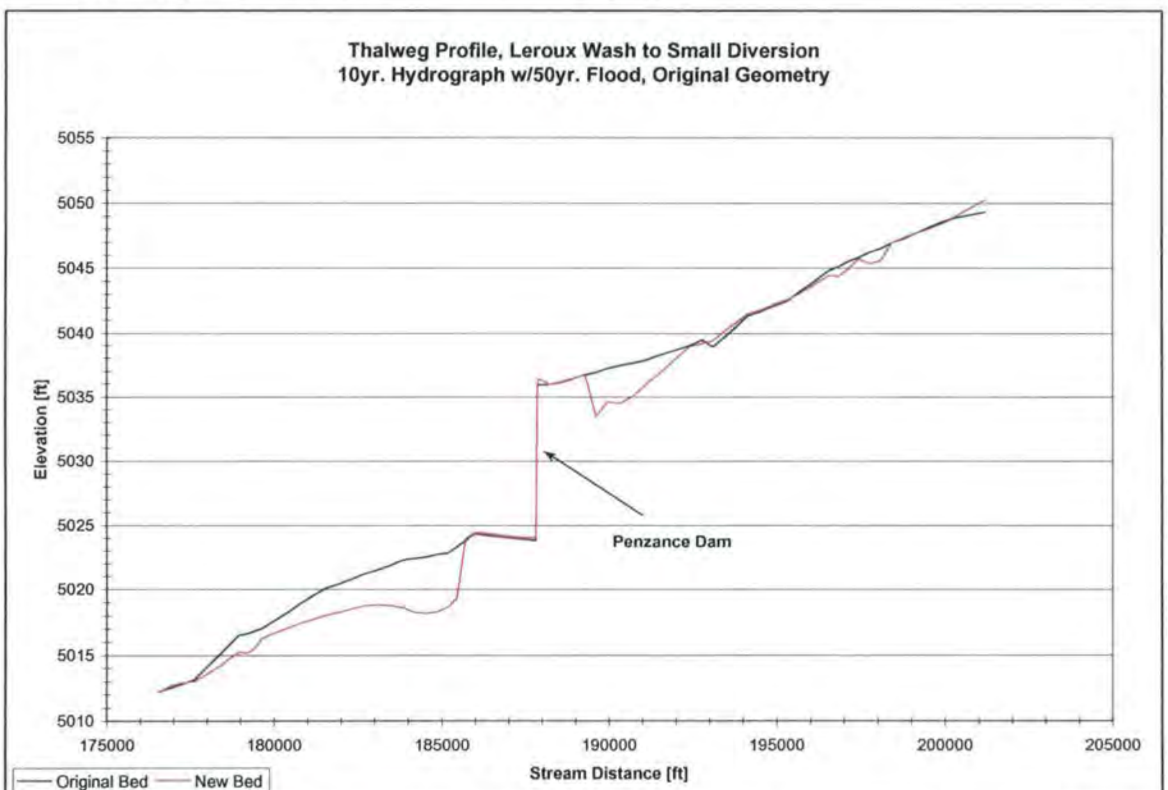


Figure I– 2. Thalweg profile from Leroux wash to the small diversion. Degradation upstream and downstream of Penzance Dam is likely artificial due to modeling complications.

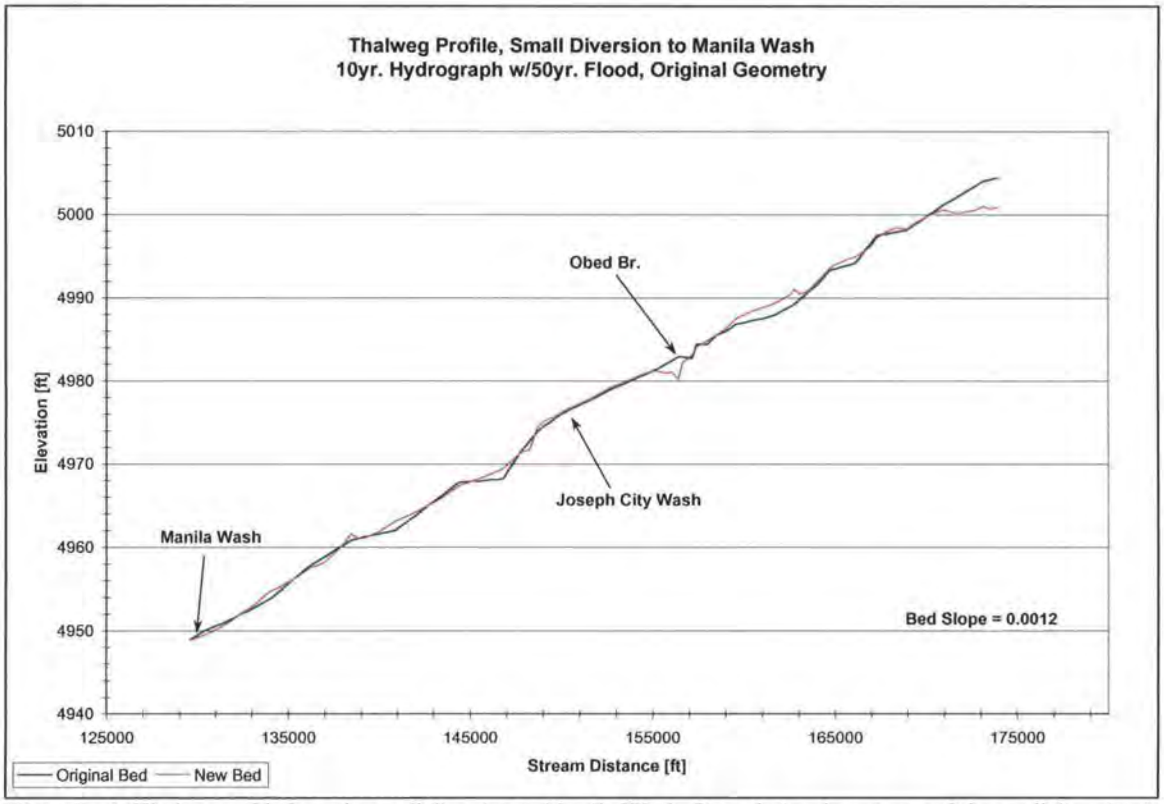


Figure I– 3. Thalweg profile from the small diversion to Manila Wash. Degradation downstream of the small diversion is likely artificial due to modeling complications.

