TECHNICAL SERVICE CENTER
DENVER, COLORADO

UPPER GILA RIVER FLUVIAL GEOMORPHOLOGY STUDY

FINAL REPORT
RECOMMENDATIONS FOR DEMONSTRATION PROJECTS
NEW MEXICO

US Department of the Interior
Bureau of Reclamation

MARCH 24, 2004

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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.

STATE OF NEW MEXICO
NEW MEXICO ENVIRONMENT DEPARTMENT
SURFACE WATER QUALITY BUREAU

RECLAMATION CONTRACT 00-GI 32-0060
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The State of New Mexico and Reclamation are Cost Share Partners in the Upper Gila River Fluvial Geomorphology Study. The views or findings of Reclamation presented in this deliverable do not necessarily represent those of the State of New Mexico.

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PREPARED BY
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FLUVIAL HYDRAULICS & GEOMORPHOLOGY TEAM

The Fluvial Hydraulics & Geomorphology Team from the Technical Service Center is leading the Upper Gila Fluvial Geomorphology Study. The team consists of geomorphologists, engineers, and biologists. The members have expertise in water resources management, fluvial geomorphology, paleohydrology, hydraulics, sedimentation, photogrammetry, mapping, fisheries biology, wildlife biology, and riparian vegetation management.

The team members are:

- Dr. Daniel R. Levish, Geologist. (Paleohydrology, Fluvial Geomorphology)
- Dr. Rodney J. Wittler, Hydraulic Engineer. (Hydraulics, Water Resources Management)
- Ms. Jeanne E. Klawon, Geologist. (Fluvial Geomorphology, Geology)
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- Dr. Ralph E. Klinger, Geologist. (Paleohydrology, Fluvial Geomorphology)
- Dr. Blair P. Greimann, Hydraulic Engineer. (Hydraulics, Sediment Transport)

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FINAL REPORT RECOMMENDATIONS FOR DEMONSTRATION PROJECTS NEW MEXICO

INTRODUCTION

The State of New Mexico, Environment Department, Surface Water Quality Bureau (NMED-SWQB), and the Bureau of Reclamation sponsored the Upper Gila River Fluvial Geomorphology Study in New Mexico. The Bureau of Reclamation, under a Joint Powers Agreement (JPA) with the NMED, began the fluvial geomorphology study of the Gila River in New Mexico between the Arizona State line and Mogollon Creek, near Cliff, New Mexico, in October 2000. This study complements an on-going Reclamation fluvial geomorphology study of the Gila River in Arizona. The Reclamation Study Manager is Mary Reece, Phoenix Area Office (PXAO). Co-Principal Investigators from the Bureau of Reclamation Technical Service Center (USBR-TSC) in Denver, Colorado, are Dr. Rodney J. Wittler, Hydraulic Engineer, and Dr. Daniel R. Levish, Fluvial Geomorphologist.

The goal of this study is to analyze the fluvial geomorphological attributes of the upper Gila River. These attributes are a function of the physical processes at work in the stream corridor. The stream corridor includes the main stem of the Gila River at flood stage and the associated riparian area, as well as tributaries within the valley of the main stem. The purpose of the study is to increase the awareness of these processes enabling improved local, state, and federal management of the stream corridor. The study includes background information gathering, field data collection, photographic analyses, and a variety of topographic, geomorphic, hydraulic, and hydrologic analyses. The study includes a qualitative assessment of the Gila River in the Upper Box.

The downstream boundary of the study is the Arizona-New Mexico State line. The upstream boundary of the study is the Cliff, New Mexico area, and specifically USGS gage 09430500 Gila River near Gila, NM, at the Hooker Dam site, 1.6 miles upstream from Mogollon Creek, roughly 7 miles northeast of Gila, New Mexico. The length of river channel in the study area, measured from USGS 7.5 minute topographic maps is roughly 66.2 miles.

STUDY AREA DESCRIPTION

The Upper Gila River basin sits in the southeast corner of Arizona and southwestern New Mexico. The upstream boundary of the study area is the Cliff-Gila area, upstream to the USGS Gage 09430500 Gila River near Gila, NM. The downstream limit of the study is the Arizona-New Mexico State line. Within the study area, the Gila River flows southward from its headwaters in the Gila Wilderness area in Catron County, New Mexico, and southwestward through Grant County into Hidalgo County and Virden, New Mexico, near the New Mexico-Arizona state line. Figure 1 illustrates the study area in the southwestern area of New Mexico. Five significant tributaries enter the Gila River upstream of Cliff, New Mexico: the West, Middle, and East Forks of the Gila River, Sapillo Creek, and Mogollon Creek. Main tributaries between Cliff and Virden include Bear, Duck, Sycamore, Mangas, and Blue Creeks. Elevations in the drainage basin range from roughly 3,850 feet at the western boundary of the study area (Arizona-New Mexico state line) to near 11,000 feet at the crest of the Mogollon Mountains in the Gila Wilderness area.

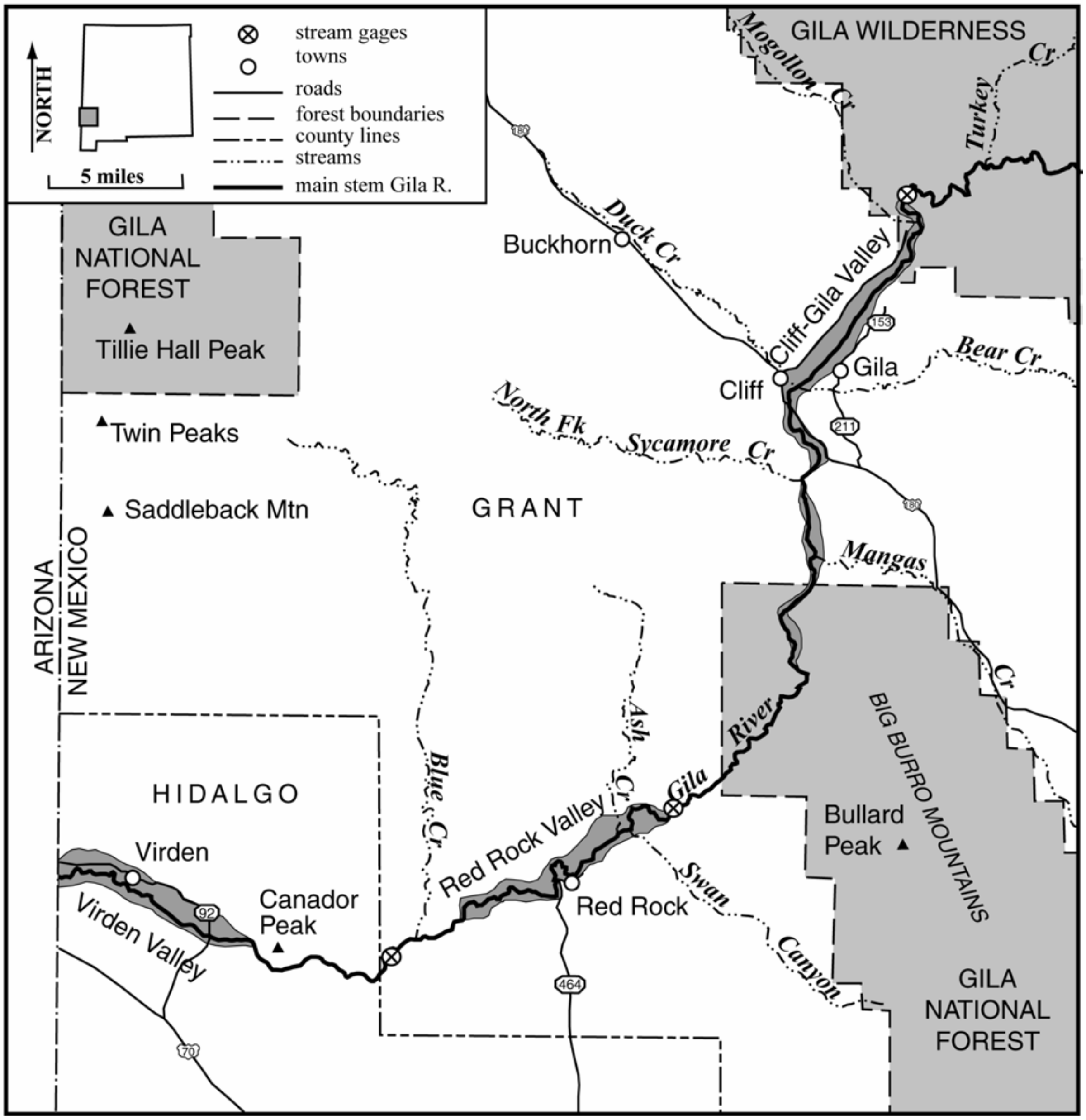


Figure 1. Study area in southwestern New Mexico.

UPPER BOX

The Upper Box, or canyon, is one of three boxes the Gila River flows through in New Mexico. The river flows through a fourth canyon, the Gila Box, in Arizona between the York and Safford valleys. The Upper Box begins downstream of the confluence of the Gila River and the East Fork Gila River, at the Highway 15 bridge. The Upper Box is roughly 37 miles long, ending at the Cliff-Gila Valley. The river has an average gradient of 0.0045 in the canyon.

CLIFF-GILA VALLEY

The Cliff-Gila Valley is home to the small towns of Cliff and Gila, New Mexico. The valley begins at the downstream end of the Upper Box, at USGS Gage 09430500 Gila River near Gila, NM, at the Hooker Dam site, 1.6 miles upstream from Mogollon Creek, roughly 7 miles northeast of Gila, New Mexico. The downstream end of the valley is near Ira Canyon, a left bank tributary. The valley is roughly 18 miles long, while the channel in the valley is over 23 miles long. The mean sinuosity in the valley is roughly 1.29. The river has an average gradient of roughly 0.0028 in the valley.

MIDDLE BOX

The Middle Box, or canyon, begins downstream of Ira Canyon and ends at USGS Gage 09431500 Gila River near Redrock, NM, and the Connor Dam site, at the mouth of the Redrock Valley. The Middle Box is roughly 9 miles long.

REDROCK VALLEY

The Redrock Valley is home to the small town of Redrock, New Mexico. Reclamation photographed the Middle Box, the Redrock Valley, and the Lower Box for photogrammetric purposes without control. Consequently, the Digital Terrain Model (DTM), or topography, does not cover these reaches of the study area. The valley is roughly 16 miles long, ending at USGS Gage 09432000, Gila River below Blue Creek, near Virden, NM.

LOWER BOX

The Lower Box, or canyon, begins at USGS Gage 09432000, Gila River below Blue Creek, near Virden, NM, and ends at the Virden Valley near Canador Peak. The canyon is roughly 4.5 miles in length.

VIRDEN VALLEY

The Virden Valley is home to the small town of Virden, New Mexico. The valley begins at the mouth of the Lower Box near Canador Peak and ends at the New Mexico-Arizona state line. This reach is roughly 7.8 miles long.

STUDY SUMMARY

This section describes the overall purpose of each report produced during this study, summarizes the major findings of the reports, and presents the individual report conclusions. There are 11 reports or products associated with this study, including this final report. They include:

1) Background Information – New Mexico
2) Field Data Collection Plan – New Mexico
3) Qualitative Assessment of Upper Box Geomorphology – New Mexico
4) Topographic Map – New Mexico
5) Composite Orthophotograph – New Mexico
6) Catalog of Historical Changes – New Mexico
7) Flood Frequency, Flow Duration, and Trends – New Mexico
8) Stable Channel Analysis – New Mexico
9) Stream Corridor Assessment Report – New Mexico
10) Geomorphic Map – New Mexico
11) Final Report and Recommendations for Demonstration Projects – New Mexico

BACKGROUND INFORMATION – NEW MEXICO

The Background Information report reviews existing studies that contain information about the upper Gila River watershed that may be useful in the present study of the upper Gila River. The references include, but are not limited to, hydrologic, geologic, and biologic data, accounts of floods and precipitation events, studies of channel change and erosion, links between flood records and climate, land use planning documents, water quality studies, and ground water studies. The report is in two parts: (1) an annotated bibliography summarizing references pertinent to the present study, with a list of useful data for each reference; and (2) a bibliography of related references that include water quality data, hydro-geological data, fisheries studies, vegetation studies, soils data, and other miscellaneous information that provides background information relevant to the study.

FIELD DATA COLLECTION PLAN – NEW MEXICO

The purpose of the Field Data Collection Plan is to summarize the "what, where, why, and how" of the field data collection portion of the Upper Gila Fluvial Geomorphology Study. Table 1 contains that summary, outlining the plans for nine types of field data to support the study.

QUALITATIVE ASSESSMENT OF UPPER BOX GEOMORPHOLOGY – NEW MEXICO

Reclamation performed a qualitative assessment of the geomorphology of the Upper Box of the Gila River, upstream of the Hooker Dam site. The purpose was to prepare a boundary condition for the analyses in the study reach below from a sediment transport, hydraulic modeling, and fluvial geomorphology standpoint. The Principal Investigators visited this reach of canyon terrain and ascended the significant tributaries to assess the sediment storage and hydraulic processes in the Upper Box.

CONCLUSIONS

There are several hypotheses regarding land use changes and changes in the geomorphology of the Gila River watershed (e.g. Klawon and Wittler, 2001). With respect to the Gila River, one hypothesis states that change in land use in the watershed is causing increased sediment yield and/or changes in flood frequency/magnitude in the river. These changes negatively influence the active and flood channel alignment downstream of the Upper box.

Table 1. Table summarizing and outlining the Field Data Collection Plan.

#	What	Where	Why	How
1	Orthophotography	Study Reach	Visual representation of study reach	Photogrammetry and GPS
2	Aerial Topography	Study Reach	Topographic base for other tasks Basis for future comparisons	Photogrammetry and GPS
3	Channel X-Sections	Bridges	Hydraulic characterization of channel & hydraulic structures Quantify channel width, depth, slope, sinuosity	Topography and selected GPS/Surveying – Field verification
4	Bed Material Sampling	Precise locations TBD upon field reconnaissance 1/10 mile < LXS < 1 mile Meet HEC-RAS and SAM Criteria	Hydraulic characterization of bed material for sediment transport analysis	See FISC guidelines
5	Bank Material Sampling	Precise locations TBD upon field reconnaissance 1/10 mile < LXS < 1 mile Meet HEC-RAS and SAM Criteria	Hydraulic and Geotechnical characterization of bank material for bank stability and erodibility analysis	See FISC guidelines
6	Scour Area Sampling	Precise locations TBD upon field reconnaissance 1/10 mile < LXS < 1 mile Meet HEC-RAS and SAM Criteria	Survey for deep scour zones adjacent to hydraulic structures and infrastructure For comparison with scour in control reaches of the channel	See FISC guidelines
7	Geomorphic Map	Study Reach Sub-Reach Dependent Exposures	Describe long-term river character Age of adjacent surfaces and history of overbank deposition – channel migration stability. Correlate to 1, 3, 4, 7, 8	USDA Soil Descriptors Excavations by shovel, power shovel, augur Radiocarbon dating
8	Tributary Inventory	Study Reach	Correlation with hydraulic and geomorphic analysis	Visual observation and Aerial Photo interpretation

Field reconnaissance for this study indicates a clear record of stability of geomorphic surfaces that bound the Gila River in the Upper Box. The record of stability predates 19th and 20th century changes in land use or management. Figure 2 shows several areas in the Upper Box with this record. A key observation from the field reconnaissance is the numerous old sycamore and pine trees rooted at an elevation near that of the current flood channel. Figure 3, Figure 4, and Figure 5 picture several of these trees. Although no specific information about the age of these trees was developed as part of this task, the larger, longer-living species appear to predate the advent of grazing and fire suppression in the 19th and 20th centuries. The observations from this limited reconnaissance study indicate that the bed elevation of the Gila River in the Upper Box has been dynamically stable for the last several centuries. Further supporting this conclusion are the truncated alluvial fans at the mouths of many tributaries. The truncated fans are at a height commensurate with the stage of the largest historical floods on the Gila River. This relationship should not be present if there had been a recent, major change in the bed elevation of the Gila River.

The information developed for this task does not support hypotheses that upstream changes in land use in the past two centuries has caused a major change in Gila River fluvial geomorphology downstream of the Upper Box. Based on this reconnaissance, the Gila River in the Upper Box has been stable over at least that period, and possibly much longer.