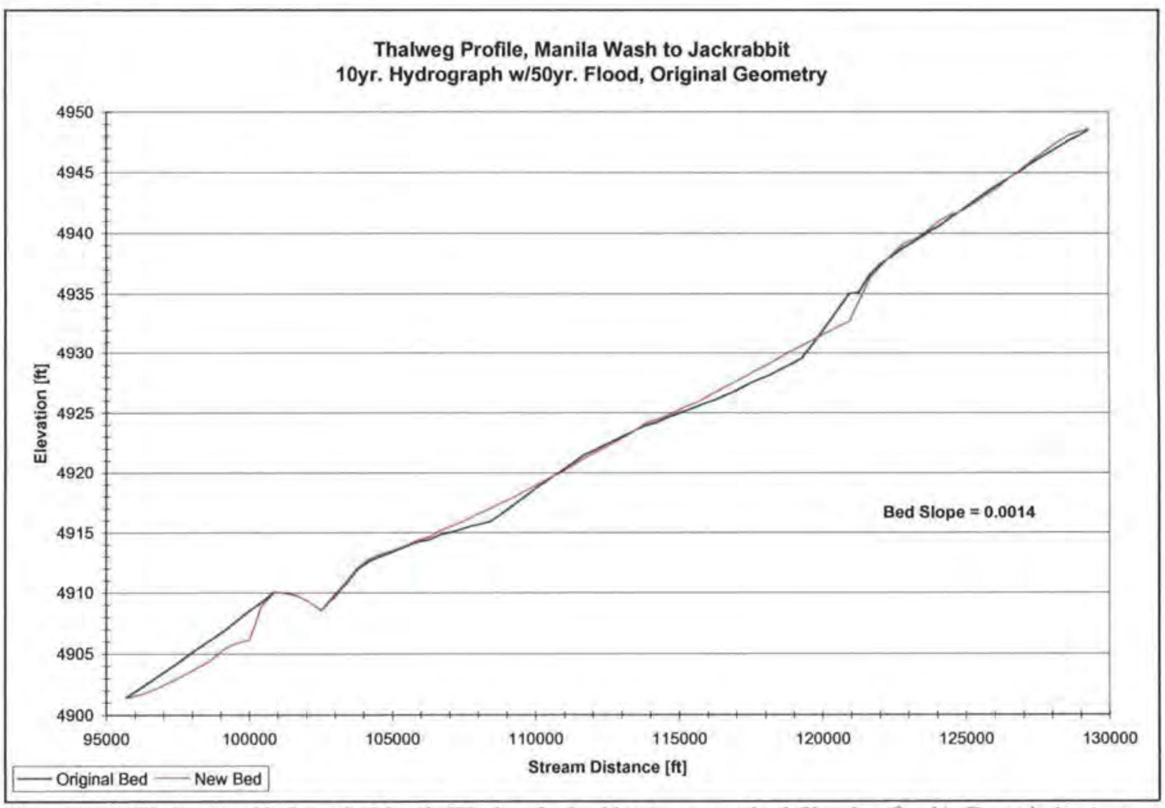


Figure I– 4. Thalweg profile from the Manila Wash to Jackrabbit (near mouth of Chevelon Creek). Degradation just downstream of the small diversion is likely similar to Penzance Dam.

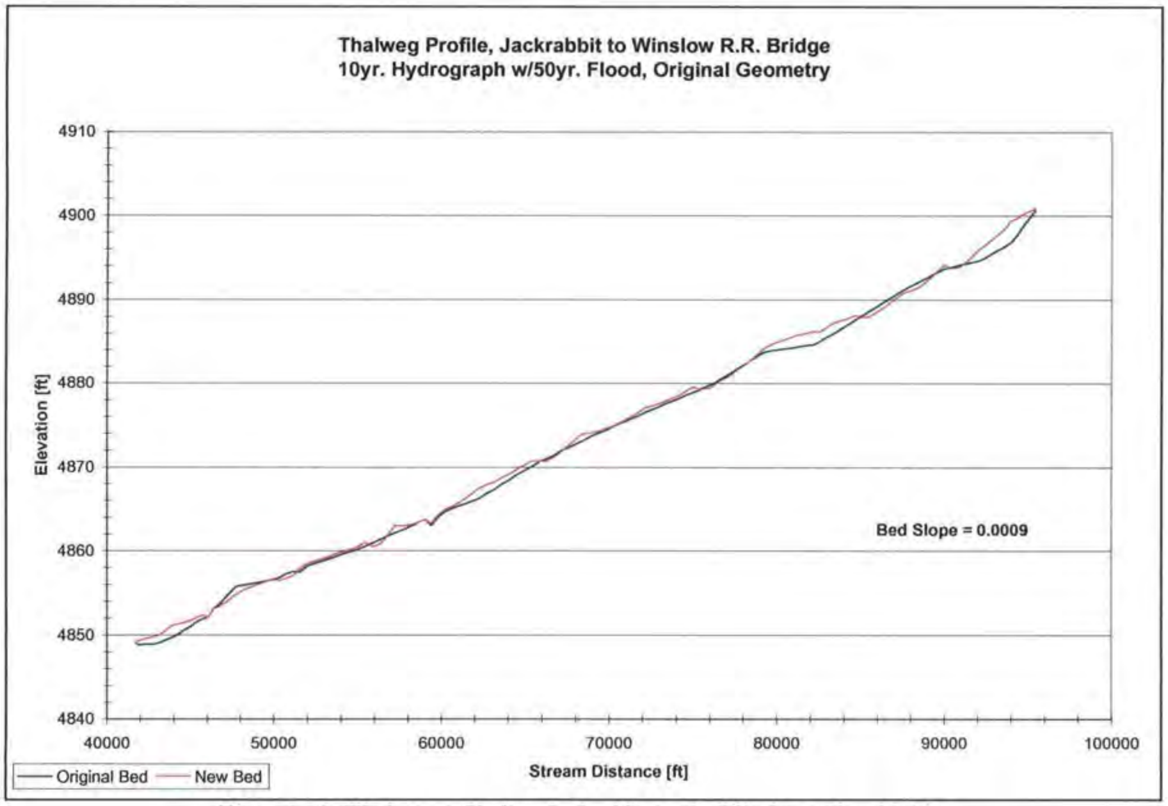


Figure I– 5. Thalweg profile from Jackrabbit to the Winslow railroad bridge.

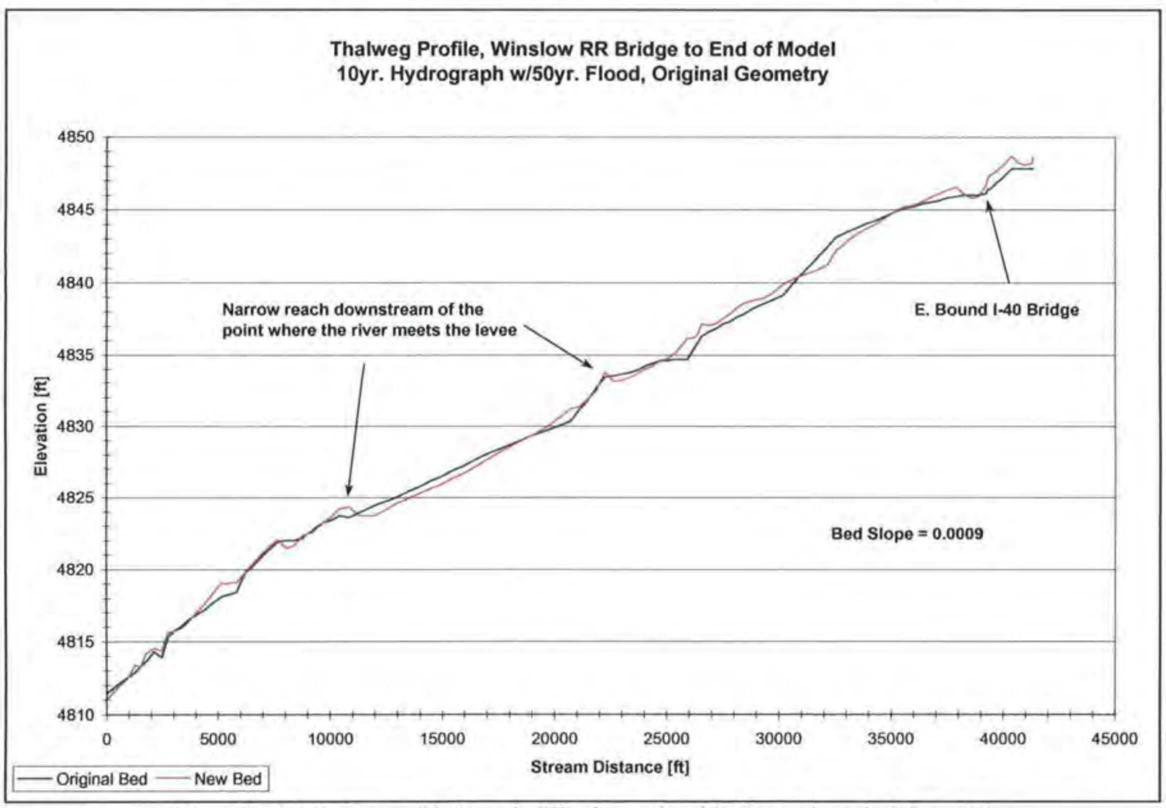


Figure I– 6. Thalweg profile from the Winslow railroad bridge to the end of the model.

APPENDIX J

SEDIMENT MODEL RESULTS USING THE 10-YEAR DRY HYDROGRAPH

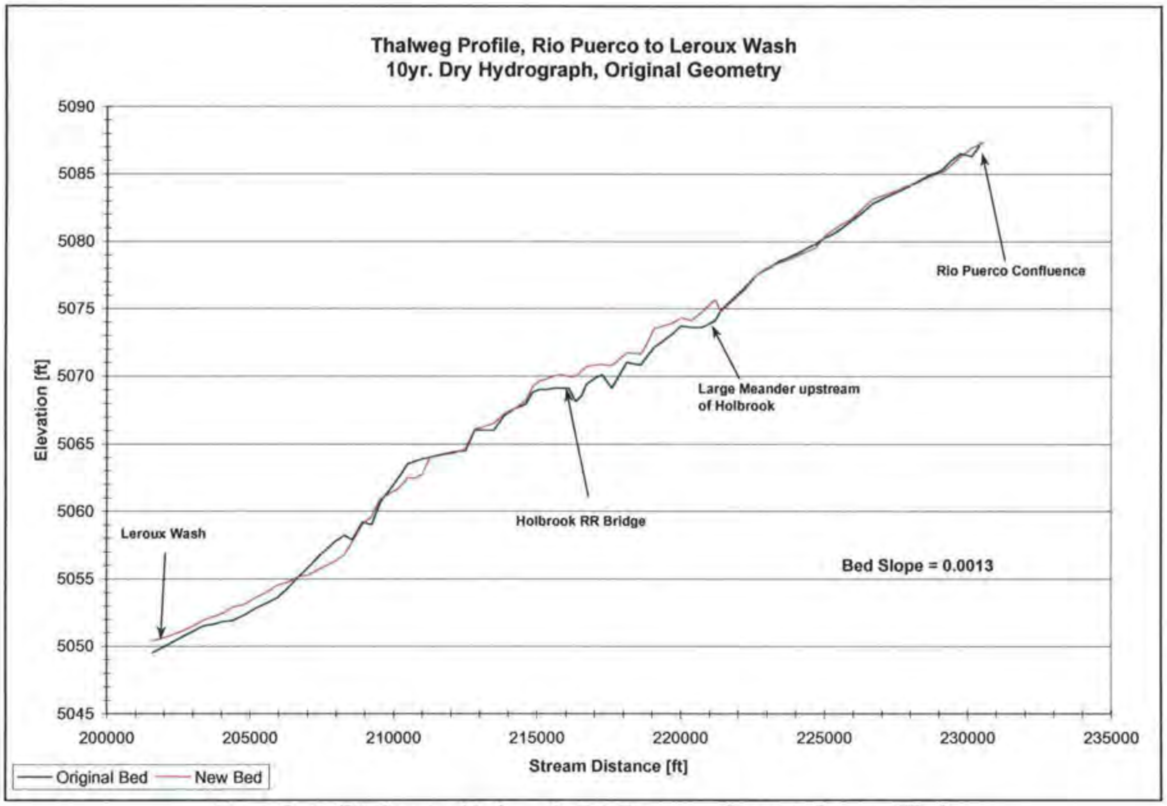


Figure J– 1. Thalweg profile from the Rio Puerco confluence to Leroux Wash.

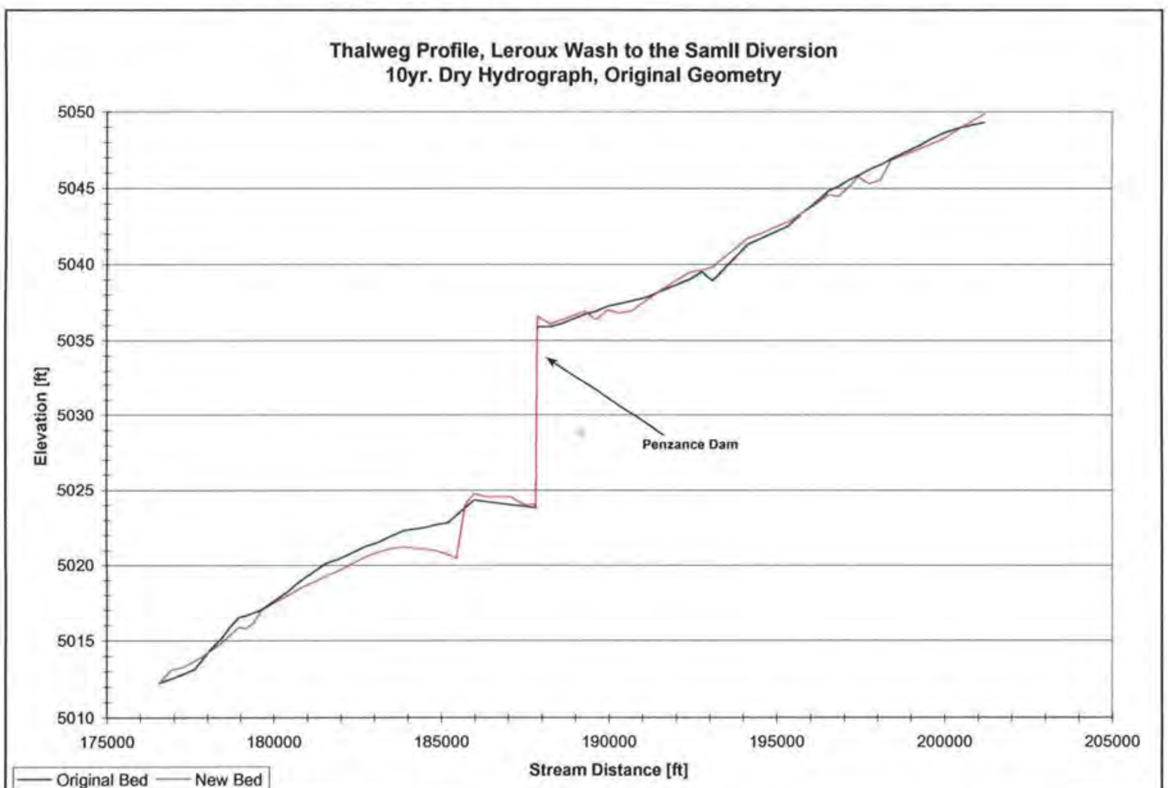


Figure J– 2. Thalweg profile from Leroux Wash to the small diversion. The degradation downstream of the dam is likely artificial due to modeling complications.