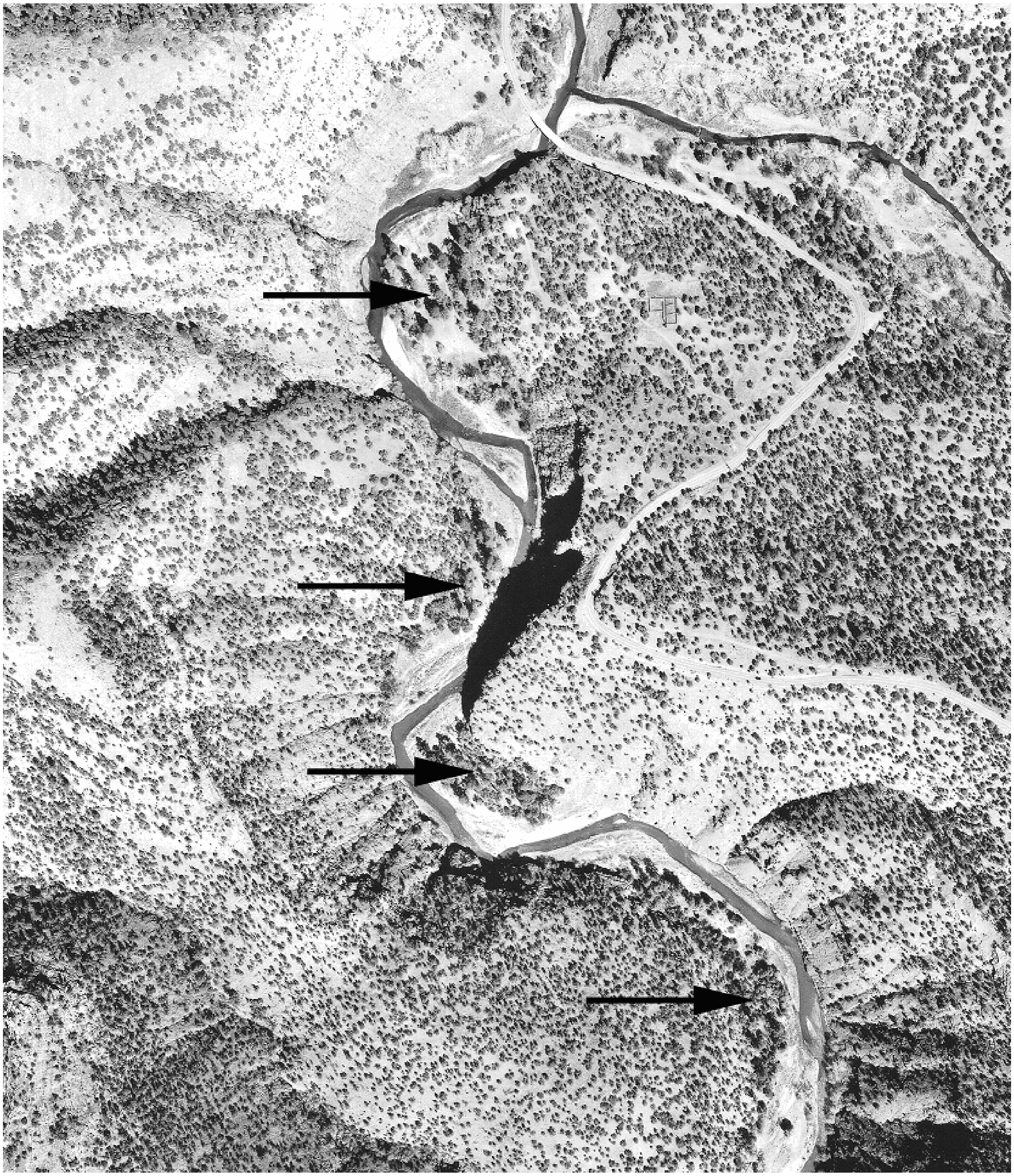


Figure 2- Aerial photograph of the upstream end of the Upper Box of the Gila River. Arrows indicate areas of stable alluvium characterized by stands of larger juniper, cottonwood, walnut, and pine trees.

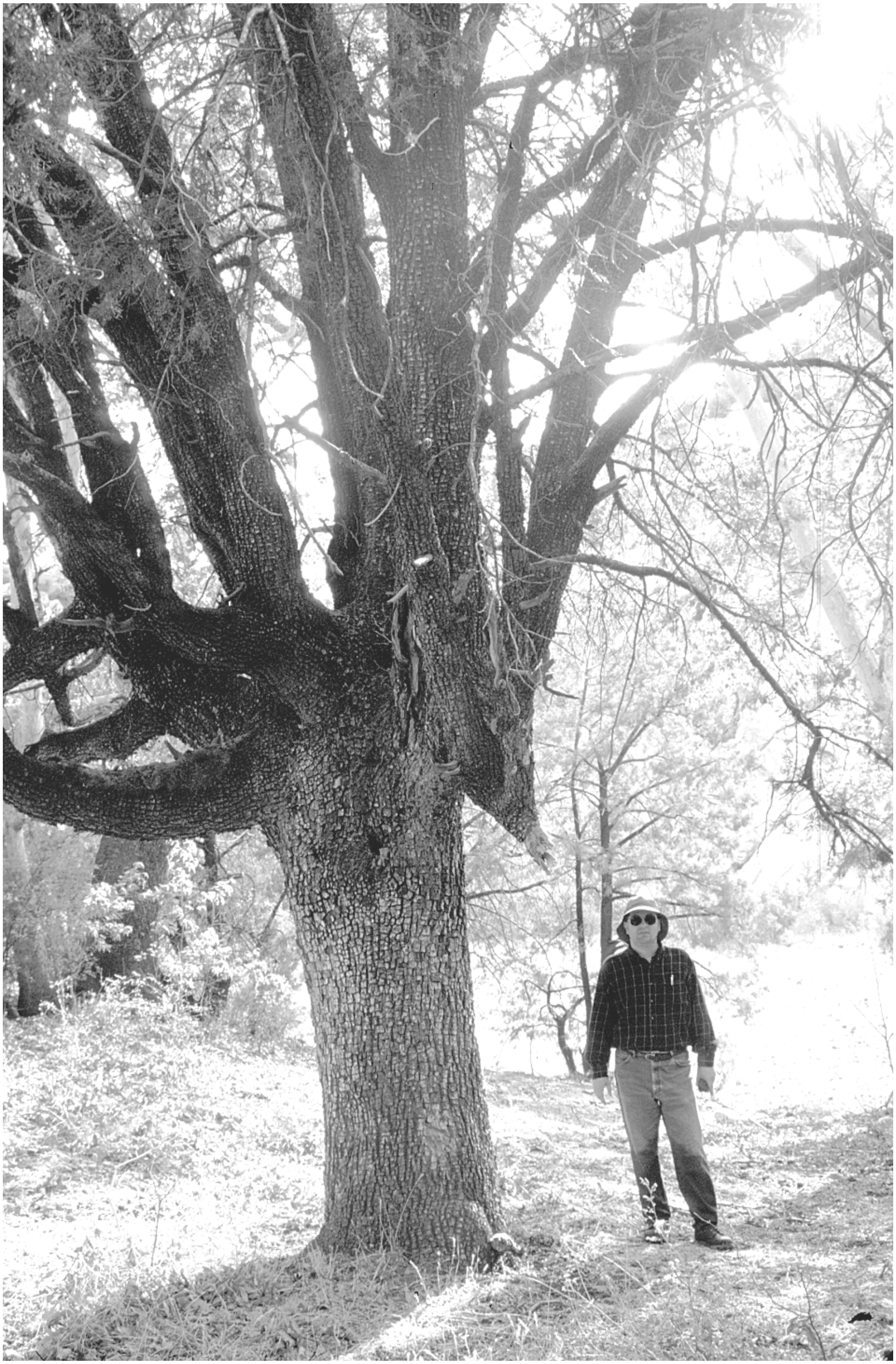


Figure 3- Large juniper on stable alluvium of the Gila River near the confluence of Turkey Creek.

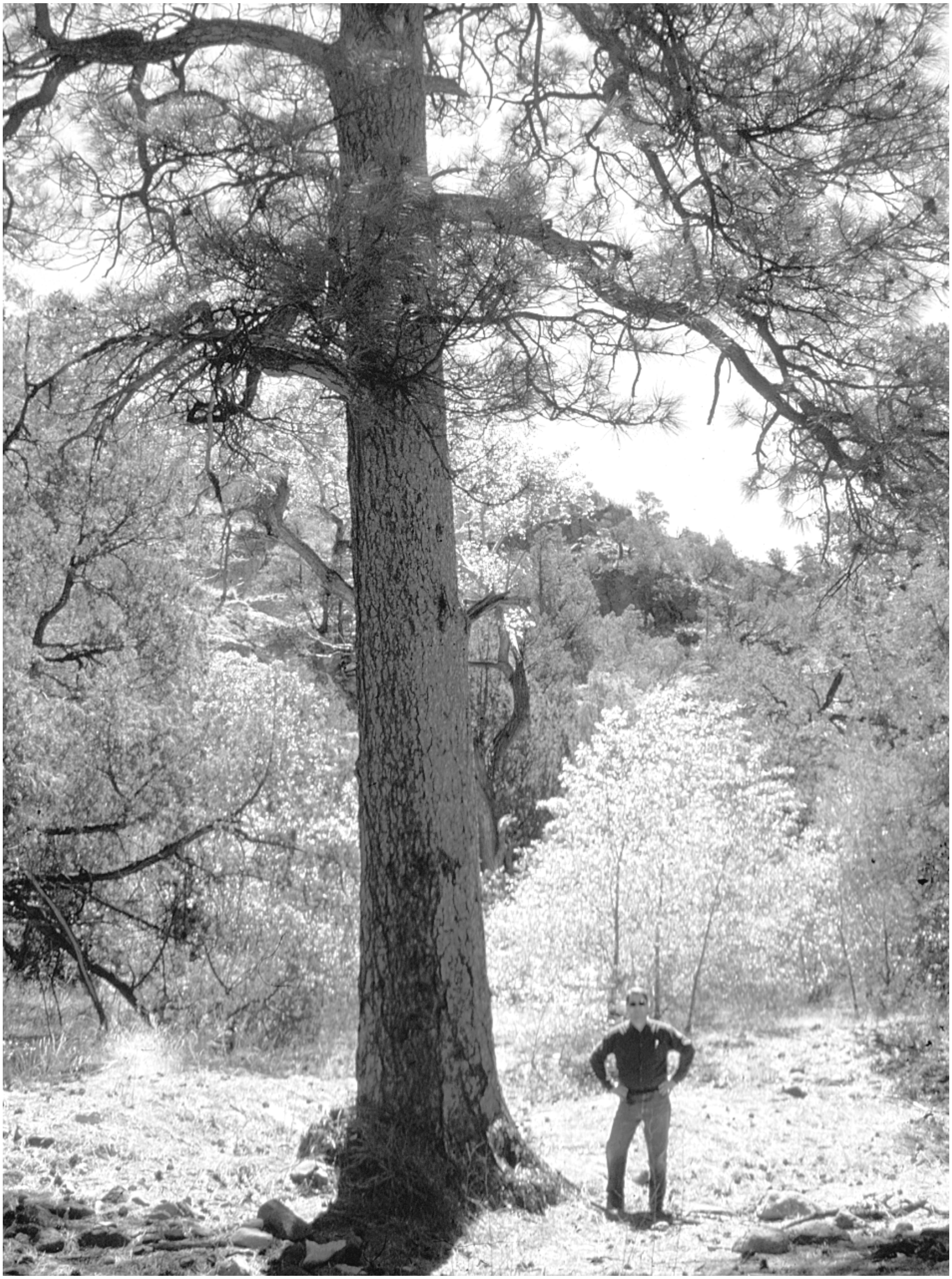


Figure 4 – Large pine tree rooted in Gila River alluvium in the upstream portion of the Upper Box of the Gila River

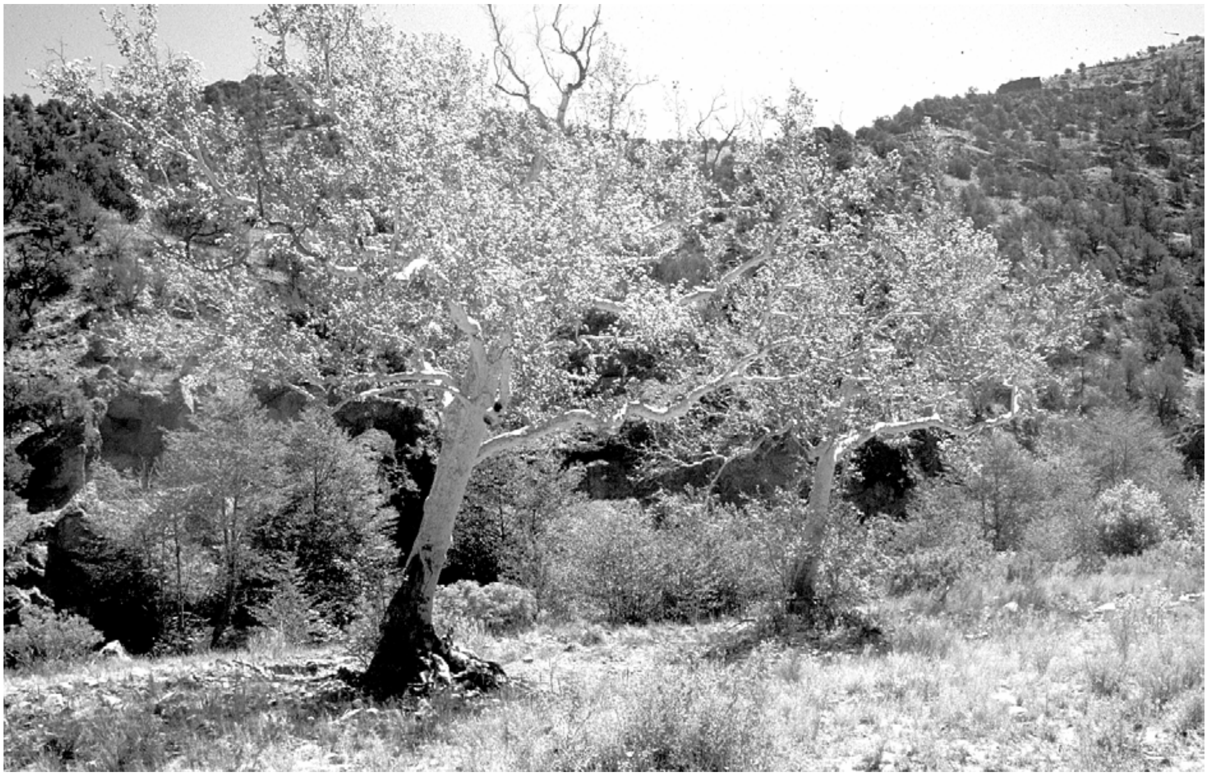


Figure 5 – Sycamore trees growing in the active flood channel of the Gila River near the upstream end of the Upper Box of the Gila River. The trees are rooted at an elevation similar to that of the current active channel.

COMPOSITE ORTHOPHOTOGRAPH – NEW MEXICO

Reclamation and a contractor produced a controlled orthophotographic mosaic from aerial photographs flown in February 2001. The orthophotographs consist of a series of mosaics of rectified aerial photographs flown at a scale of roughly 1:10,000.

TOPOGRAPHIC MAP – NEW MEXICO

Reclamation produced a digital terrain model (DTM) at a contour interval of 0.61 meters, based on the aerial photography and subsequent to production of the Composite Orthophotographs.

CATALOG OF HISTORICAL CHANGES – NEW MEXICO

The Catalog of Historical Changes documents changes in the alluvial channel of the Upper Gila River, New Mexico from 1935 to 2001. This report includes an analysis of trends in channel behavior and stability of river reaches based on lateral migration and changes in channel widths.

CONCLUSIONS

The Catalog of Historical Changes is a history of Gila River flood channel width changes in the study reach. From 1935 to the early 1960's, under a hydrologic regime characterized by the infrequency of large peak annual floods, the Gila River narrowed, with vegetation encroachment, levee construction, and agricultural development. From the 1970's to 2001, the frequency and magnitude of peak annual floods increased. In response, by 2001 the river widened to roughly the same width, on average, as in 1935.

Figure 6 shows the average width data by photograph year for both the *Active Channel* widths and *Flood Channel* widths. The plot superimposes the two widths on the stream gage record at the Gila River below Blue Creek near Virden, NM. Figure 7 shows the average flood channel width data separated by valley.

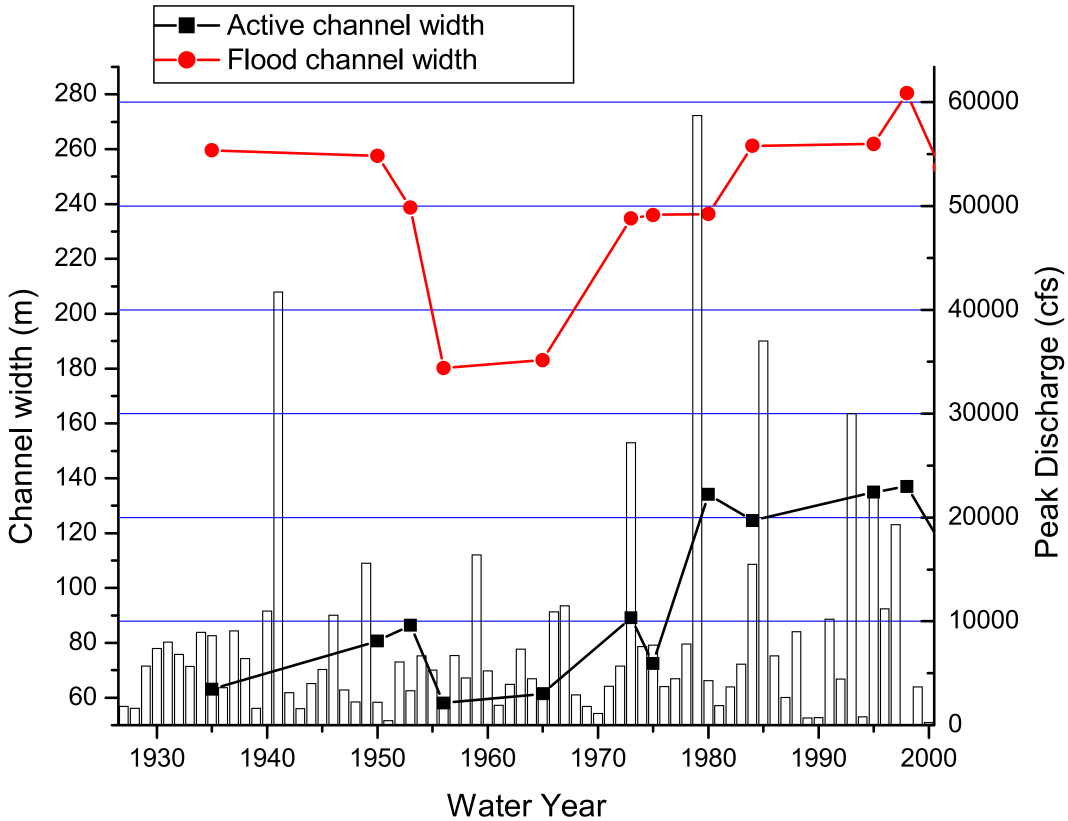


Figure 6. Average width data by photograph year. Active channel widths and flood channel widths are superimposed on the stream gage record at the Gila River below Blue Creek near Virden, NM.