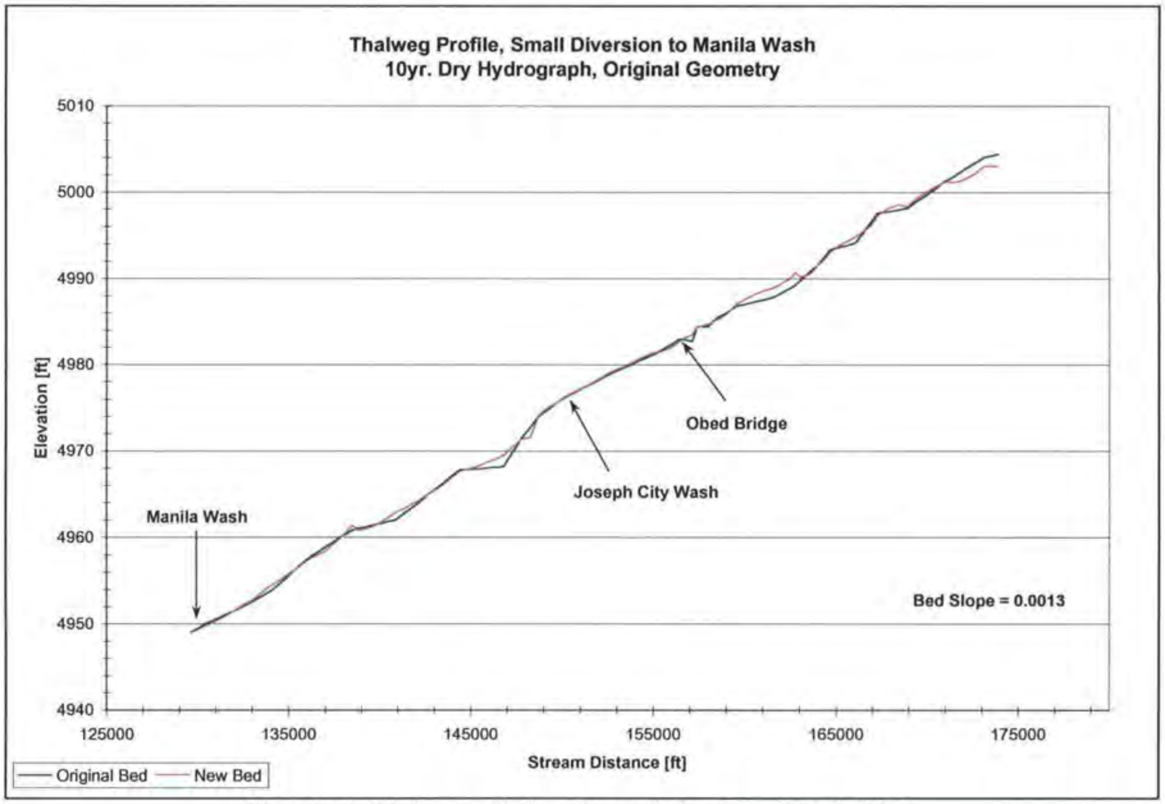


Figure J– 3. Thalweg profile from the small diversion to Manila Wash.

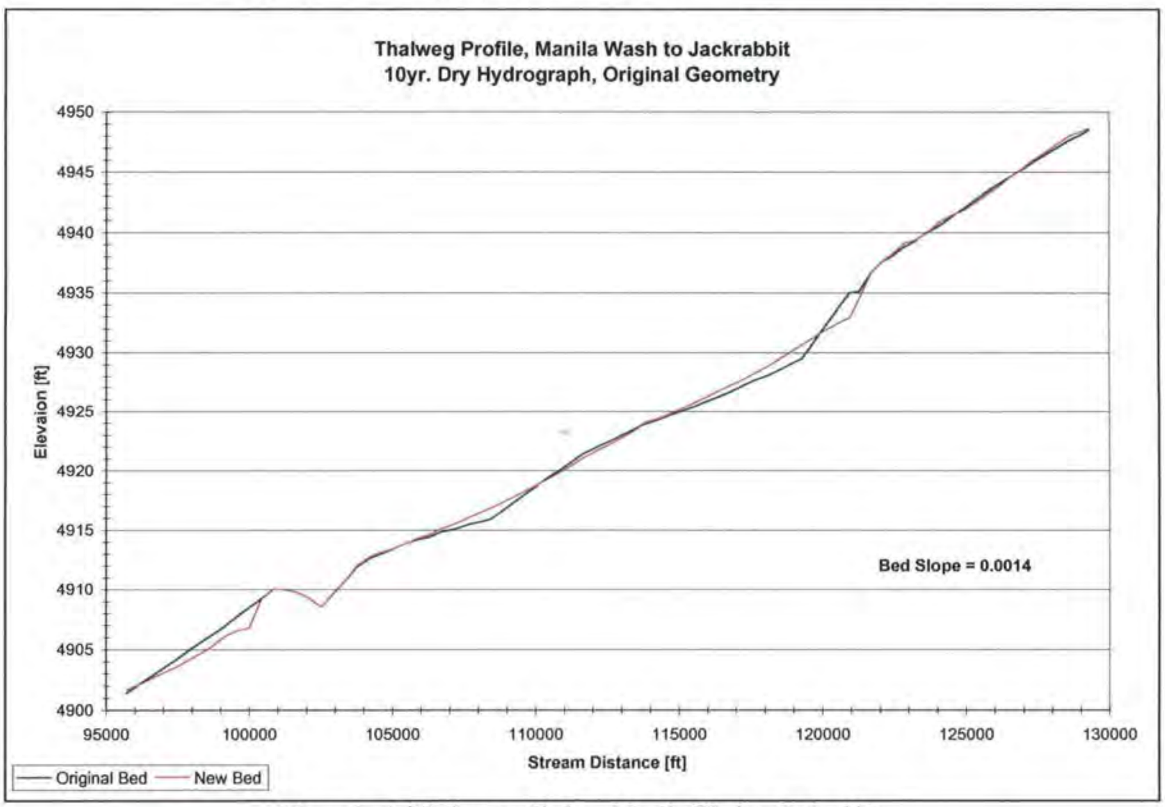


Figure J– 4. Thalweg profile from Manila Wash to Jackrabbit.

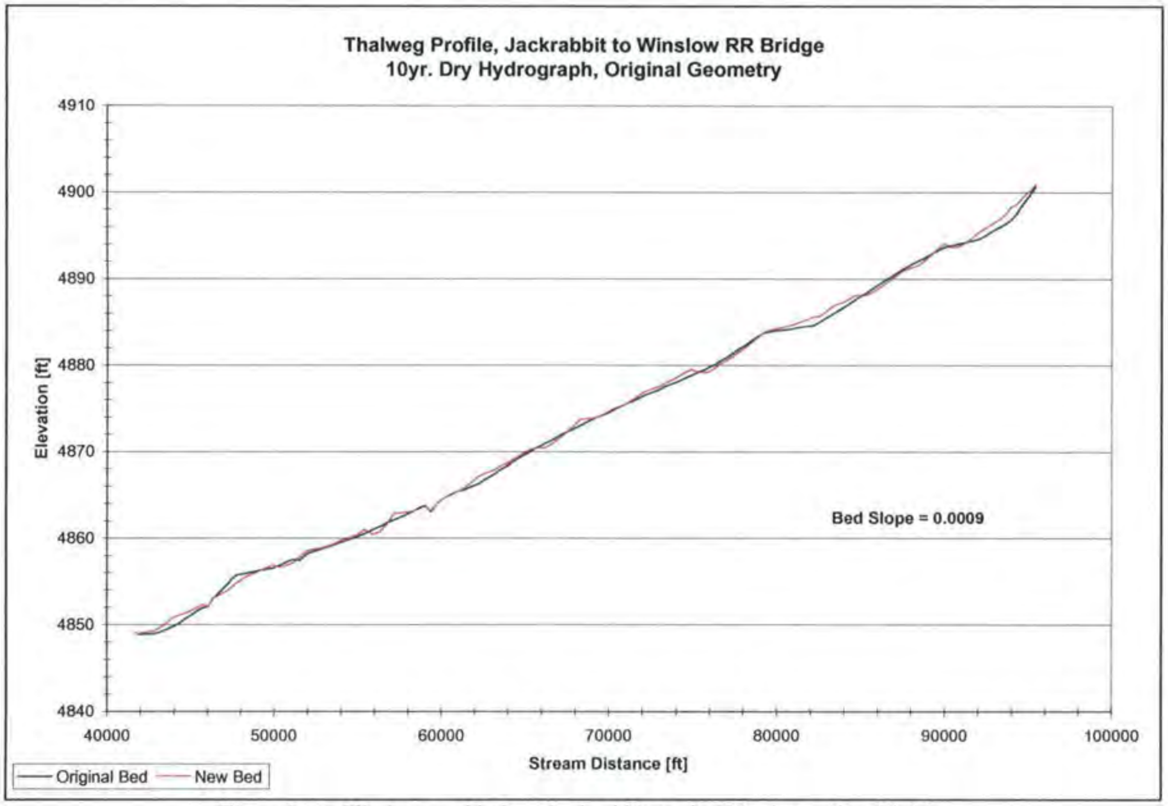


Figure J– 5. Thalweg profile from Jackrabbit to the Winslow railroad bridge.