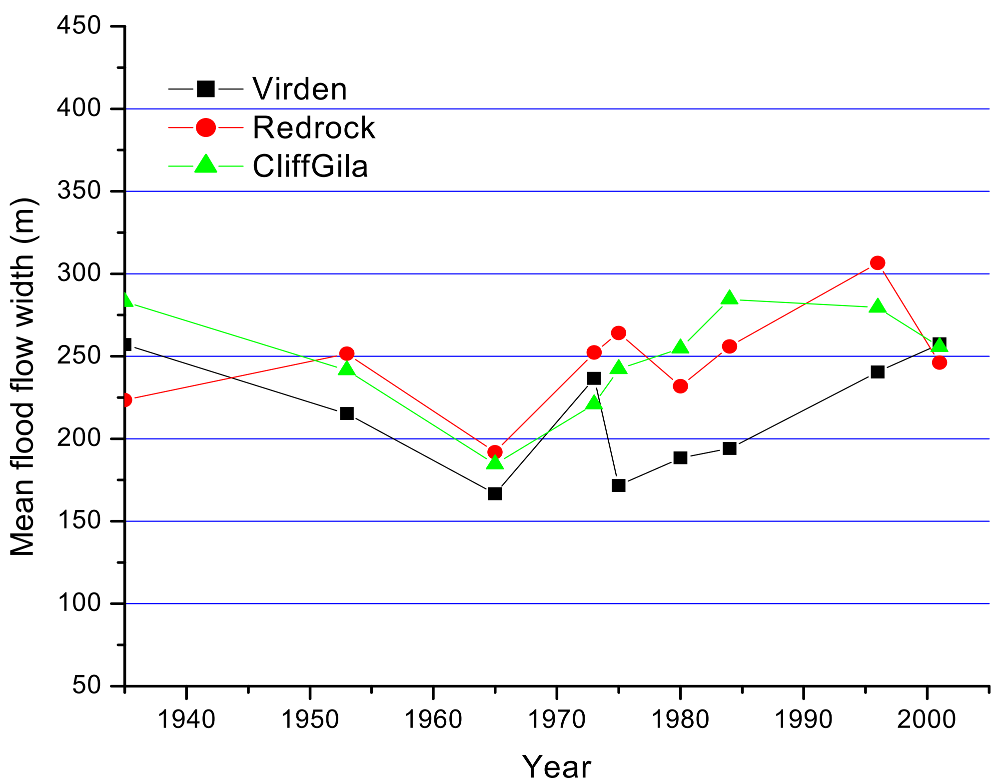


Figure 7. Average flood channel width data separated by valley.

The following figures, Figure 8, Figure 9, and Figure 10, illustrate a time-lapse of channel changes in the Riverside area, downstream from the Highway 180 bridge. The three photographs show both lateral changes in the channel alignment and changes in channel width.

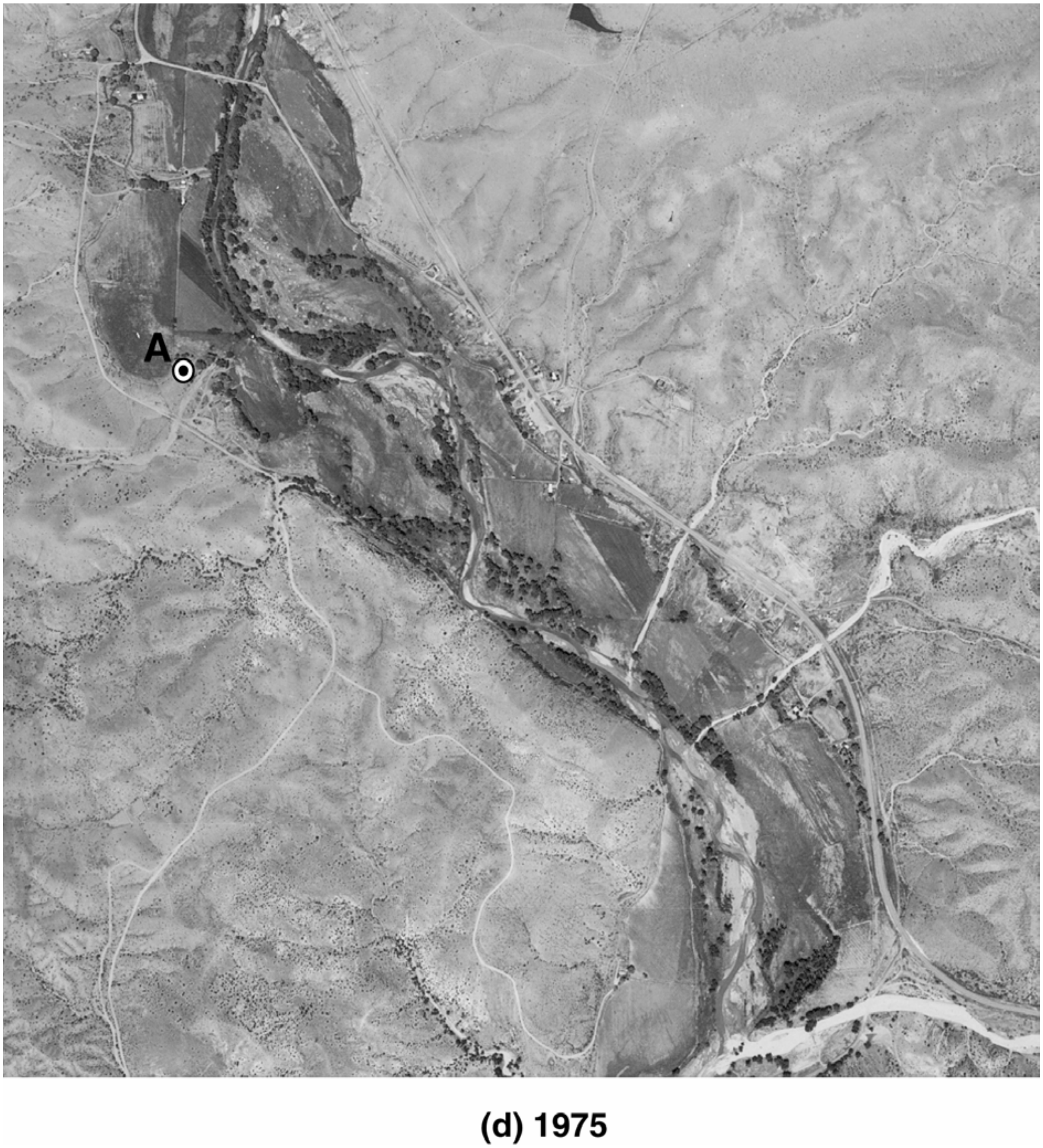
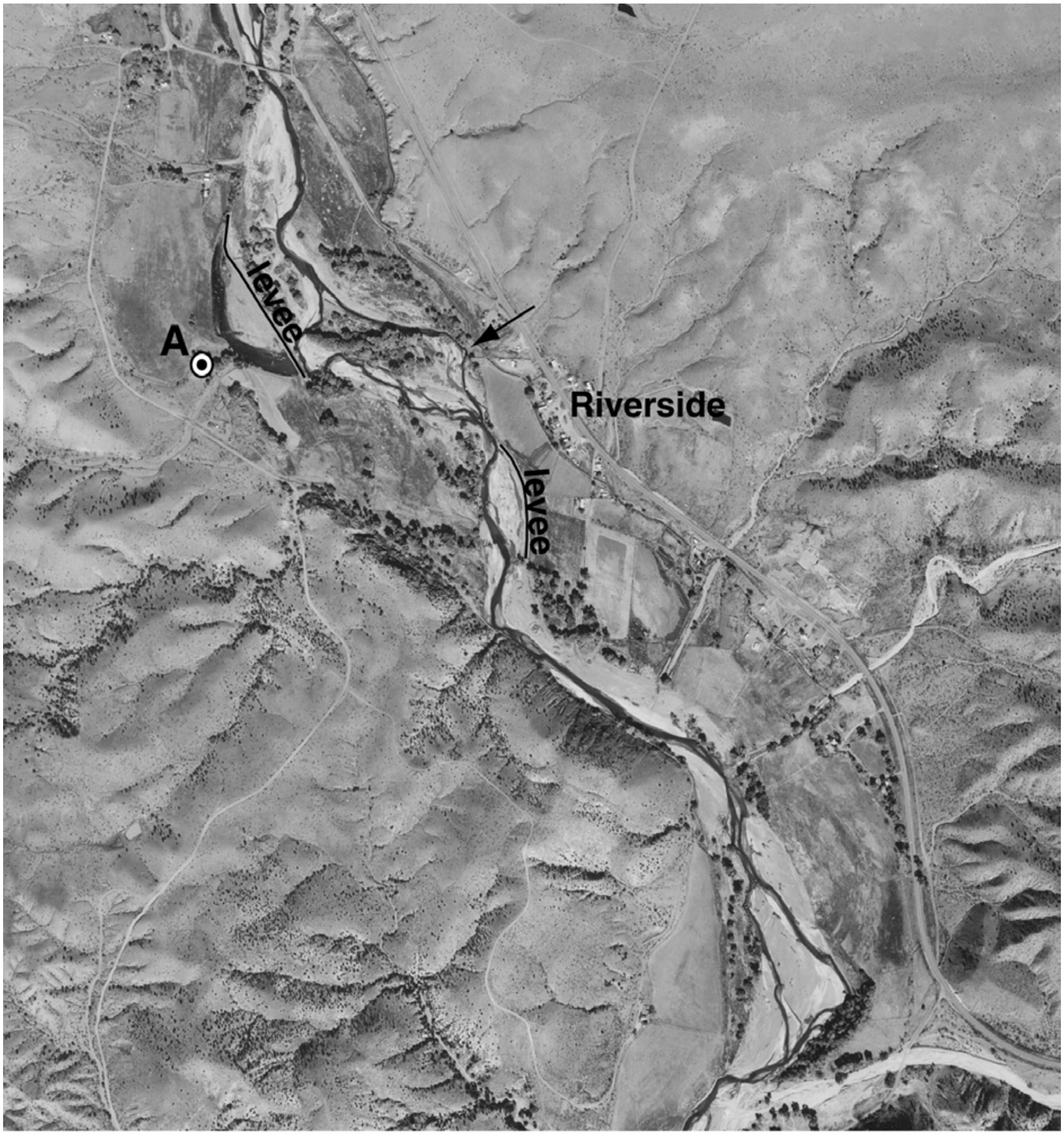
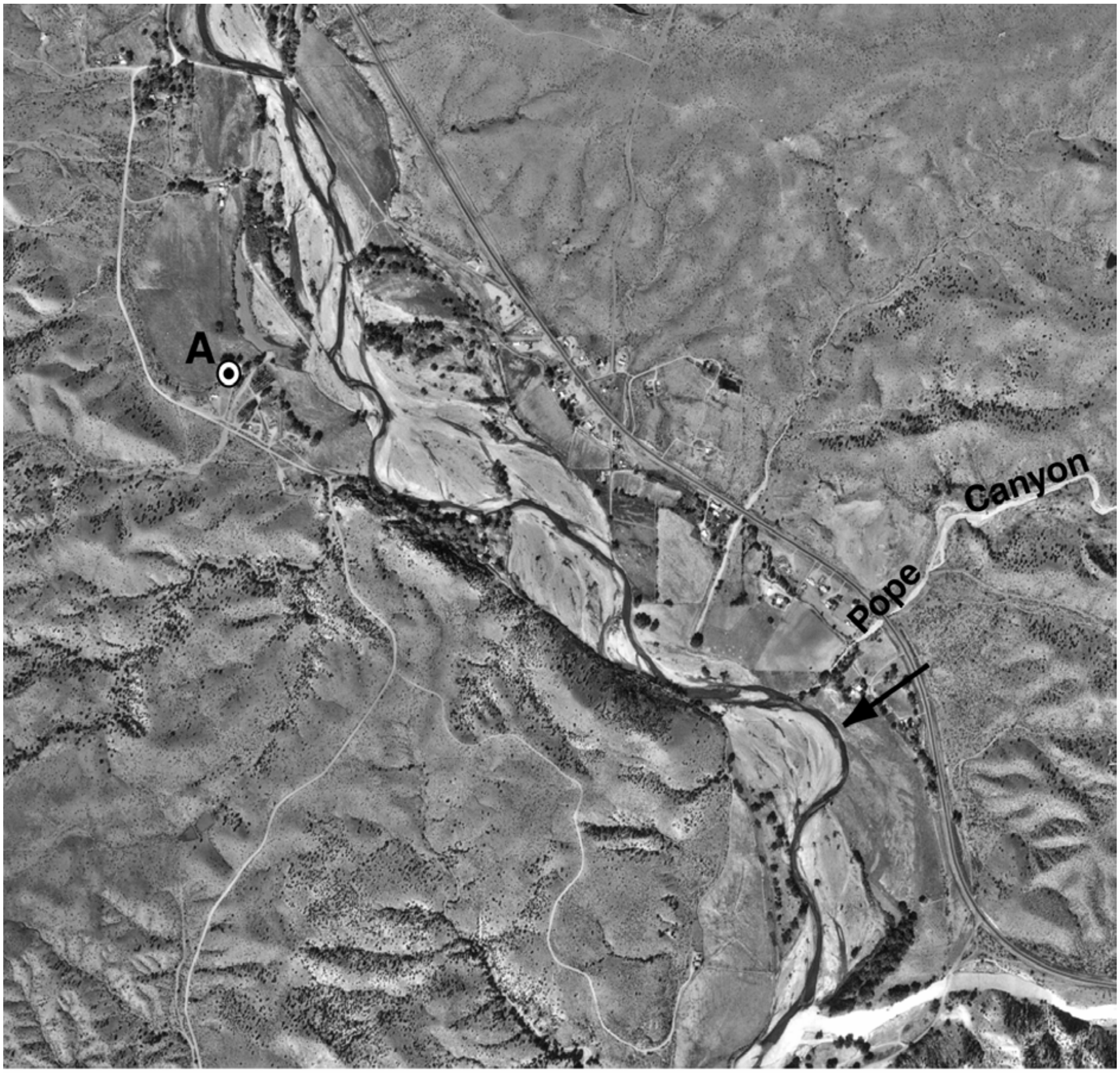


Figure 8. 1975 aerial photograph of Riverside area. Iron Bridge is near the top of the photograph. Mangas Creek enters the Gila at the bottom of the photograph.



(e) 1980

Figure 9. 1980 aerial photograph of Riverside area. Iron Bridge is near the top of the photograph. Mangas Creek enters the Gila at the bottom of the photograph.



(f) 1996

Figure 10. 1996 aerial photograph of Riverside area.

Channel changes correlate to large floods on the Gila River. During periods of frequent floods, channel width increases, while in periods of infrequent floods channel width decreases. Levees, bridges, and diversions, as well as agricultural development of land that was previously part of the channel, artificially narrowed the channel. In most cases, flood channel widths at specific channel locations are variable, but not unprecedented in the historical record. Reaches of high variability, however, indicate multiple locations where recent channel changes are unique in historical aerial photography. These types of channel changes are present in the three valleys.

The analysis of change using flood channel widths for Virden, Redrock, and Cliff-Gila Valley show that Cliff-Gila Valley has experienced more perturbations in the period of study than either Virden or Redrock Valley, and that more unprecedented channel positions were formed between 1980 and 1996 than at any other time in the historic period. Major channel changes occurred following large floods. The largest floods in the Gila River system have lasting effects that dominate channel morphology for decades following their occurrence.

FLOOD FREQUENCY, FLOW DURATION AND TRENDS – NEW MEXICO

This report summarizes flood frequency, flow duration and trends for sites within the Gila River basin from Gila Wilderness in New Mexico to approximately the Arizona-New Mexico State line. The primary bases for the flood frequency, flow duration and stream flow trend analysis are U.S. Geological Survey (USGS) peak discharge and mean daily flow records. Precipitation trend analysis originated in data from the National Weather Service (NWS) cooperative network.

Figure 11 shows the peak discharge time series for the Gila River near Gila, NM. Note the change in frequency and magnitude of peak discharges following 1970. Figure 12 shows the peak-discharge time series for the Gila River below Blue Creek near Virden, NM. Note the similar trend after 1970.

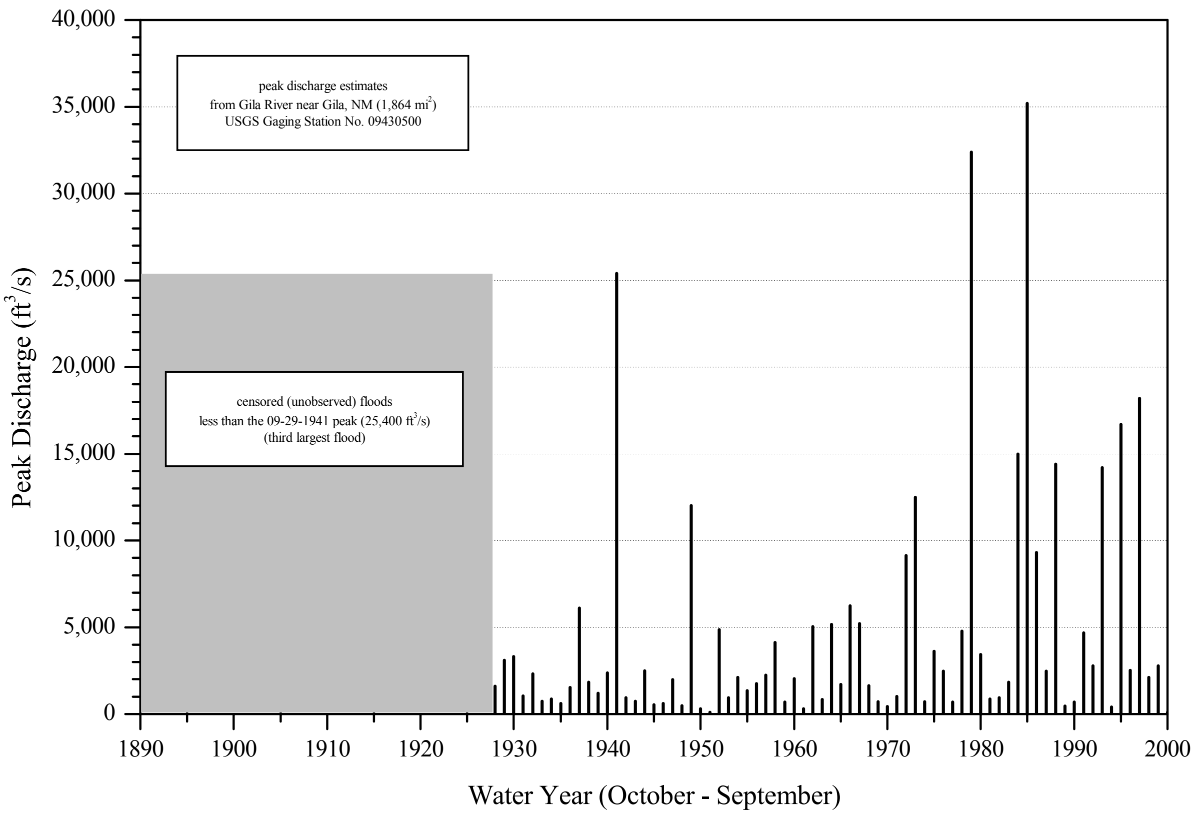


Figure 11. Peak discharge time series for the Gila River near Gila, NM.

CONCLUSIONS

Rains from fall and winter storm systems cause the major floods in the Gila River basin. These storms are cold frontal systems colliding with warm, moist air or tropical storms. Extreme flood-producing storms are widespread and cover the majority of the Upper Gila basin. Instantaneous peak discharge data confirm that the largest-magnitude floods occur in the fall and winter and are predominately from rainfall and rain on snow. The largest floods have occurred in water years 1941, 1979 (December 1978), and 1985.

The log-Pearson Type III distribution fits annual peak discharge estimates at the three Gila River gaging stations using the Expected Moments Algorithm and available historical information. The results indicated that the distribution adequately fit the data. Peak discharge probability estimates indicate the 2-year flood ranges between 1,970 ft^3/s and 6,390 ft^3/s and the 100-year flood ranges between 38,600 ft^3/s and 43,000 ft^3/s at the 3 locations. Flood volume frequency (1-, 3-, and 5-day annual maxima) estimates are consistent for the different durations at each site, as well as between gaging stations.

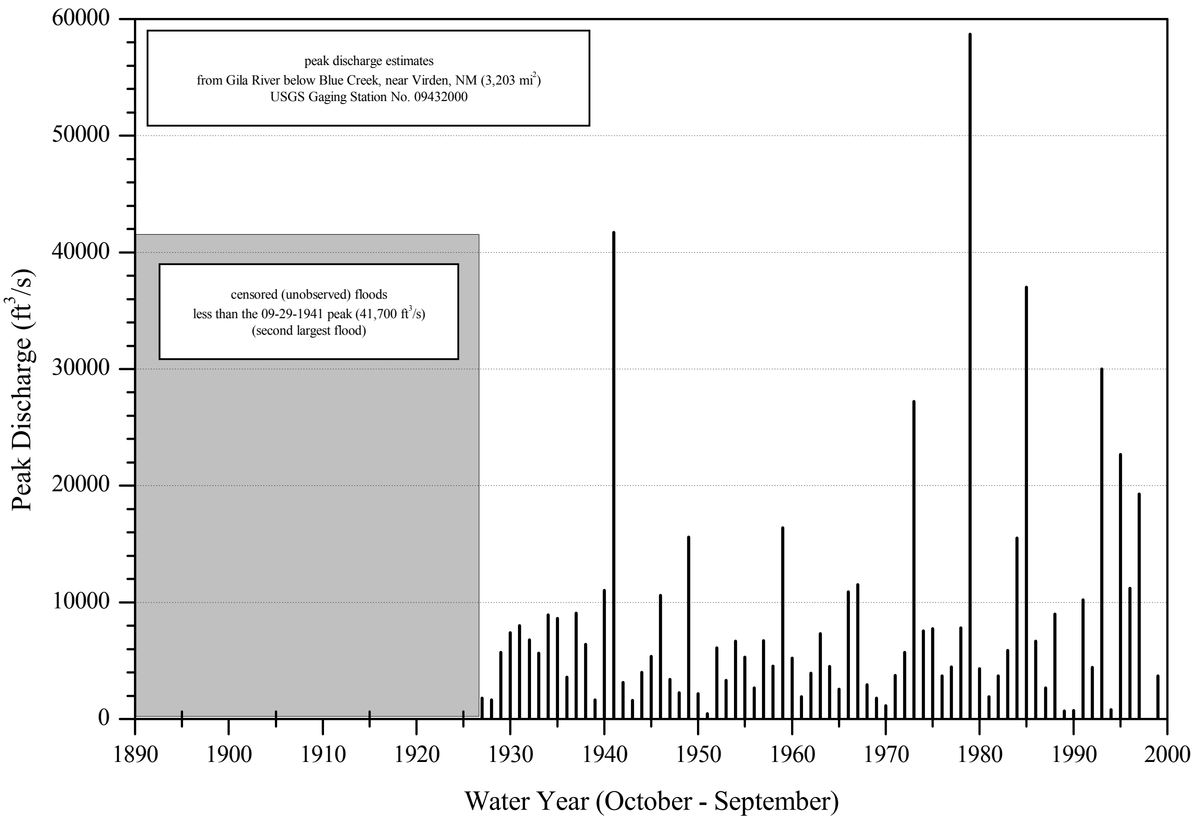


Figure 12. Peak discharge time series for the Gila River below Blue Creek near Virden, NM.

Period-of-record Flow Duration Curves (FDC) for the water year indicated that mean daily flows are typically less than about 500 ft^3/s for 90 percent of the time at all five gaging stations. Mean daily flows for the November-April winter season are nearly always greater than the summer July-October season. Mean daily flows are zero about 10 percent of the time at the Mogollon Creek near Cliff gage.

Significant, positive precipitation trends were found in annual, winter, spring and summer total precipitation at seven sites within and near the upper Gila watershed. The 1941-2000 and 1951-2000 periods had notable significant increases in precipitation at Lordsburg and Cliff, and at Fort Bayard, Lordsburg, Cliff, Redrock, and Glenwood, respectively. Positive trends in annual maximum one-day total precipitation were notable at Gila Hot Springs (1958-2000) and at Mimbres Ranger Station (1951-2000 and 1961-2000 periods). There was no statistically significant increase in seasonal, annual, or 1-day maximum precipitation at any of the eight stations analyzed for the 1971-2000 period.

There are significant positive trends in 3-day maximum flood discharge at the Gila River near Gila and Gila River near Virden gages. The trends are consistent for the 1931-2000 and 1941-2000 periods. In addition, there are increasing trends in peak flow, daily maximum, and 3-day maximum at the Gila gage for 1931-2000, 1941-2000 and 1951-2000. There was no increase at the Virden gage for peak flow and 1-day maximum. Notably, there were no significant trends identified for flood discharge quantities at the five gaging station locations for the recent 40-year (1961-2000) or 30-year (1971-2000). Winter and annual 1-day maximum precipitation increases may partly explain flood discharge trend results. Many significant trends in high and low flow percentiles were also identified for the Gila and Virden gages.

STABLE CHANNEL ANALYSIS – NEW MEXICO

This report presents an analysis of the channel stability of the Gila River in the Cliff-Gila valley in New Mexico. The stability analysis uses the RISAD module of the SAM analytical model to determine the dynamic stability of sub-reaches of the upper Gila River. One measure of fluvial geomorphic stability is the competence of a river to transport its sediment load. A deficit or surplus in transport capacity is the measure of instability. The history of channel width adjustment is another indicator of stability. This report presents an analysis of current channel widths compared to stable widths predicted by the SAM analytical model. There is also a comparison to historical channel widths reported in the Catalog of Historical Changes – New Mexico (Klawon, 2002).

STABLE CHANNEL DEFINITION

A working definition of a stable channel is no unidirectional changes in mean bed elevation or grade over a substantial period. There are several analytical tools available to the hydraulic engineer to determine the stability of a river reach. Tools used in this analysis include HEC-RAS and RISAD. HEC-RAS is the standard-step backwater analysis program of the US Army Corps of Engineers. RISAD is a module of the SAM program, likewise developed by the US Army Corps of Engineers, that determines the stable channel depth, width, and slope for given bed material and effective flow rate.

This study analyzed a portion of the study reach using both tools. The Study Reach is the Gila River channel from the Arizona-New Mexico State line to the Cliff, New Mexico area, specifically USGS gage 09430500 Gila River near Gila, NM, at the Hooker Dam site, 1.6 miles upstream from Mogollon Creek, roughly 7 miles northeast of Gila, New Mexico.

STUDY REACH

The study reach and sub-reaches (4) extend from the Upper Box to the Middle Box, roughly between Mogollon Creek and Ira Canyon. The Stable Channel Analysis excludes the Virden Valley, and the Red Rock Valley, as well as the canyon reaches.

ANALYSIS REACH

The *Analysis Reach* extends from USGS gage 09430500 to Ira Canyon at the downstream end of the Cliff-Gila Valley. The analysis models roughly 37,432 meters (23.26 miles) of channel. Reclamation collected 16 bed material samples in the Analysis Reach. Figure 13 plots the gradations from all 16 gradations. There are at least three irrigation or other diversion structures, and three bridges in the reach.

STABLE CHANNEL CURVES

The measure for stability is the relative proximity of the 2001 modeled channel values to the RISAD generated Stable Channel Curves. Figure 14 through Figure 18 show stable channel curves of four sub-reaches of the Analysis Reach as well as a composite plot of the entire Analysis Reach. The zone above the stable channel curve indicates a tendency for the channel bed to degrade at a rate roughly inversely proportionate to the proximity to the curve. The zone below the stable channel curve indicates a tendency for the channel bed to aggrade. Points far to the left or right of the curve minimum indicate tendency for the channel to either widen or narrow. Points on or in close proximity to the stable channel curve, indicate, by definition, dynamic stability. Outliers usually indicate either sections with geologic (bed-rock) control or sections near diversion dams. The extremal hypothesis of stable channel analysis states that the channel will tend towards the minimum slope of the stable channel curve. Judgment regarding the trend of the river channel, both width and slope, comes from assessment of the relative position of the current channel conditions to the minimum slope on the stable channel curve.

CONCLUSIONS

The Upper Gila River Analysis Reach tends toward stability, meaning there is little indication of either systemic aggradation or degradation. The *Recent Flow Width* is within stability guidelines for the analysis. These widths range between 64.7 meters (212 feet) to 77.0 meters (253 feet). The average energy slope within the analysis reaches ranges from 0.0036 to 0.0061. These values are all within stability criteria generated by the stable channel analytical modeling.

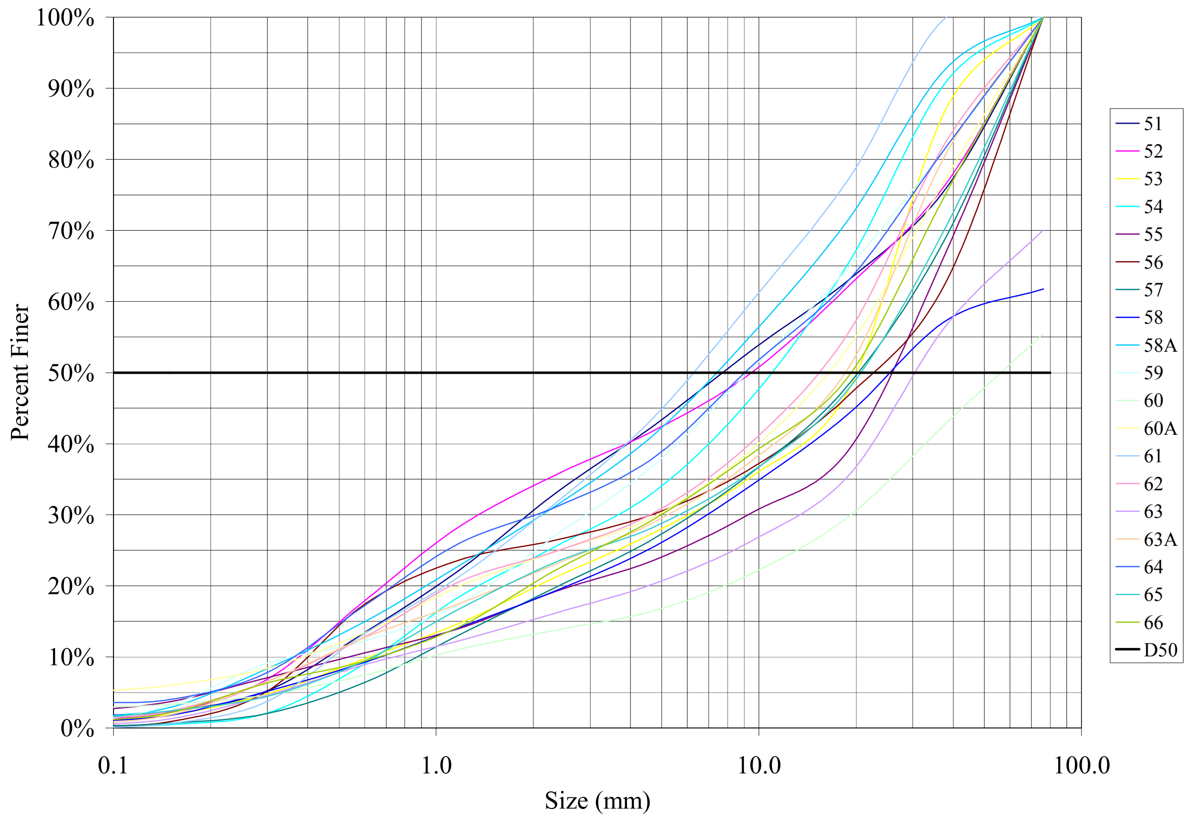


Figure 13. All gradations.

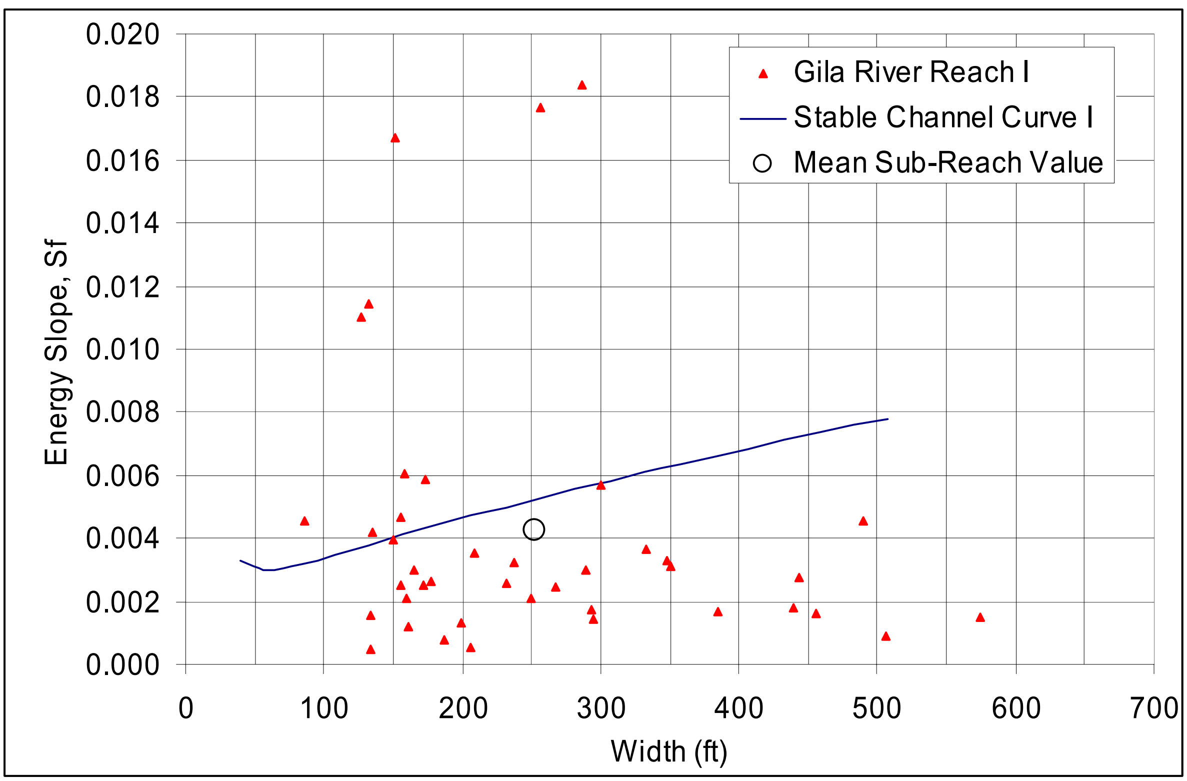


Figure 14. Stable channel analysis of sub-Reach I.

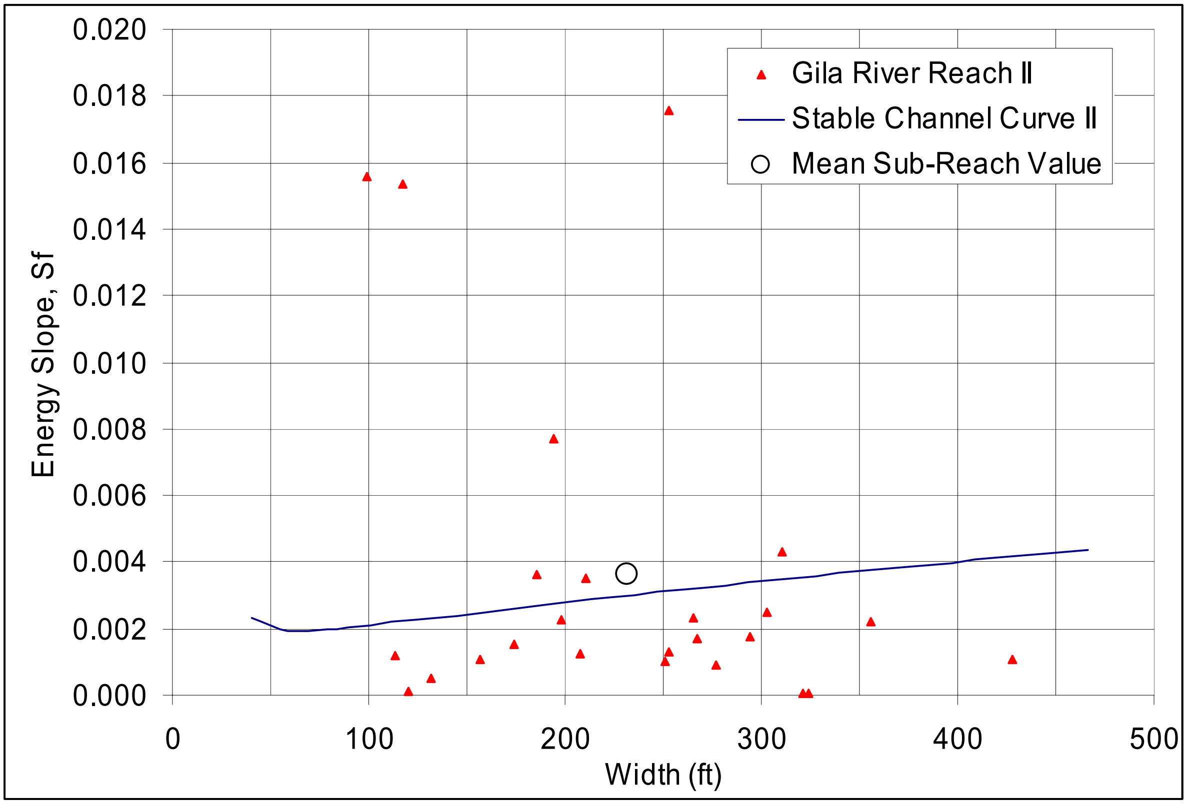


Figure 15. Stable channel analysis of Sub-Reach II.