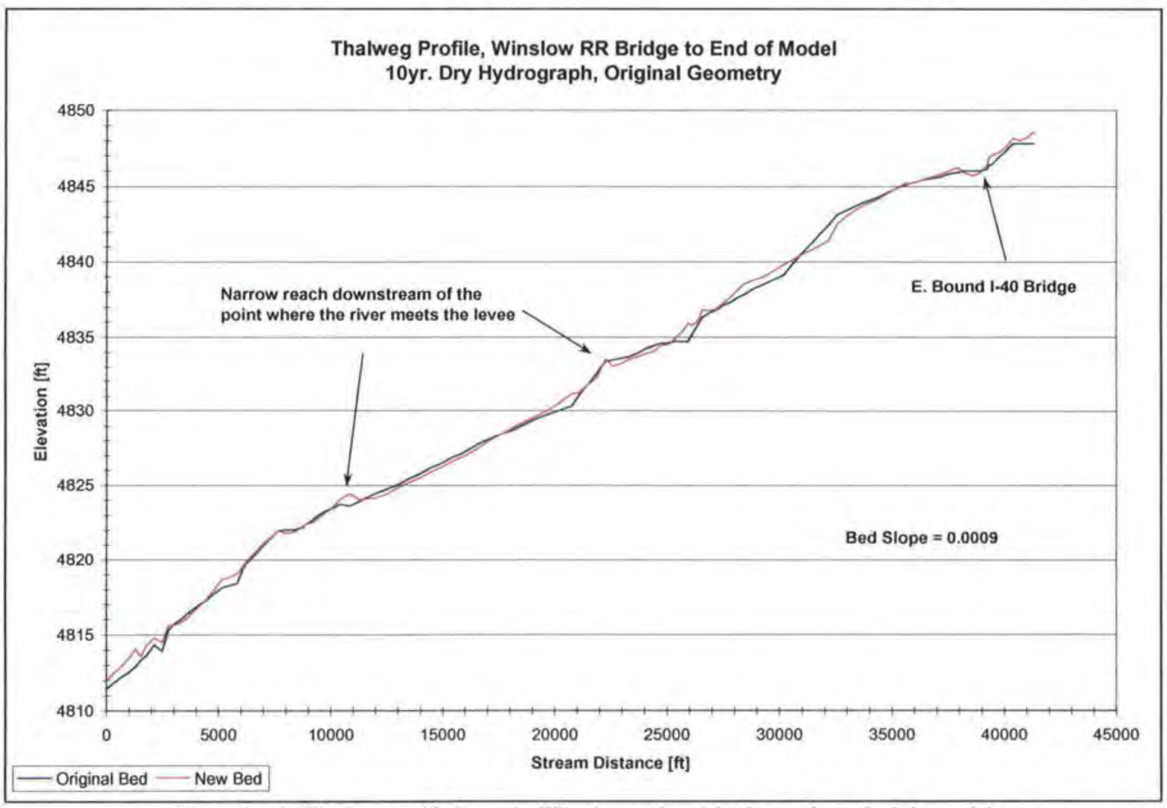


Figure J– 6. Thalweg profile from the Winslow railroad bridge to the end of the model.

APPENDIX K

SEDIMENT MODEL RESULTS USING THE 50–YEAR HYDROGRAPH

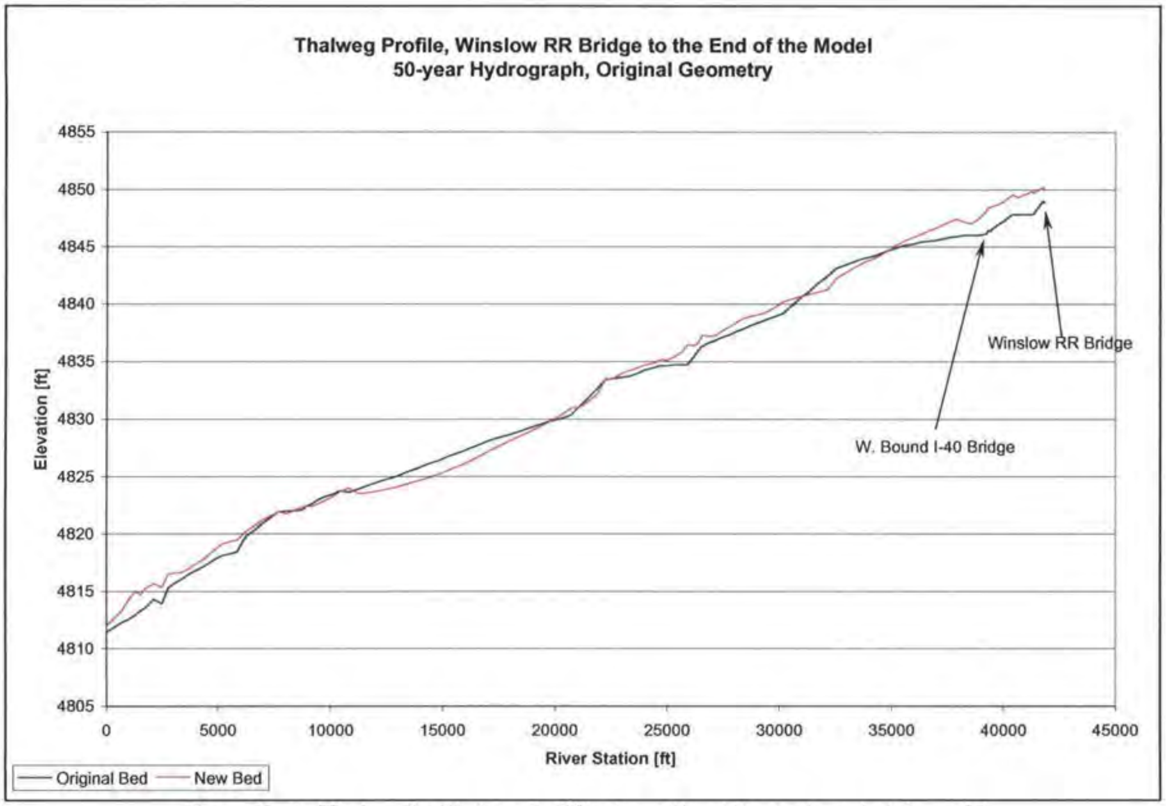


Figure K– 1. Thalweg Profile from the Winslow railroad Br. to the end of the model