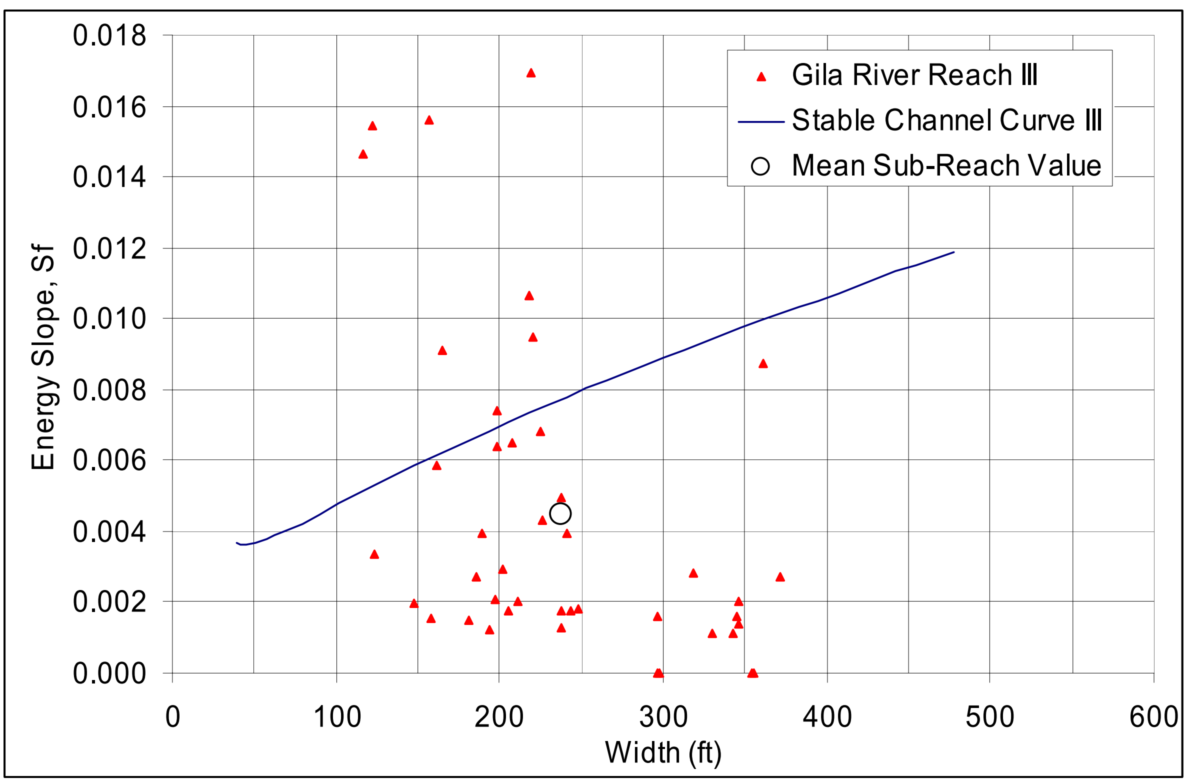


Figure 16. Stable channel analysis of Sub-Reach III.

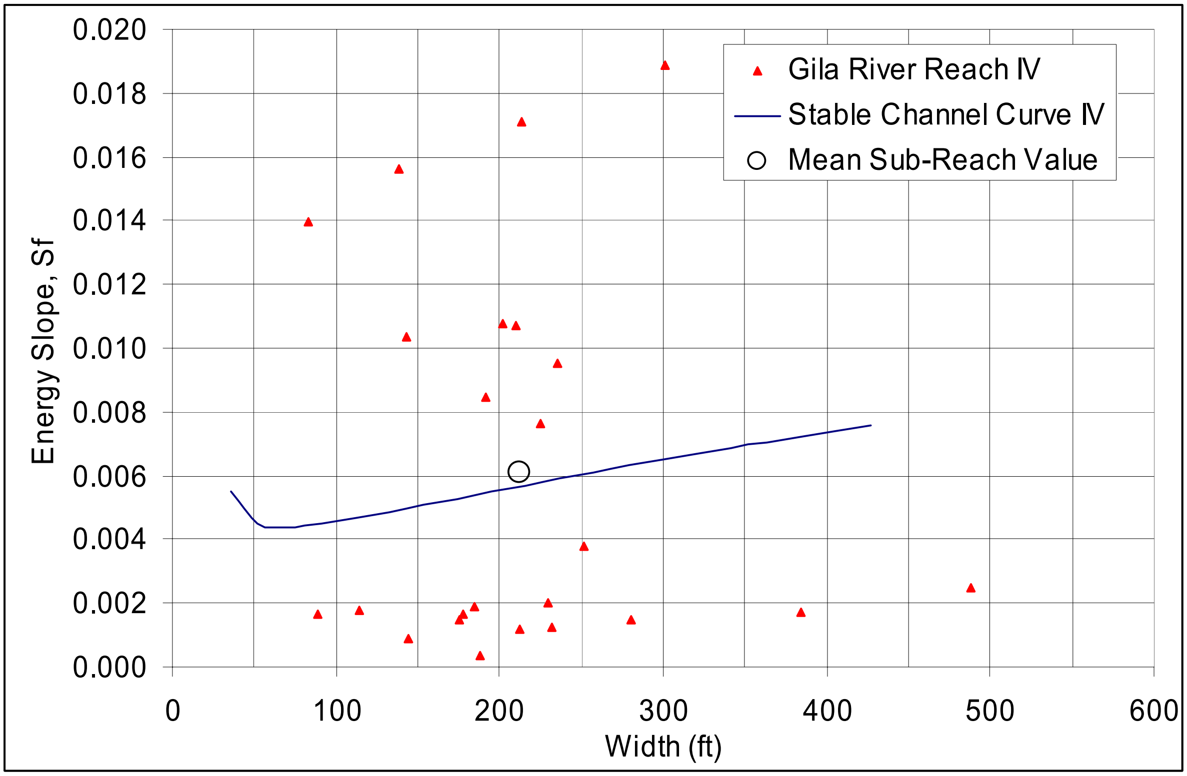


Figure 17. Stable channel analysis of Sub-Reach IV.

The computed stable values for Sub-Reach I indicate a stable channel top width between 12 and 155 meters and a stable energy slope between 0.00327 and 0.00781. For Sub-Reach II, the computed stable values for the top width are between 12 and 142 meters, and a stable energy slope between 0.00230 and 0.00436. For Sub-Reach III, the computed stable values for the top width are between 12 and 146 meters and a stable energy slope between 0.00369 and 0.01185. For Sub-Reach IV, the computed stable values for the top width are between 11 and 130 meters and a stable energy slope between 0.00553 and 0.00758. The computed average values for top width and energy slope from the HEC-RAS model for all the Sub-Reaches lay within the generated stable regions.

Figure 18 shows the analysis for the entire Analysis Reach. The analysis used the average bed material gradation, that is, the average of the 16 gradations in the analysis reach, as well as mean hydraulics of the reach.

Field investigations did not reveal general aggradation or degradation occurring within the Analysis Reach. Hydraulically, the river accesses its floodplain, except in areas with intact levees. This indicates that local channel widening occurs only in areas of the river where distinct hydraulic features, such as levees or bedrock, confine the natural flow path of the *Flood Flow Width* channel, or the channel has adjusted to decadal changes in the hydrologic regime. Observations indicate that the current levee system is not functional, with few intact levees within the Analysis Reach. The primary effect of the current levee system in the Cliff-Gila Valley is to separate flow, shunting the river onto the flood plain (farm land) in several locations.

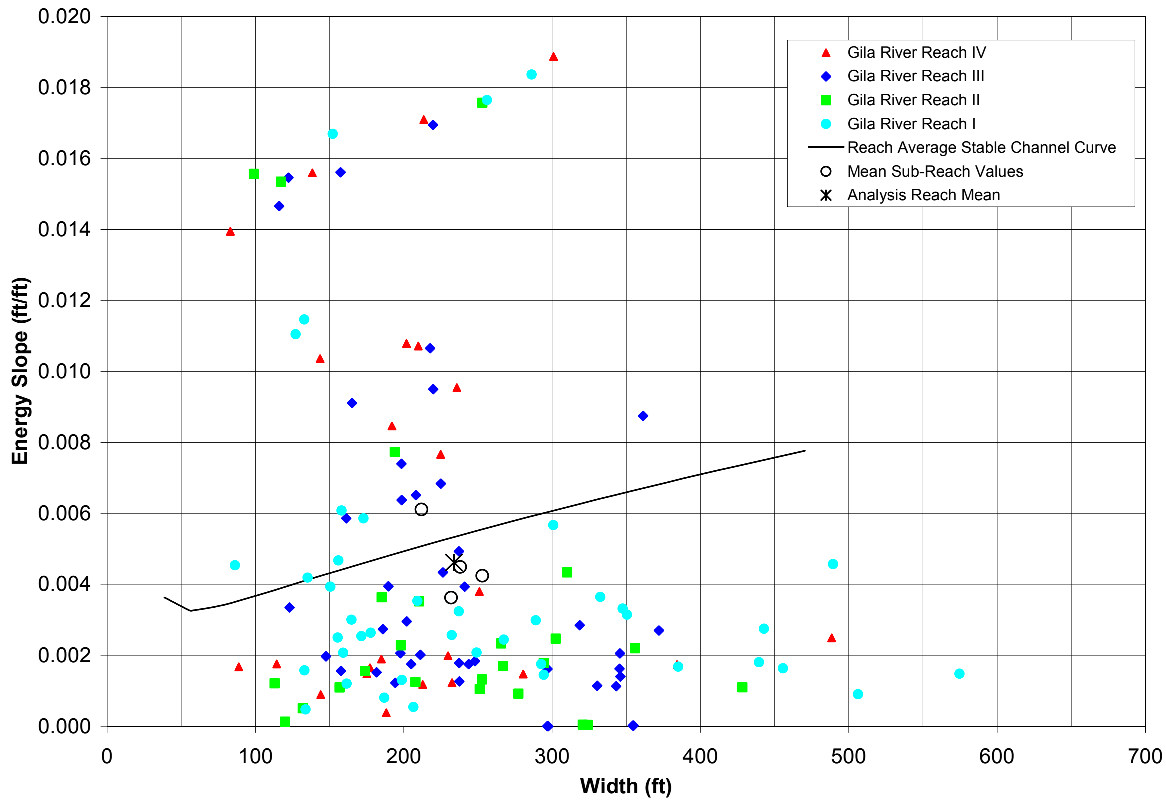


Figure 18. Stable channel analysis of Analysis Reach.

STREAM CORRIDOR ASSESSMENT – NEW MEXICO

The Stream Corridor Assessment Report synthesizes the findings of the Background Information, the Catalog of Historical Changes, Flood Frequency, Flow Duration, and Trends, the Qualitative Assessment of Upper Box Geomorphology, Geomorphic Map and Analysis, and the Stable Channel Analysis. Combined, these studies provide a coherent framework to understand the active physical processes that shape the Gila River in the study reach.

The Geomorphic Analysis, Causal Analysis, and Geomorphic Map are not individual reports or products. Those analyses and maps are contained within this report.

GEOMORPHIC ANALYSIS

The goal of the Geomorphic Analysis is to understand the long-term behavior of the Gila River with emphasis on understanding historical changes in terms of expected behavior. The basis of the Geomorphic Analysis is the Catalog of Historical Changes, the Qualitative Analysis of the Upper Box, and the Geomorphic Map. The geomorphic map, presented in ten 11x17 sub-maps, is in Appendix A. The results of these three separate analyses all converge towards one overall controlling factor of the observed historical geomorphic changes along the Gila River. Based on these analyses it appears that over the long term the Gila River has been dynamically stable both vertically and laterally. It also appears that the observed geomorphic changes are not the results of a system-wide change in sediment yield or a change in hydrology. In fact, the reaches that have not been substantially modified by humans still display the same long-term stability. The conclusion that is supported by all the geomorphic data collected for this study is that human disturbance of the Gila River, primarily in alluvial reaches, has led to the geomorphic change observed historically.

Components of Geomorphic Investigation

Geomorphic investigation for the Upper Gila River Geomorphology Study in New Mexico consisted of three primary components. The Catalog of Historical Changes documented historical change of the Gila River channel based on an analysis of historical aerial photographs (Klawon, 2002). The qualitative assessment looked at the Holocene history of the Upper Box (Levish, 2002). The geomorphic map portrays historical geomorphic change in the Gila River in light of channel modifications.

Catalog of Historical Changes

The Catalog of Historical Changes (Klawon, 2002) documents changes in the alluvial channel of the Upper Gila River, New Mexico from 1935 to 2001. The Catalog of Historical Changes primarily employed repeat aerial photography from separate years that spans the 66 total years. The study looks at various measures of channel width and compares them to major floods during the same period. The goal was to test the hypothesis of unidirectional channel change in the Gila River system.

The results of the Catalog of Historical Changes show that channel widths on average are the same in 2001 as in 1935. It shows that the Gila River channel appears to narrow, primarily from the encroachment of vegetation, between periods of large floods. The episodic nature of floods on the Gila River (England, 2002) exacerbates this complex pattern. As shown in the Catalog of Historical Changes, agriculture also encroaches on the river during these episodes without large floods. In order to protect land resource investment, levees are constructed to protect the fields that have been developed between floods in what was the active flood channel following the last large flood. If the next large flood causes these levees to fail, then the potential for significant property loss increases.

Qualitative Assessment of the Upper Box

The Qualitative Assessment of Upper Box Geomorphology, New Mexico (Levish, 2002) examines the geomorphic history of the Upper Box, just upstream of the Cliff-Gila Valley. This assessment tests the hypotheses of change in upper watershed hydrology and sediment yield as the causative mechanism of historical geomorphic change along the Gila River downstream of the Upper Box. A premise of the hypothesis is that the geomorphic record of Upper Box would record any major changes in the upper basin that might be reflected in the downstream valleys.

The Qualitative Analysis of the Upper Box shows that there is a clear record of stability of the geomorphic surfaces that bound the Gila River in the Upper Box that predates 19th and 20th century land use changes. This record does not support speculation that upstream changes in land use in the past two centuries has caused a major change in Gila River fluvial geomorphology downstream of the Upper Box. This record of stability places doubt on the hypothesis that changes in the upstream watershed are a major cause of geomorphic change from the downstream end of the Upper Box to the Arizona State line.

Geomorphic Map – Appendix A

Appendix A presents the Geomorphic Map. The original intent of the geomorphic map was to map the ages of surfaces along the Gila River downstream of the Upper Box in New Mexico to the border with Arizona. The goal was that interpretation of the Geomorphic Map would allow for understanding of the Gila River. In particular, it would be another test of hypotheses that observed geomorphic change in the Gila River in the study reach is the result of upstream changes in land use. Through the early course of the study, it became clear that there was no large-scale system wide change in the Gila River. In fact, based on early field work, the Catalog of Historical Changes and the Qualitative Assessment of the Upper Box, it became clear that the historical geomorphic changes observed along the Gila River were the result of human disturbance particularly the construction of levees, their subsequent failure, and flow redirection by levees.

These findings shifted the focus of the Geomorphic Map from a map showing the age of geomorphic surfaces that bound the Gila River, to a map that documents the causative factors of property loss along the river. Once it became clear that speculated changes in the Gila River watershed were not responsible for the historical geomorphic change, the important task was to document how human disturbance had resulted in these changes.

Field work and review of aerial photographs revealed that levees constructed following the flood in December 1978 that are visible in aerial photographs from November of 1980 are very closely related to the majority of property lost since 1980 along the Gila River in New Mexico. In addition, diversion structures, bridges, and tributary alluvial fans also have strong local impact. Based on this observation the goal of the Geomorphic Map was revised to show the levees visible in the 1980 aerial photographs and their close correspondence to property loss and active bank erosion.

Levees and Property Loss

Levees constructed on the Gila River lead to property loss in several ways. First, when the levees fail during floods, the flow tends to exit through the levee failure nearly perpendicular to the normal flow direction of the river. This results in erosive, high-energy flows at right angles to the pre-existing bank. Since the banks of the Gila River are formed of vertically accreted flood sediment, these high-energy flows rapidly erode the former banks. Once outside the levees the water flows down the valley slope eventually leading to a failure from the outside of the levee so the floodwater can return to the channel. This results in a diagnostic asymmetrical downstream bend (Figure 19 and Figure 20). These exaggerated bends or meanders can propagate downstream. At the downstream end of these exaggerated bends, the flow is nearly perpendicular to the normal flood channel and aimed at the opposite bank. This may result in levee failure or bank erosion on the bank opposite the exaggerated bend. This in turn causes an exaggerated bend or meander in the new location by the same process. This process can continue downstream until flood discharge decreases or some restraining feature is encountered.

Second, the levees redirect flow. Levees constructed at angles that intersect to the flood flow of the river result in flow redirection. This may erode property on the opposite bank where the flow is aimed. In extreme cases, it may cause the river to cut a new flood channel causing major erosion (Figure 21). This process will also propagate downstream by continued flow redirection from opposite banks. It will propagate downstream until something is encountered that slows or stops bank erosion and forces the Gila River back into its natural flood channel.

Finally, the levees decrease sediment transport capacity. This causes aggradation or a buildup of the channel bed between the levees. This in turn raises that stage of floodwater passing through the levees. When the levees fail, this leaves the former channel of the Gila River at a higher elevation than the new channel cut by the river in the area that was formerly outside the levees.

In some cases, two or three of these mechanism work together at the same time. This can result in the river creating a channel in a place in the valley where it has not been for hundreds or thousands of years. The result is substantial and dramatic property loss. This process may be exacerbated by the method of levee construction. As Soles (2003) points out, the levees were generally constructed by pushing up river alluvium resulting in a low area just behind the levees. This probably increased the likelihood and severity of levee failures and subsequent property loss.

Figure 19. Asymmetrical downstream-exaggerated meander typical of erosion resulting from levee failure. Enlargement March 4, 2001 aerial photograph in the vicinity of the Seeds of Change Farm.

Figure 20. Asymmetrical, exaggerated meander south of Virden near the mouth of Windham Canyon. This meander is the result of levee construction and subsequent failure resulting in substantial property loss. See the Geomorphic Map Location 23 for comparison.

Figure 21. Flow under the Highway 180 Bridge (top) apparently helped cause erosion upstream of the Iron Bridge. To slow this erosion a levee was constructed upstream of the Iron Bridge redirecting flow downstream resulting in considerable erosion. Compare with Locations 11-15 on the Geomorphic Map.

Age of Surfaces Undergoing Active Erosion

Bank exposures were examined from the Arizona state line through the Upper Box (Levish, 2002). For estimating the age of actively eroding banks from downstream of the Upper Box to the Arizona state line, 12 detailed soil and stratigraphic description sites were selected. The soils and stratigraphy observed at these sites and others were very similar to soils and stratigraphy described in detail in the Duncan Valley of Arizona (Klawon, 2003). In addition, numerous radiocarbon age obtained from soils and deposits in the Duncan Valley provide a means to estimate the age of alluvium along the Gila River in New Mexico.

Understanding the age of alluvial deposits that bound a river helps provide long-term constraints on the lateral stability of the channel. The typical pattern that would be expected along a river in the southwest is a progression in age of deposits away from the active river channel. The older the deposits the less likely it should be that they would be actively eroding. That is not to say that rivers do not migrate laterally and erode older deposits. However, if a river is eroding laterally in many locations and eroding older deposits, that is not a condition with a high probability and generally indicates some form of imposed instability.

Based of the properties of the soils and stratigraphy at the 12 detailed descriptions location and correlation with radiocarbon ages from Arizona (Klawon, 2003), the majority of actively eroding banks are more than a few hundred years old. In fact many of the soil and stratigraphic properties observed in the exposed banks suggest that the banks that many of the banks currently eroding are more than 500 to several thousand years in age. This strongly implies that for the last several hundred to several thousand years the Gila River in New Mexico, including the Upper Box, has had remarkable lateral stability. Further, the close correspondence between banks that are eroding and levee construction and subsequent failure indicates that the construction of levees resulted in lateral instability not previously recorded in the past several hundred to several thousand years.

Patterns of Levee Construction and Property Loss

Levee construction along the Gila River following the December 1978 flood appears to have lead to major geomorphic change in the lateral stability of the Gila River and subsequent property loss. Soles (2003) and Donegon (1997) discuss the failure of these levees as well as possible reasons and results. Based on the ages of alluvial surfaces that bound the Gila River in New Mexico, the type of lateral instability introduced by the levee construction is not expected under most conditions. The perturbations created by the levees have therefore apparently resulted in lateral instability of the channel that would not be expected without levee construction. Levee construction following the December 1978 flood significantly constricted the Gila River Channel. Levee construction was apparently not based on any hydraulic analysis (Donegon, 1997). This is borne out by the pattern of levee construction that seems to suggest little design analysis (Figure 22). The Geomorphic Map (Appendix A) shows examples of property loss from levee failure at locations 1-4, 5-8, and 23-30, indicated on the maps. Examples of flow redirection caused by levees are at Geomorphic Map locations 11-15, 17, and 18.

Impact of Diversion Structures

Diversion structures in the Gila River in New Mexico generally have impact upstream and downstream. The upstream impact is caused by the storage of sediment behind the diversion structure. The distance of the upstream impact is controlled by the height of the structure. The structure backs up sediment until it reaches the top. This causes aggradation of the bed of the river for a distance upstream controlled by the local slope of the river. The aggradation results in unexpected lateral instability of the river channel causing bank erosion upstream. The Geomorphic Map (Appendix A) shows examples of geomorphic change associated with diversion structures at locations 16, 22, and 26.

Figure 22. Levees upstream of the Highway 211 Bridge visible on 1980 aerial photographs. The distance between the levees is irregular and in places the levees are not parallel to each other. The levees are also constructed oblique to the flood channel that will lead to eventual levee failure.

The downstream impact of diversion structures is based on the orientation of the structure to the channel flow direction at high flows. During floods, the flow is perpendicular to the diversion structure. If the structure is oriented at an angle to the high flow channel, it will result in aiming the flow at a bank downstream. This will result in erosion. However, the impact does not stop with the first eroded bank. The eroding bank accentuates the perturbation to flow introduced by the diversion structure resulting in redirection of flow to the opposite bank. The type of erosion from flow rebounding off eroding banks can be propagated downstream for long distances and can result in severe bank erosion.

Impact of Bridges

The openings under bridges may constrict or redirect floodwaters. Constriction of flow will result in a decrease in sediment transport capacity and aggradation of the bed. Similar to diversion structures, bridges may redirect flood flows. Bridges may also stop or slow down the downstream propagation of flow redirection because the abutments are often armored and may slow or prevent bank erosion. This may have the unintended result of preventing the downstream propagation of exaggerated meandering because the abutments are difficult to erode. The Geomorphic Map (Appendix A) shows examples of geomorphic change due to bridges at locations 11 and 20.

Channelization of Tributaries and Alluvial Fan Formation

The channelization of tributaries to the Gila River has resulted in the formation of alluvial fans in the Gila River flood channel. This is primarily a concern in the Virden Valley since the valley is quite narrow. Straightening the channels of the tributaries increases their slope. This increase in slope causes increased sediment transport. When the tributaries enter the Gila River channel, their sediment transport capability is rapidly reduced resulting in an alluvial fan. Good examples of this process in the Virden Valley include the alluvial fans at the mouths of Mexican Canyon, Moore Canyon, and Windham Canyon. The formation of alluvial fans in the Gila River flood channel forces the flow in the Gila River to the opposite bank. This can result in erosion of the opposite bank. The Geomorphic Map (Appendix A) shows examples of the influence of alluvial fan tributary channelization at locations 24 and 25.

In some cases, it appears that older alluvial fans have stopped the downstream propagation of flow redirection and exaggerated meandering by forcing the Gila River back into the pre-levee flood channel. This appears to be the case at Winn Canyon in the Cliff-Gila Valley and at Greenwood Canyon near Riverside. This also may be the case at Schoolhouse Canyon downstream of the Bill Evans Lake diversion.

Geomorphic Limit of Floods

The Geomorphic Limit of Floods as shown on the Geomorphic Map, bounds the geomorphic evidence of sediment transport or erosion from floods. Floodwater in most cases will extend further out than this boundary. The point of this boundary is to demonstrate the minimum pre-levee width of floods along the Gila. As shown by the long-term stability of the banks, flow over these areas did not result in property loss. In fact, the buried soils observed at many sites show that to the contrary the floods deposited thin layers of sediment resulting in vertical growth of the banks (Figure 23). Modification of flood flow inside this boundary is likely to result in eventual property loss. Any modification of flow inside this boundary should be critically evaluated by detailed hydraulic modeling to predict possible unwanted property loss or damage.

Cause of Historical Geomorphic Change

Some attribute observed historical geomorphic change along the Gila River in New Mexico to changes in hydrology or land use changes in the upper basin. Based on all the geomorphic information gathered for this study this does not appear to be the case. In fact, the geomorphic and Holocene stratigraphic record of the Upper Box suggest that there has been very little impact on the Gila River system from historical change in the upstream watershed.

Figure 23. Another eroded bank in the Virden Valley that resulted from levee failure. The bank is composed of vertically accreted flood plain sediment and is likely more than several thousand years old.

Contrary to previous speculation, the major agent in historical geomorphic change along the Gila River in New Mexico is human disturbance. This disturbance includes levee construction, bridge construction, diversion construction, and tributary channelization. The geomorphic and Holocene stratigraphic record of the Gila River in New Mexico is one of vertical and lateral stability before the construction of these features or in areas where they have not significantly impacted the river.

The primary cause of geomorphic change of the Gila River in the Cliff-Gila Valley (Geomorphic Map locations 1-19) is due to levee construction and subsequent failure. The banks of the Gila River are generally constructed of vertically accreted flood plain deposits, allowing rapid levee failure resulting in dramatic property loss. The effect of levee failure and exaggerated meandering of the Gila River will propagate downstream resulting in repeated levee failure and unexpected widespread laterally instability of the channel. This results in property loss and an unexpected pattern of large asymmetrical meanders. This is not a pattern that would be expected for the Gila River under pre-disturbance conditions.

Property loss in the area of Riverside downstream of the Iron Bridge is likely the result of flow redirection by a levee constructed just upstream of the Iron Bridge. It is possible that this levee was constructed in response to flow redirection caused by the Highway 180 Bridge. The construction of this levee upstream of the Iron Bridge resulted in redirection of flow and nearly out of phase meandering of the Gila River in the valley near Riverside. This is documented by flow of the Gila River that is now nearly perpendicular to the former banks.

There has been significant property loss downstream of the diversion for Bill Evans Lake. It is not clear if this is the result of the diversion structure or the unintended result of efforts to mitigate the impact of the diversion. The result is meandering that is nearly out of phase with the former banks of the Gila River.

Many factors have caused the historical geomorphic change observed in the Virden Valley (Geomorphic Map locations 19-30). These include the impact of levee construction and failure, channel aggradation and flow redirection by diversion dams, aggradation by the Highway 92 Bridge, and tributary alluvial fans resulting from tributary channelization and straightening. This has resulted in a complex pattern of geomorphic change that in some cases is probably the result of the interaction of several causative processes. For instance, near the state line, the proximity of these factors has resulted in nearly continuous bank erosion and property loss probably resulting from the interplay of levee construction and subsequent failure, tributary alluvial fans impinging on the flood channel, and diversion dam aggradation and flow redirection.

Conclusions

The pattern of historical geomorphic change observed along the Gila River in New Mexico is probably not the result of changes in the upper watershed or changes in hydrology. In every case where historical geomorphic change has been documented in this study, the proximate cause is human disturbance of the Gila River channel. In some cases, there are multiple disturbances that probably all contribute to bank erosion and property loss.

Levee construction and subsequent failure is probably the most important factor in the observed pattern of historical change (see Geomorphic Map locations 1-4, 5-8, 23-30). The levees constructed following the flood in December 1978 appear to be directly responsible for widespread property loss and channel change. In addition, flow redirection by levees also caused widespread erosion particularly in the area downstream of the Iron Bridge (see Geomorphic Map locations 11-15, 17, & 18). The impact of levee failure propagates downstream through exaggerated meandering of the Gila River channel. This results in a chain of meanders formed in formerly stable flood plain deposits.

Bridges and diversion structures appear to play a lesser role in historical geomorphic change, but their role can be locally significant (see Geomorphic Map locations 11, 16, 20, 22, 26). Alluvial fans resulting from tributary channelization and straightening are important in the Virden Valley (see Geomorphic Map locations 24 & 29). These factors may also work to exacerbate the impact of levee failure and flow redirection.

CAUSAL ANALYSIS

There are multiple hypotheses that can potentially explain the current state of the fluvial geomorphology and the active physical processes that shape the Gila River in New Mexico. The goal of this analysis is to test these hypotheses to determine which ones can be supported and which ones can be invalidated. It is never possible to absolutely verify a hypothesis for a physical system that is as complex as the Gila River. However, it can be relatively straightforward to invalidate some hypotheses and find support for others.

The causation hypotheses for the Gila River fluvial geomorphology in the Cliff-Gila and Virden Valleys can be grouped into two types. The first type is based on the influence of factors external to the Gila River in those valleys. This means that changes in the characteristics of runoff or sediment flux from the upper Gila River drainage basin is the cause of geomorphic change in the Cliff-Gila and Virden Valleys. The second type of causation hypotheses is based on the influence of factors internal to the Cliff-Gila and Virden Valleys. This type of hypothesis would explain the observed fluvial geomorphology in these valleys based on local factors, primarily modification of the river through mechanical means.

The basic causation hypotheses for the fluvial geomorphology of the Gila River in the Cliff-Gila and Virden Valleys can be stated as:

1. There is no perceptible geomorphic change in these valleys.
2. A change in the upper Gila River drainage basin characteristics has resulted in increased runoff or a change in runoff characteristics. This change in runoff characteristics has resulted in geomorphic change in these valleys.

3. A change in the upper Gila River drainage basin characteristics has resulted in a change in sediment flux. This change in sediment flux has resulted in geomorphic change in these valleys.
4. Some combination of hypothesis two and three.
5. Local modification of the river in the valleys has resulted in geomorphic change. This type of local modification would consist of levee construction and subsequent failure, flow redirection by levees, reduced sediment transport resulting from levee construction, and encroachment by tributary alluvial fans into the Gila River from channelized tributaries.

The tests of these hypotheses are relatively simple. To invalidate the first hypothesis of no geomorphic change, some geomorphic change would need to be documented. The tasks that test this hypothesis are the Background Information, the Catalog of Historical Changes, the Geomorphic Map and Analysis, and the Stable Channel Analysis. The goal of the Flood Frequency, Flow Duration, and Trends is to test the second hypothesis about changes in runoff characteristics. The Qualitative Assessment of Upper Box Geomorphology, the Stable Channel Analysis, and the Geomorphic Map and Analysis are designed to test the third hypothesis about changes in sediment flux. Hypothesis four, that change is the result of a combination of a change in runoff and sediment flux is tested in a similar fashion as hypotheses two and three. The Background Information, the Catalog of Historical Changes, and the Geomorphic Map and Analysis are intended to test the last hypothesis that change is the result of local river modification.

The hypothesis that there is no perceptible geomorphic change along the Gila River in the Cliff-Gila and Virden Valleys is easily invalidated. The Background Information, the Catalog of Historical Changes, and the Geomorphic Map and Analysis all chronicle substantial geomorphic change in the Gila River in these Valleys.

Although the *Flood Frequency, Flow Duration, and Trends* document some positive trend in precipitation and runoff over the past 70 years, it does not document a trend over the past 40 years. Qualitatively this is explained by a pattern seen throughout the southwestern and western U.S. This pattern generally displays episodes of frequent large floods followed by episodes of fewer or no large floods. These episodes can be irregular and may differ by geographic area and may last several decades to more than 50 years. The Gila River experienced two of these episodes during the twentieth century with a period of few large floods culminating in the early 1970's followed by an era of more frequent large floods that continues at least through the early 1990's. The results of this analysis appear to invalidate the hypothesis of unidirectional change in runoff resulting in geomorphic change. Instead, over the past several decades, once in an episode of floods, there is apparently no detectable trend in runoff.

The *Qualitative Assessment of Upper Box Geomorphology* concludes that the Gila River in the Upper Box has been stable for at least the last several hundred to perhaps the last several thousand years. This conclusion indicates that there has not been a significant change in sediment flux from the upper Gila River drainage basin over that time interval. This invalidates hypothesis three, that a change in sediment flux from the upper basin is the cause of geomorphic change in the Cliff-Gila and Virden Valleys. This is further borne out by the Stable Channel analysis that indicates dynamic channel stability in these valleys. The *Geomorphic Map and Analysis* does not document a major historical change in sediment flux in either valley, also invalidating the hypothesis of a system-wide change in sediment flux.

The information gathered for this analysis invalidates the fourth hypothesis, that geomorphic change is the result of some combination of a change in runoff and a change in sediment flux. As there is no apparent trend in runoff over the past four decades and no apparent change in sediment flux over hundreds or thousands of years, there is no evidence to support a combination of the two causing geomorphic change.

The hypothesis that local modification of the Gila River channel is responsible for the observed geomorphic change in the Cliff-Gila and Virden Valleys is supported by all the available data. The fact that change in runoff and sediment flux from the upper Gila River basin can be discounted as the cause of geomorphic change points to a factor that must be present in each of the valleys. The Catalog of Historical Changes and the Geomorphic Map and Analysis document the close correspondence between levee construction and subsequent failure and redirection of flow by levees and significant geomorphic change along the Gila River in the Cliff-Gila and Virden Valleys. Further, the construction of levees led to decreased sediment transport resulting in channel aggradation. Finally, the straightening of steep tributaries has resulted in the rapid formation of pro-grading alluvial fans in the Gila River channel. In many cases these fans have resulted in erosion of the opposing bank due to decreased channel capacity.

GEOMORPHIC AND CAUSAL ANALYSIS CONCLUSIONS

It appears that levee construction and subsequent failure has resulted in the majority of geomorphic change observed in the Cliff-Gila and Virden Valleys. The lack of significant observable change in sediment flux and flood characteristics indicates control over geomorphic change in these areas is not external. That is, change is not the outgrowth of change in runoff or sediment yield from the upper drainage basin. This points to a causative mechanism present in both valleys. The Catalog of Historical Changes and the Geomorphic Map both record the close association between levee construction and geomorphic change. This provides the mechanism that is internal to both valleys and does not require geomorphic change to be the result of the change in external conditions.

Along much of the Gila River in the Cliff-Gila and Virden Valleys, the levees visible in the 1980 aerial photographs are still present today. They have survived several large floods. This includes the majority of the length of the Gila River in the study reach. However, where the levees have failed or redirected flow, there has been dramatic geomorphic change. In some areas where the levees have failed, it appears that the levees where constructed in response to other causes of geomorphic change such as tributary alluvial fan encroachment into the Gila River. It does appear in most cases that the construction and failure of the levees has resulted in a much larger loss of property than would be expected from other causes.