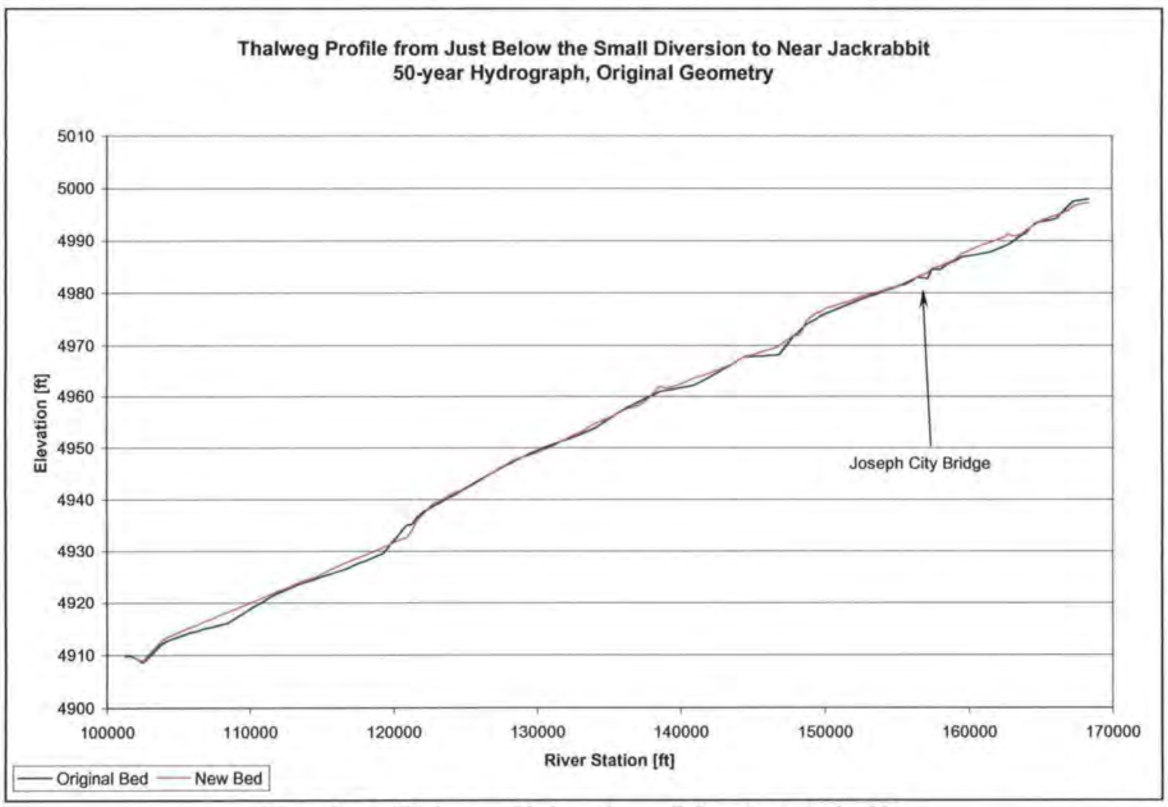


Figure K– 2. Thalweg profile from the small diversion to Jackrabbit.

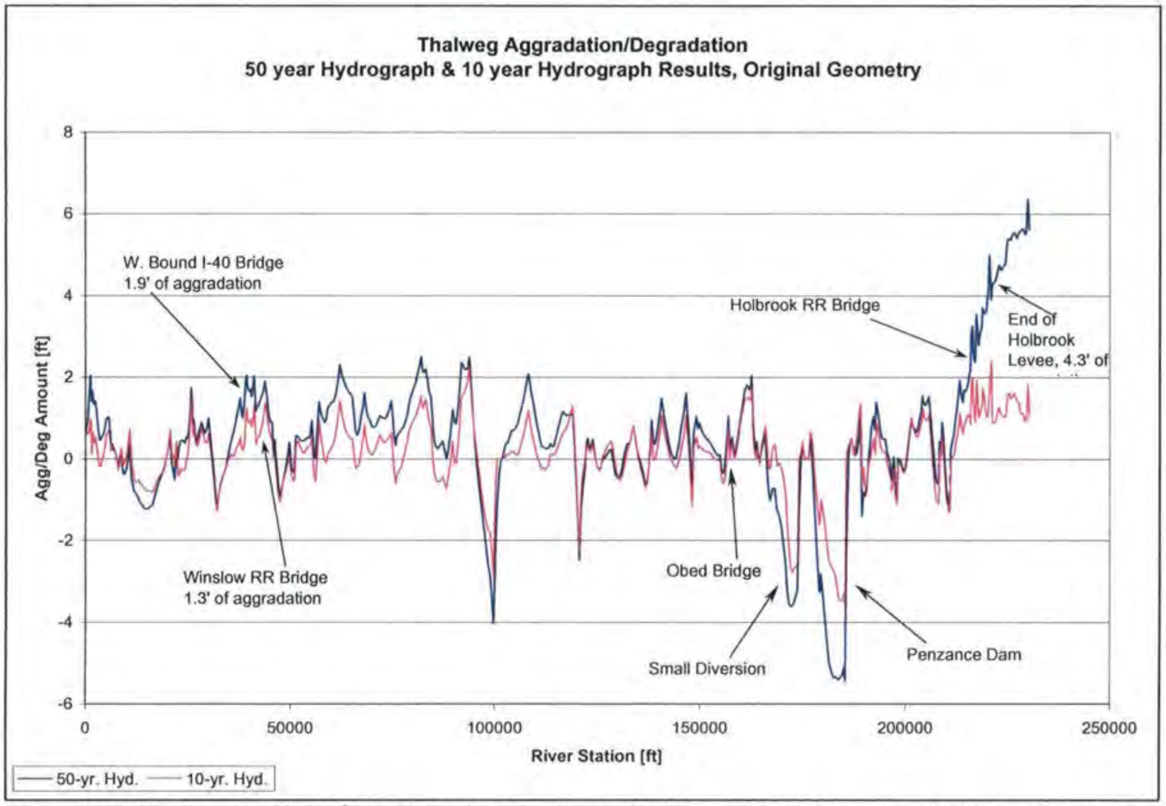


Figure K– 3. Thalweg aggradation/degradation for the entire reach of the model, results compared to the results using the 10 year hydrograph

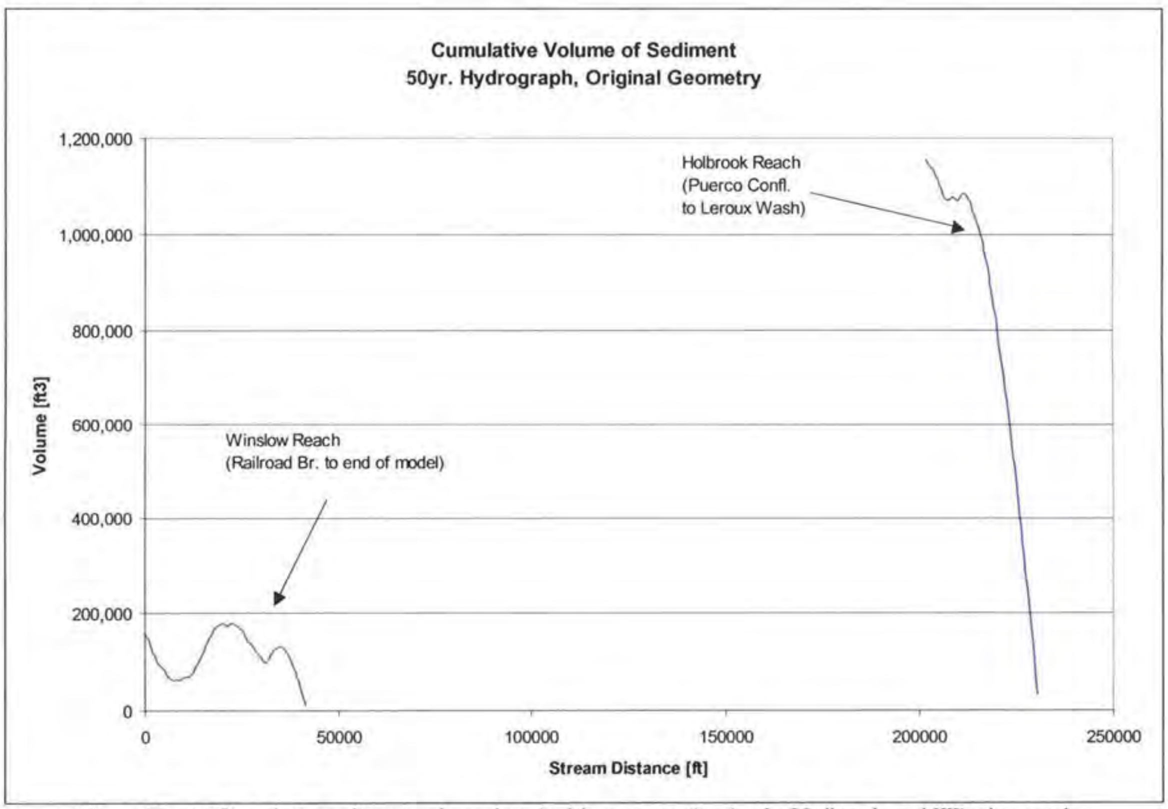


Figure K– 4. Cumulative sediment volume deposited by cross section in the Holbrook and Winslow reaches.

Appendix L

SEDIMENT MODEL RESULTS USING THE 60,000 FT^3/S FLOOD

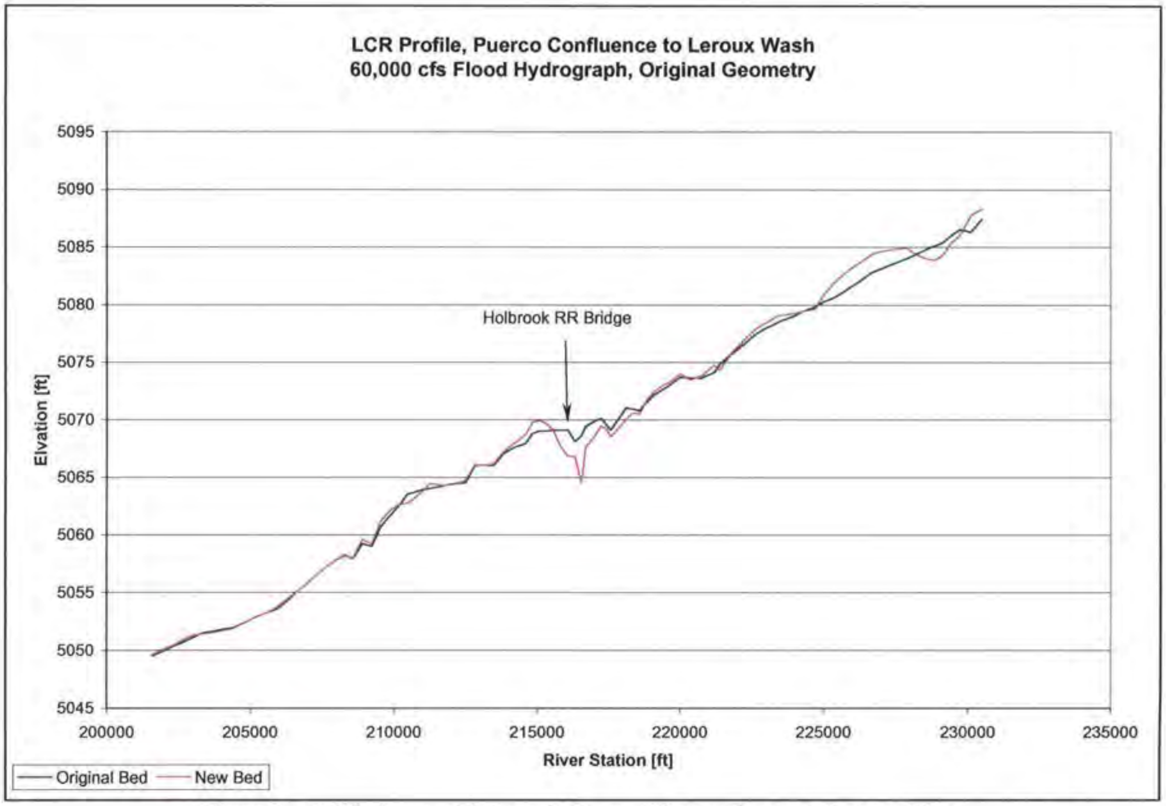


Figure L– 1. Thalweg profile from the Puerco River confluence to Leroux Wash.

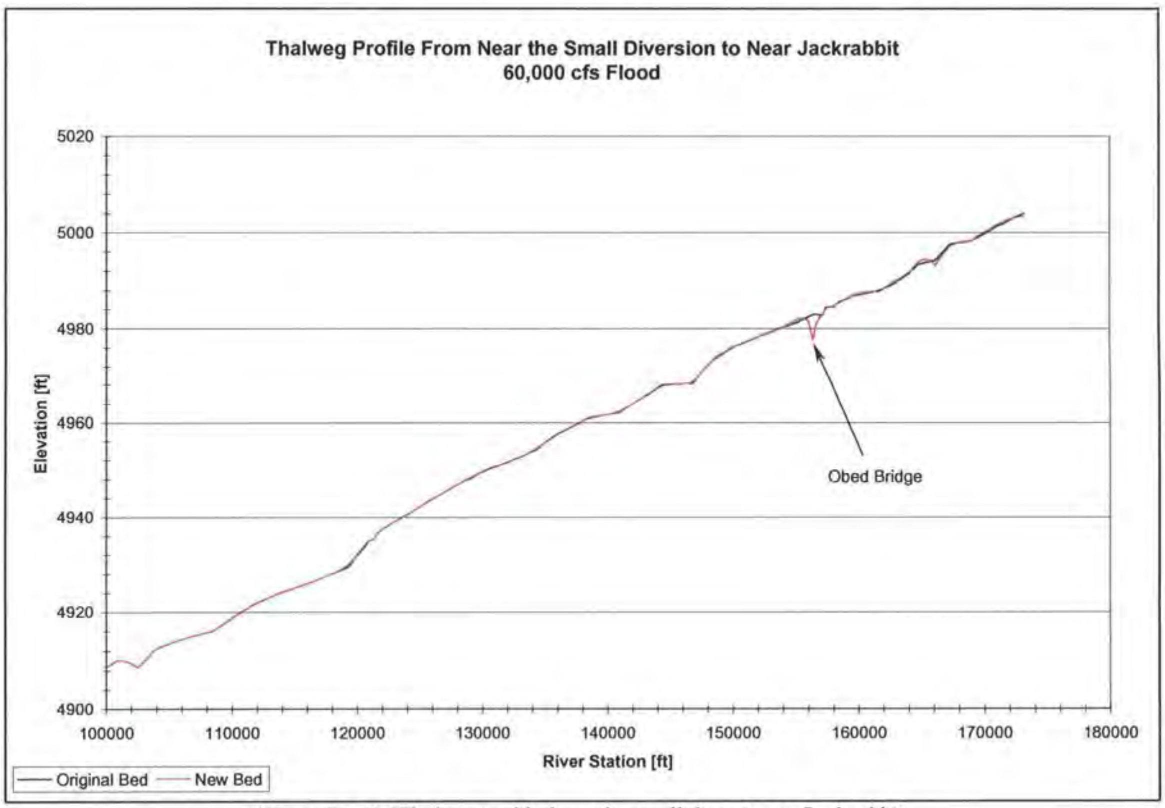


Figure L– 2. Thalweg profile from the small diversion to Jackrabbit.