The close correspondence between the presence of levees and local, significant geomorphic change, points to them as the causative mechanism of geomorphic change along the Gila River in the Cliff-Gila and Virden Valleys. In addition, the pattern of change is consistent with that expected from levee failure and/or flow redirection. To a lesser extent, tributary channelization has resulted in less significant geomorphic change of the Gila River. This is best displayed in the Virden Valley and results in rapidly encroaching alluvial fans cause erosion of the opposing bank. In summary, it appears that the construction and following failure of levees and the channelization of tributaries has resulted in the geomorphic changes observed historically along the Gila River in the Cliff-Gila and Virden Valleys.

STREAM CORRIDOR ASSESSMENT CONCLUSIONS

All the available information and analysis gathered and produced for this study shows that modification of the Gila River channel in the Cliff-Gila and Virden Valleys has resulted in the observed geomorphic change. Direct tests of other hypotheses regarding changes in runoff or sediment flux from the upper Gila River drainage basin do not support these hypotheses. Instead they point to the fact that change in the study reach is the result of factors internal to that area.

It appears that levee construction and subsequent failure has resulted in the geomorphic change observed in the Cliff-Gila and Virden Valleys. This inference follows from several lines of evidence. The lack of significant change in sediment flux and flood characteristics shows that the control over geomorphic change in these areas is not external. That is, the change is not the outgrowth of change in runoff or sediment yield from the upper drainage basin. This points to a causative mechanism present in both valleys. The Catalog of Historical Changes and the Geomorphic Map both record the close association between levee construction and geomorphic change. This provides the mechanism that is internal to both valleys and does not require geomorphic change to be the result of the change in external conditions.

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The close correspondence between the presence of levees and local, significant geomorphic change, points to them as the causative mechanism of geomorphic change along the Gila River in the Cliff-Gila and Virden Valleys. In addition, the pattern of change is consistent with that expected from levee failure and/or flow redirection. To a lesser extent, tributary channelization has resulted in less significant geomorphic change of the Gila River. This is best displayed in the Virden Valley and results in rapidly encroaching alluvial fans cause erosion of the opposing bank.

It appears that the construction and following failure of levees and the channelization of tributaries has resulted in the geomorphic changes observed historically along the Gila River in the Cliff-Gila and Virden Valleys. For any local mitigation of these geomorphic changes it would be important to fully understand and document the effects of channel modification in the area of interest. As shown by the example downstream of the Iron Bridge, the influence of flow redirection by levees or levee failure can propagate downstream for quite a distant. Any future channel modification should specifically address the influence of upstream alteration on the proposed modification as well as the impact of the proposed modification on the opposing bank and downstream.

RECOMMENDATIONS FOR DEMONSTRATION PROJECTS

With an understanding of the cause of the geomorphic changes on the Gila River, Reclamation and NMED-SWQB prepared these recommendations for demonstration projects. The recommendations are broad, made in four sub-reaches of the overall study reach, and are designed to counteract the causation that has led to the loss of land resources along the Gila River in New Mexico. The recommendations are based upon four overall management goals and follow four sets of screening criteria.

MANAGEMENT GOALS

The New Mexico Environment Department, Surface Water Quality Bureau manages the non-point source pollution monitoring of the upper Gila River. Many of the factors that drive non-point source pollution are a function of the fluvial geomorphology of the river, the condition of the watershed, the hydrology, and human activities along the river and in the watershed. The underlying hypothesis driving the Upper Gila Fluvial Geomorphology Study is that a stable Gila River, stable from a hydraulic/fluvial geomorphological perspective, is a necessity for minimizing non-point source pollution in the river. NMED-SWQB undertook this study to understand the fluvial geomorphology of the river, the causes of instability, and the identification of potential remedies for reducing non-point source pollution associated with sediment and bank stability.

In that respect, the causation analysis leads directly to four management goals that the public and public agencies charged with managing the Gila River would be well advised to implement:

1) Do not overly constrain the river width for flood control purposes
2) Modify flood control practices to insure that the river is reattached to its floodplain
3) Do not interfere with the direction of flow in the flood channel
4) Educate the public and stakeholders on the fluvial processes that drive the river form, and the influence that human interaction has on the river, and the rivers resultant behavior during small, intermediate, and large floods.

SCREENING CRITERIA

Selection and design of specific demonstration projects should occur in the context of these screening criteria:

1) Immediate Risk
2) Stressor Reduction
3) Reattachment of River to Floodplain
4) Remediation

Immediate Risk refers to areas where we suspect that small, intermediate, or large floods would have immediate impact, resulting in the loss of substantial land resources. The mechanism of loss follows incipient bank instability due to macro flow redirection, and the subsequent change in the course of the river. These areas are usually in close proximity to reaches where the width of the river is overly constrained, resulting in loss of sediment transport capacity, followed by local aggradation and perching of the river. A perched river in a levied environment is at great risk of avulsion and redirection, resulting in substantial loss of land resources. Demonstration projects that protect land resources, and or alleviate the immediate risk, should be considered.

Stressor Reduction refers to areas that directly cause instability either upstream or downstream of the stress-creating feature. In most cases, the primary stressors on the Gila River are narrowed reaches with reduced flood and sediment transport capacity. Reducing the stress that these areas create on the form of the river includes levee setback, levee realignment, levee removal, bridge widening, bridge realignment, and in rare cases, installation of new levees for redirection the flow away from at-risk land resources. Reducing the cause of the processes that have led to the loss of land resources on the Gila River is the overall goal of the demonstration projects and the management of the River. Demonstration projects that reduce the stress on the river system should be considered.

Reattachment of River to Floodplain refers to changes in flood control practices that allow the river to access its floodplain during small, intermediate, and large floods. Miles of continuous levees prevent the river from accessing its floodplain. The geomorphic implications of long-term operation of levee flood control are systemic aggradation or degradation. Fortunately, the Gila River has not systemically aggraded or degraded. Local reaches of aggradation, or perching of the stream bed, have caused levee breaches, channel avulsion, and loss of large quantities of top soil, and land resources. Demonstration projects that have the effect of reattaching the river to the floodplain should be considered.

Remediation refers to improving areas damaged in previous floods, for the reasons outlined in the causal analysis, and restoring pre-causation alignments, sediment transport capacity, and flood capacity. An example is the exaggerated meander loops, or "dog-ears" created during floods. One such example is upstream of the Highway 211 Bridge in the Cliff-Gila Valley. Remediation at this site might include deconstructing the remaining portions of the severely damaged levee, and using the levee material to fill the meander loop there to the existing floodplain elevation. Filling this meander would restore the river alignment and reattach the river to the floodplain, and remedy the loss of the land resource. Consideration should also be given to the impact of the Highway 211 Bridge on this area before settling on this solution to the remediation example. Demonstration projects that pass the other screening criteria and remedy land resources losses should be considered.

INVENTORY CONSIDERATIONS

This inventory considers hydraulic and geomorphic considerations. It does not include any other considerations. Developing specific locations and types of demonstration projects should include T&E, Economic, Legal, and other considerations. We are counting on our partners, cooperators, and stakeholders to assist in developing the specific demonstration projects in light of these other considerations.

RECOMMENDATIONS

REACH A – SHELLEY IRRIGATION DITCH DIVERSION ABOVE OTHO WOODROW FARM DOWNSTREAM TO HIGHWAY 180 BRIDGE

Dominant Causation: Levee failure and subsequent flow redirection.

Geomorphic Goal: Allow river flood channel to return to a form similar to 1935

Remove levees

Restore meander phase/amplitude (fill-in abnormal meanders to floodplain elevation and remove perturbations)

Insure that temporary diversion dams will erode during medium flood flows and above.

REACH B – HIGHWAY 180 BRIDGE DOWNSTREAM TO GREENWOOD CANYON ALLUVIAL FAN

Dominant Causation: Bridge and levee flow redirection and out-of-phase meandering

Geomorphic Goal: Restore meander phase/amplitude (fill-in abnormal meanders to floodplain elevation and remove perturbations)

Widen Highway 180 Bridge

Restore meander phase/amplitude (fill-in abnormal meanders to floodplain elevation and remove perturbations)

REACH C – BILL EVANS DIVERSION DOWNSTREAM TO MANGAS CREEK ALLUVIAL FAN

Dominant Causation: River maintenance flow redirection and out-of-phase meandering

Geomorphic Goal: Maintain Bill Evans diversion without causing meander perturbations. Replacing the existing check-dam at the diversion with inflatable dams that allow passage of sediment during flood events and flows one-half of the effective discharge and greater are an option. The inflatable dam would check flow only during low flows, allowing nominal fluvial processes to continue upstream and downstream with minimal impact from the diversion.

Restore meander phase/amplitude (fill-in abnormal meanders to floodplain elevation and remove perturbations)

REACH D – LOWER BOX DOWNSTREAM TO STATE LINE

Dominant Causation: Levee failure, tributary alluvial fans, and bridges.

Geomorphic Goal: Allow river flood channel to return to a form similar to 1935.

Manage diversions. Replacing existing diversion dams with inflatable dams that allow passage of sediment during flood events and flows one-half of the effective discharge and greater are an option. The inflatable dam would check flow only during low flows, allowing nominal fluvial processes to continue upstream and downstream with minimal impact from the diversion.

Restore meander phase/amplitude (fill-in abnormal meanders to floodplain elevation and remove perturbations)

GENERALIZED MONITORING PLAN

The purpose of this monitoring plan is to collect the data necessary to discern changes to the Gila River channel over time due to the implementation of channel and levee altering demonstration projects. The monitoring plan will also track the performance of these types of projects. The basis of the geomorphology and stable channel analysis developed for this study is topographic data derived from aerial photography flown in 2001.

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 demonstration project 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. 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 (roadway, local landmark, etc.), and is not prone to disturbance or vandalism. Detailed notes describing location and distances to nearby landmarks such as telephone poles, fence posts, bridge piers, trees, etc. should be developed for each cross section and incorporated into a permanent monitoring project database.

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 following implementation of a demonstration project. These data should then be averaged to provide the baseline that would be considered representative of the current river conditions.

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 Gila 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. 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. 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 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. The measure of channel length can be collected by two different methods, field survey or from aerial photography. 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. 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. 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. 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%.

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 24A 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 24A. 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 24A. 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 24A. In cross sections that contain multiple threads or channels, measure the thalweg for each channel.
- The position of any boundaries or essentially permanent features in the cross section such as roads, 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.

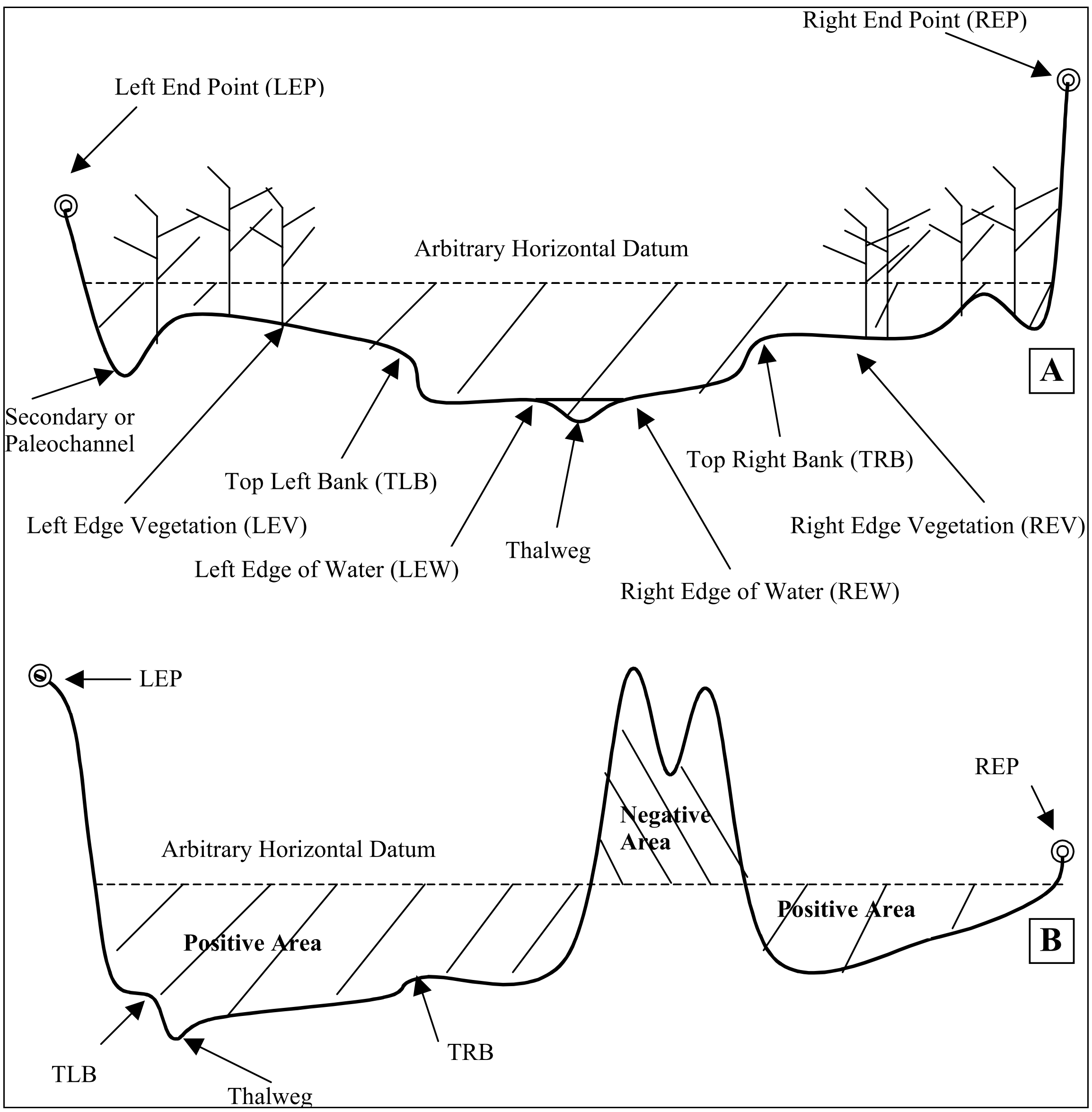


*Figure 24. **A.** Diagram showing typical cross section and placement of arbitrary horizontal datum. **B.** Diagram showing a cross section with a portion of the cross section above the datum.*

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 Gila 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 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 24 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 24A. 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.

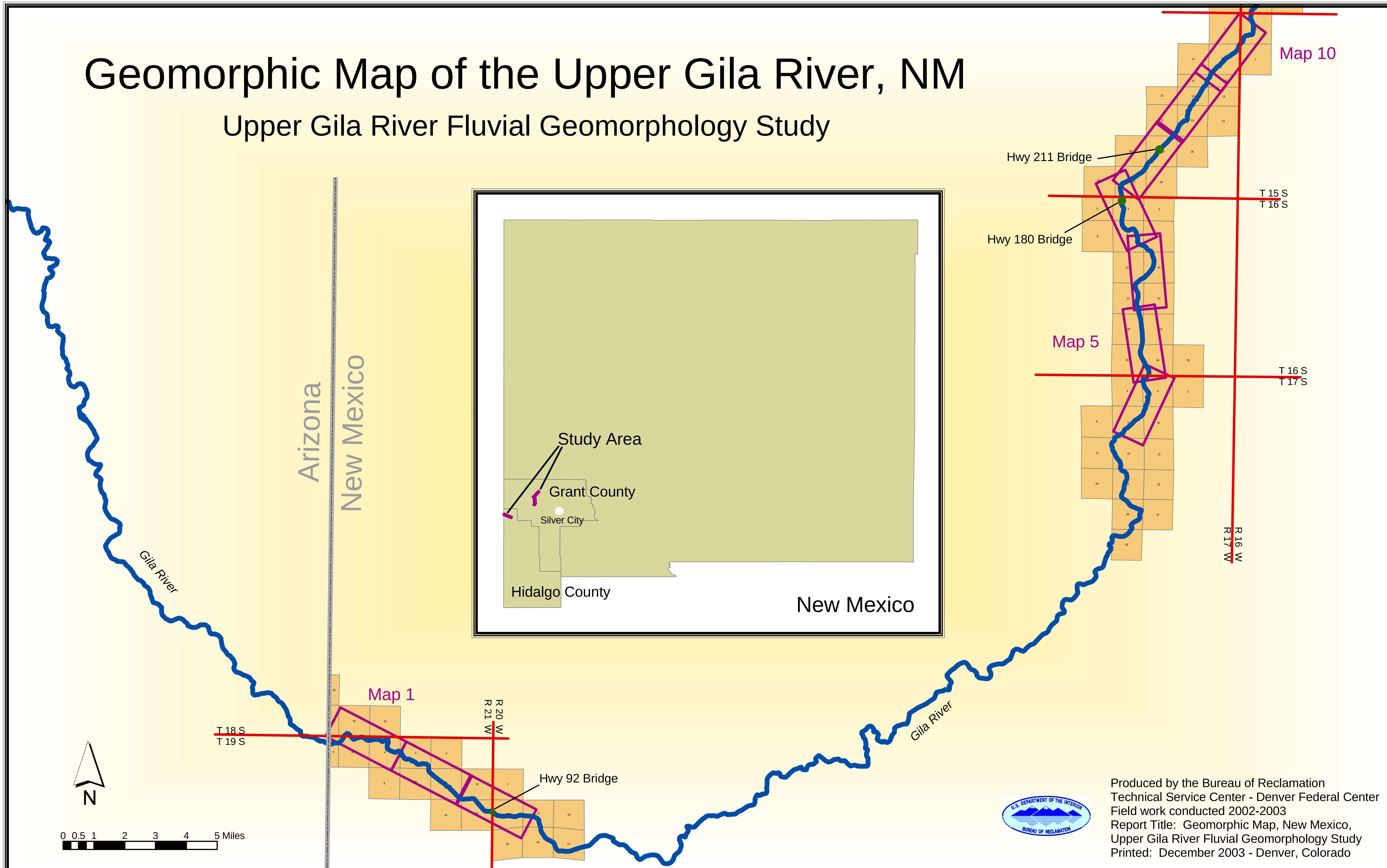
It is important to note that each cross section has its own unique horizontal datum and that all cross sectional areas calculated in a given cross section must utilize the horizontal datum established for that cross section. The datum is established at an arbitrary elevation in the cross section that 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 24A. 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 24B. 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. Second, 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 24 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.