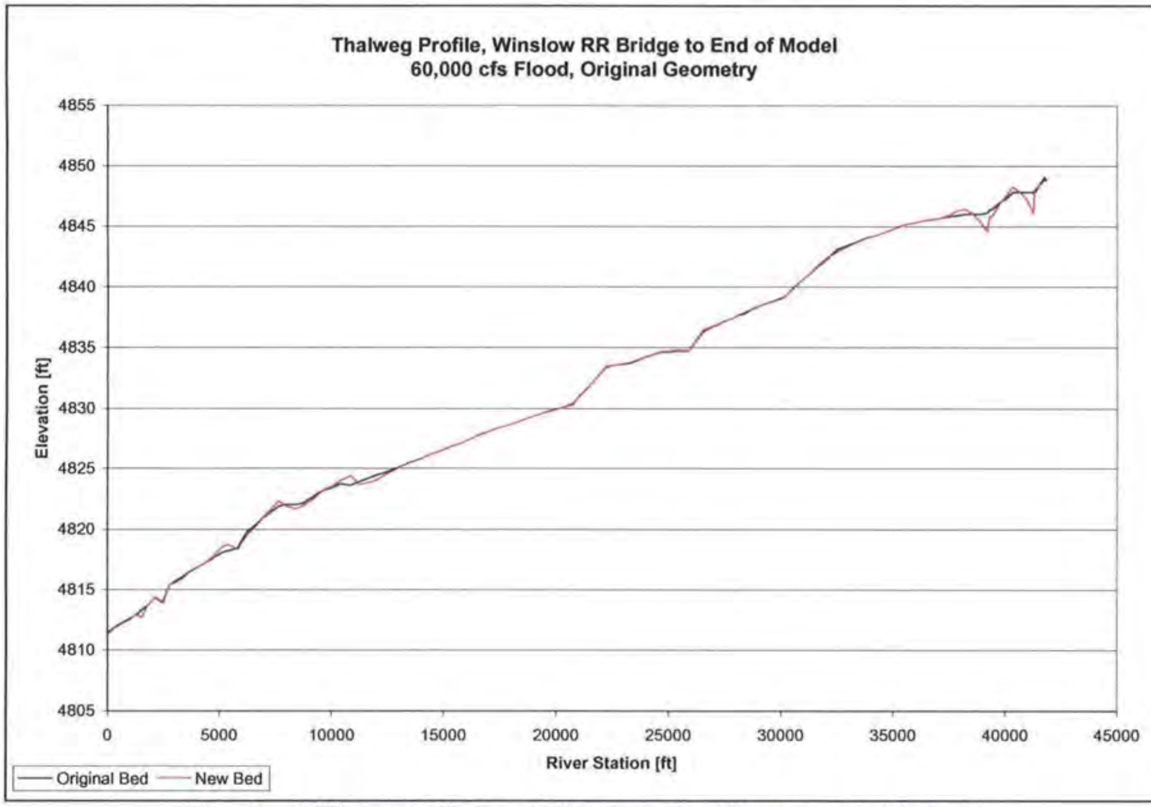


Figure L– 3. Thalweg profile from the Winslow railroad Br. to the end of the model.

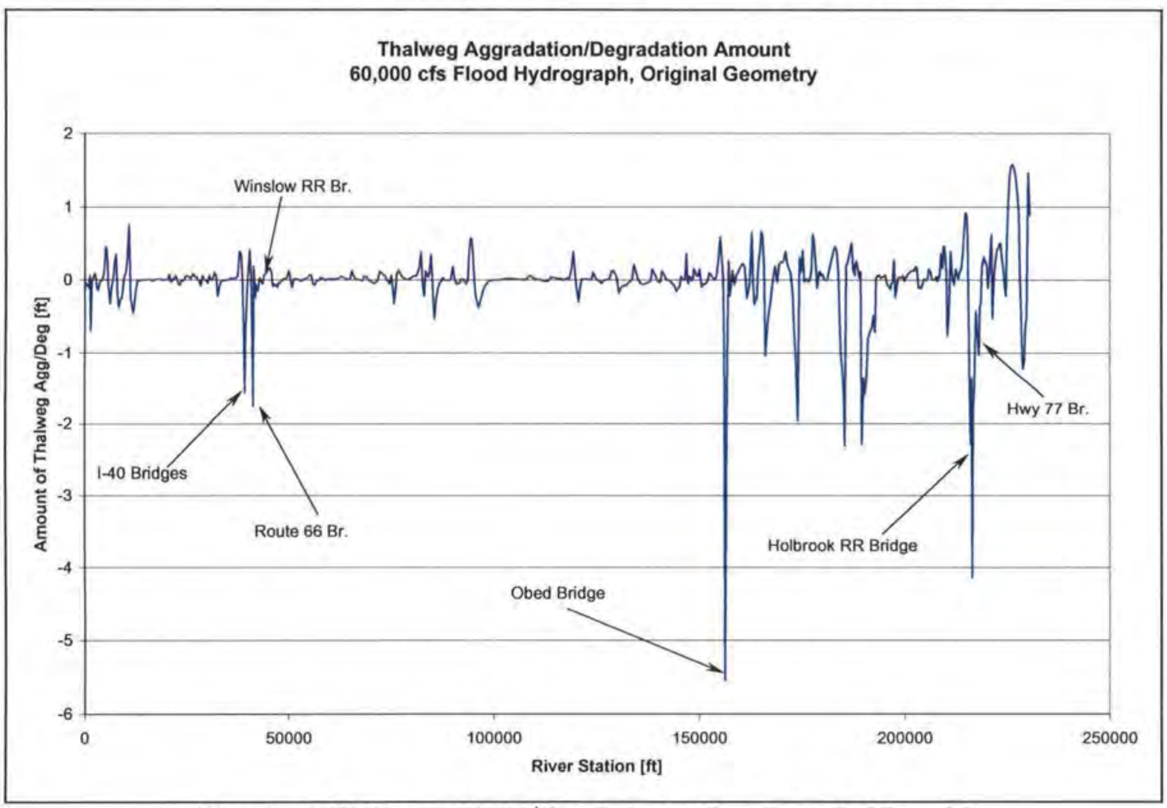


Figure L– 4. Thalweg aggradation/degradation over the entire reach of the model.

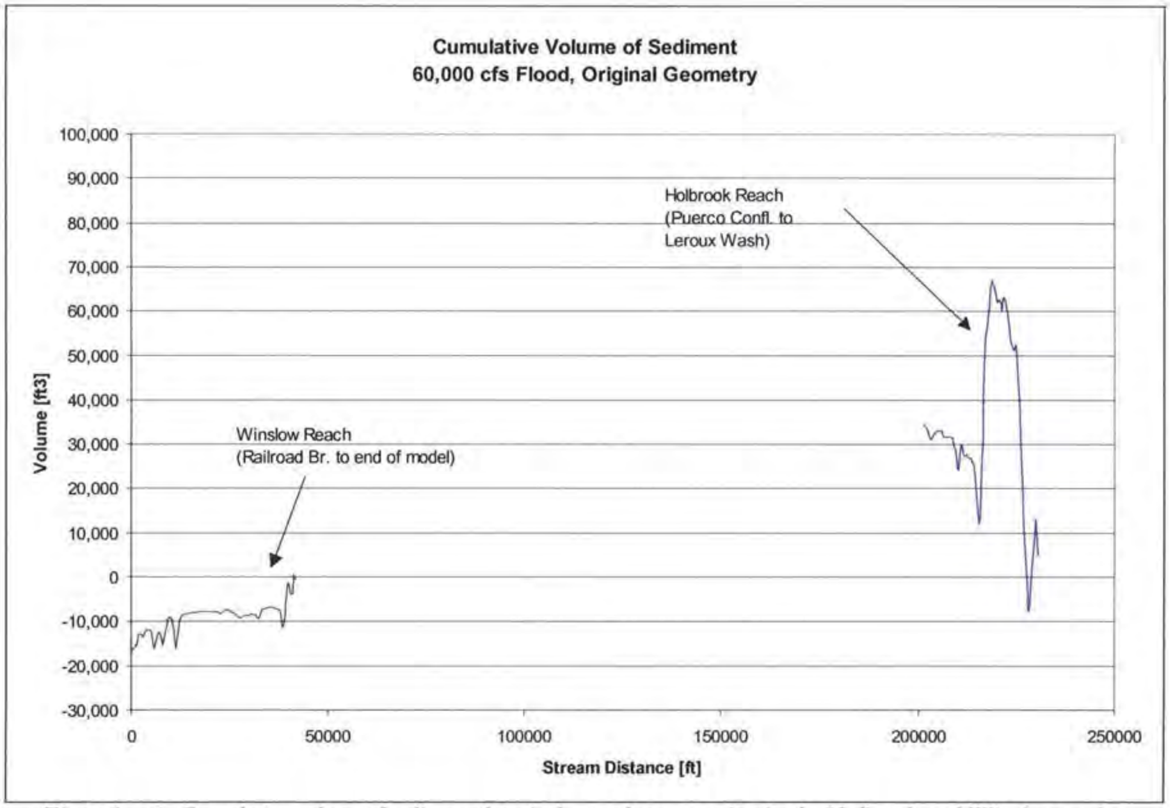


Figure L– 5. Cumulative volume of sediment deposited at each cross section in the Holbrook and Winslow reaches.

Appendix M

COMPARISON OF SABOL 1995 AND RECLAMATION 2000 AERIAL SURVEYS