Appendix A

GEOMORPHIC MAP



Geomorphic Map of the Upper Gila River, NM
Upper Gila River Fluvial Geomorphology Study
Arizona
New Mexico
Study Area
Grant County
Silver City
Hidalgo County
New Mexico
Map 10
Hwy 211 Bridge
T 15 S
T 16 S
Hwy 180 Bridge
Map 5
T 16 S
T 17 S
R 16 W
R 17 W
Gila River
Gila River
Map 1
T 18 S
T 19 S
R 20 W
R 21 W
Hwy 92 Bridge
N
0 0.5 1 2 3 4 5 Miles
U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
Produced by the Bureau of Reclamation
Technical Service Center - Denver Federal Center
Field work conducted 2002-2003
Report Title: Geomorphic Map, New Mexico,
Upper Gila River Fluvial Geomorphology Study
Printed: December 2003 - Denver, Colorado

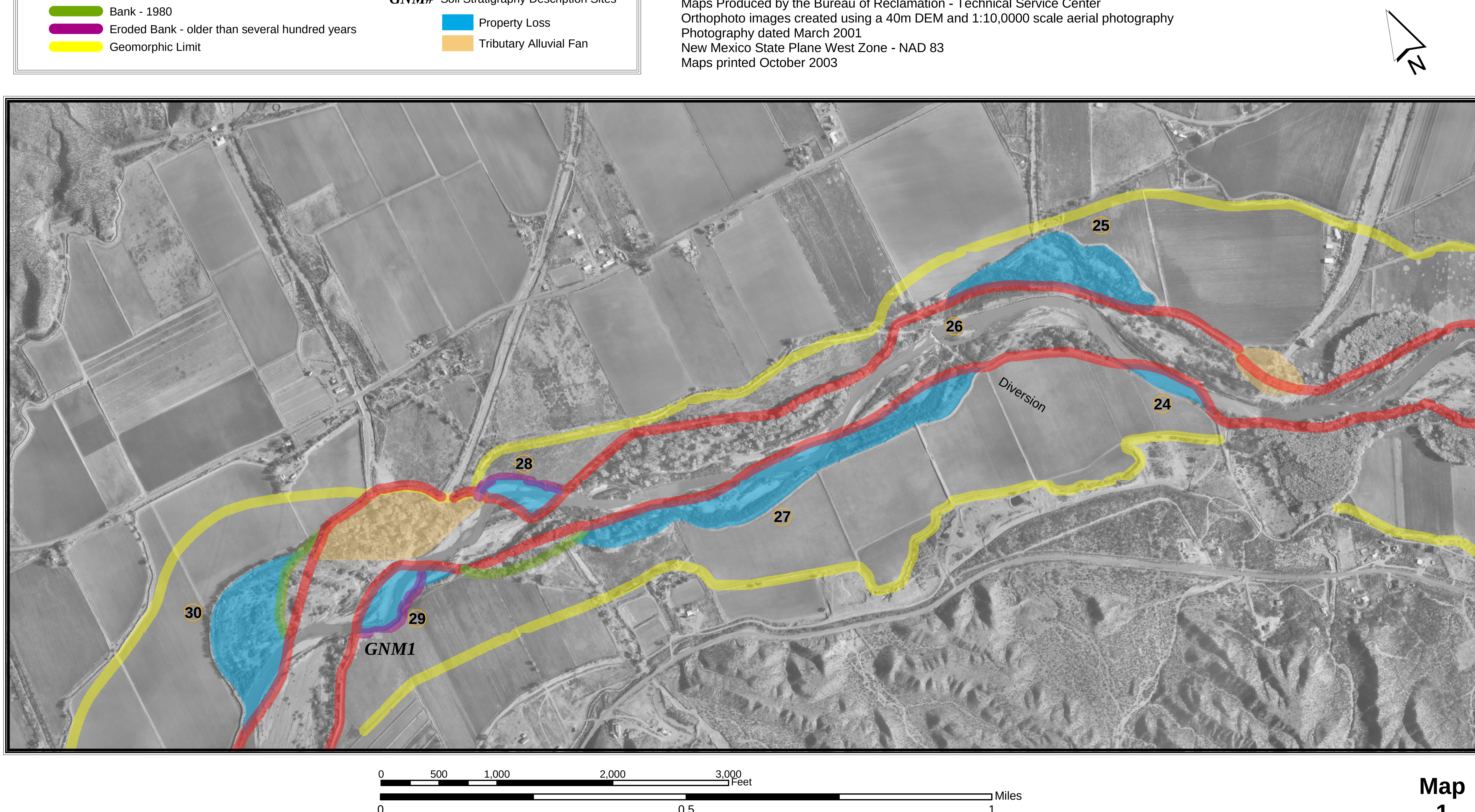
Geomorphic Map of the Upper Gila River, NM

Upper Gila River Fluvial Geomorphology Study

Gila River Geomorphology

- Levee - present in 1980
- Bank - 1980
- Eroded Bank - older than several hundred years
- Geomorphic Limit
- # Geomorphic Analysis Location
- *GNM#* Soil Stratigraphy Description Sites
- Property Loss
- Tributary Alluvial Fan

Maps Produced by the Bureau of Reclamation - Technical Service Center
Orthophoto images created using a 40m DEM and 1:10,0000 scale aerial photography
Photography dated March 2001
New Mexico State Plane West Zone - NAD 83
Maps printed October 2003



Map 1

Geomorphic Map of the Upper Gila River, NM

Upper Gila River Fluvial Geomorphology Study

Gila River Geomorphology

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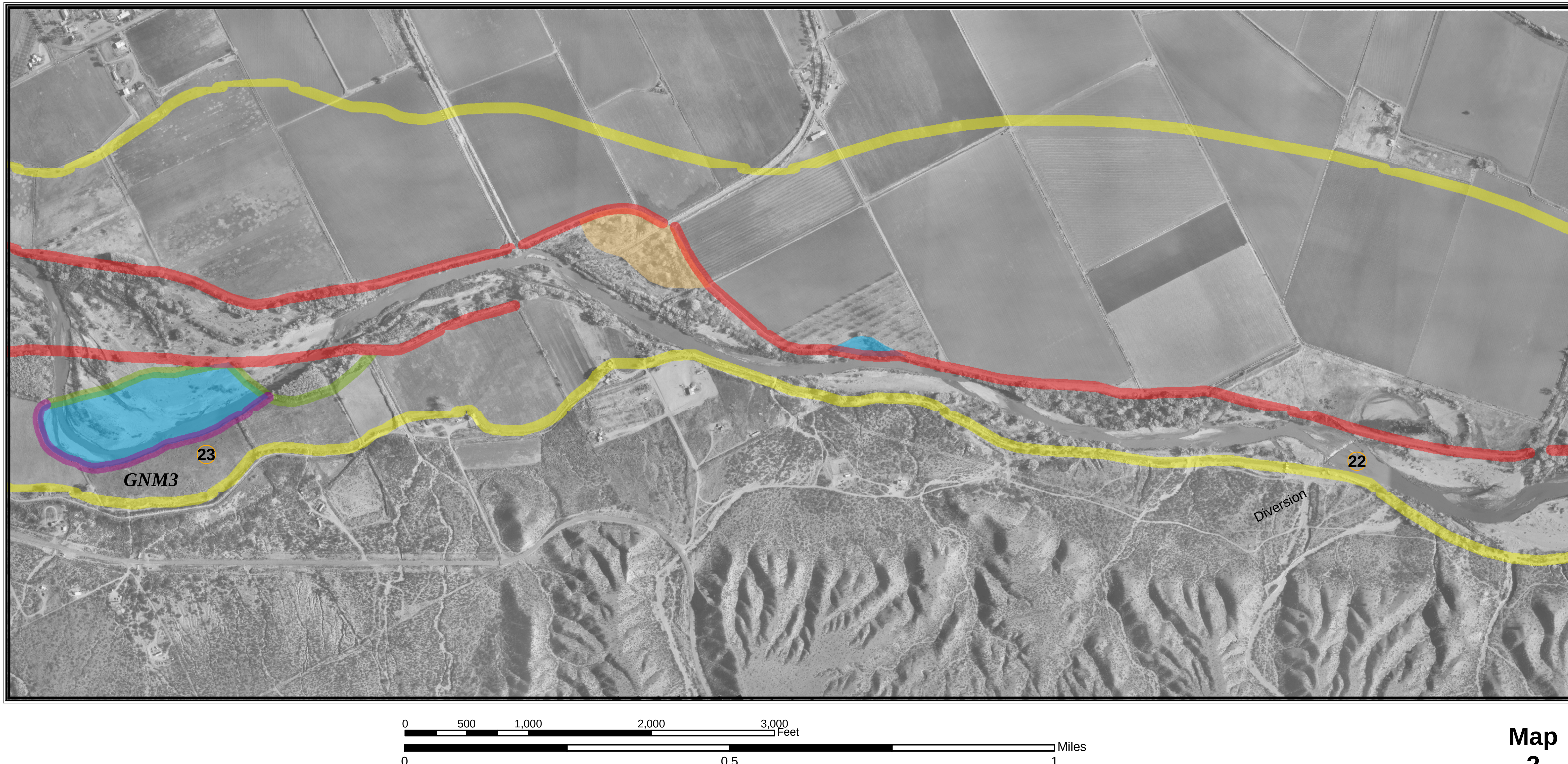

Map 2

Geomorphic Map of the Upper Gila River, NM

Upper Gila River Fluvial Geomorphology Study

Gila River Geomorphology

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- Bank - 1980
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- Geomorphic Limit
- # Geomorphic Analysis Location
- *GNM#* Soil Stratigraphy Description Sites
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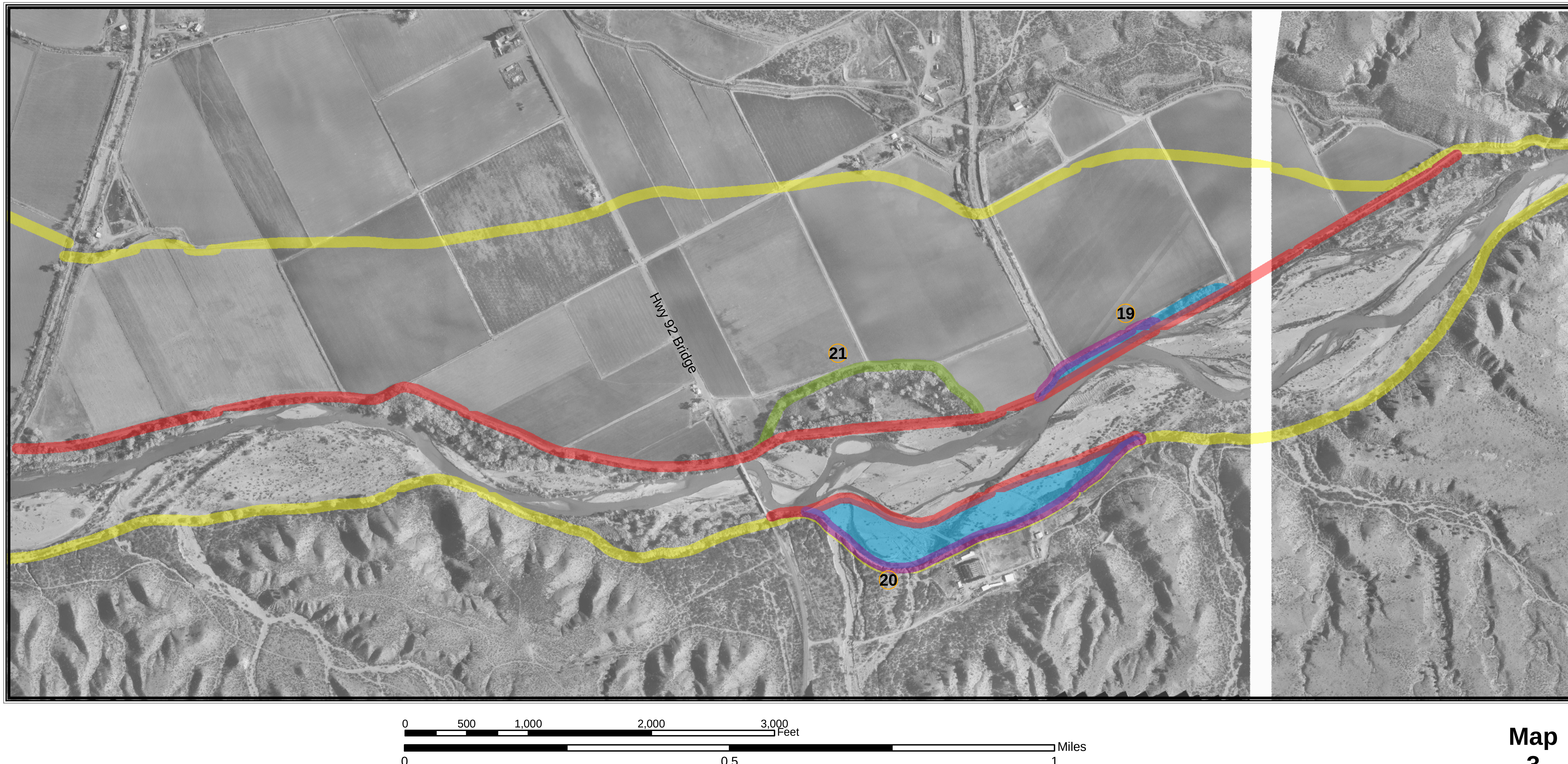

Map 3

Geomorphic Map of the Upper Gila River, NM

Gila River Geomorphology

Levee - present in 1980
Bank - 1980
Eroded Bank - older than several hundred years
Geomorphic Limit

Geomorphic Analysis Location
GNM# Soil Stratigraphy Description Sites
Property Loss
Tributary Alluvial Fan

Upper Gila River Fluvial Geomorphology Study

Maps Produced by the Bureau of Reclamation - Technical Service Center
Orthophoto images created using a 40m DEM and 1:10,0000 scale aerial photography
Photography dated March 2001
New Mexico State Plane West Zone - NAD 83
Maps printed October 2003

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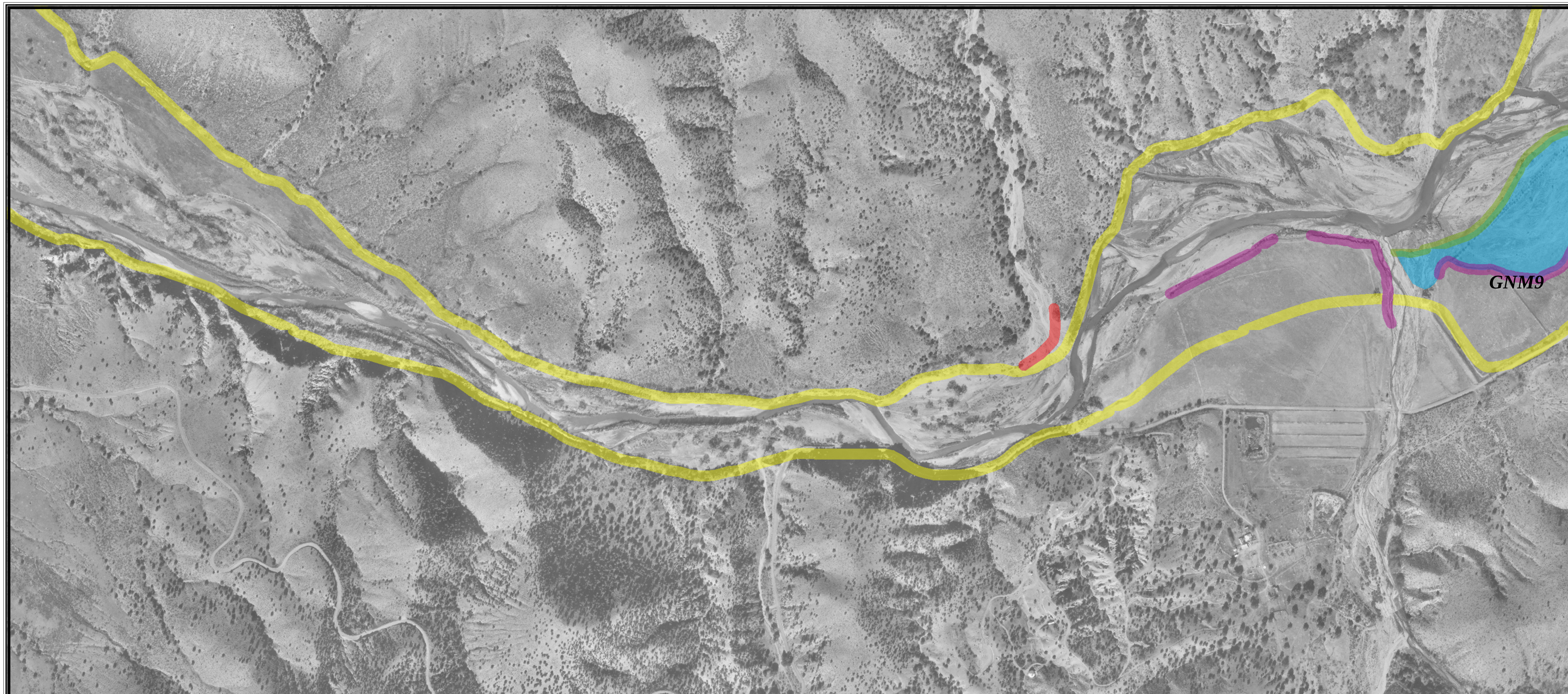

0 500 1,000 2,000 3,000 Feet

0 0.5 1 Miles

Map 4

Geomorphic Map of the Upper Gila River, NM

Upper Gila River Fluvial Geomorphology Study

Gila River Geomorphology

- Levee - present in 1980
- Bank - 1980
- Eroded Bank - older than several hundred years
- Geomorphic Limit
- # Geomorphic Analysis Location
- *GNM#* Soil Stratigraphy Description Sites
- Property Loss
- Tributary Alluvial Fan

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Photography dated March 2001
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Maps printed October 2003

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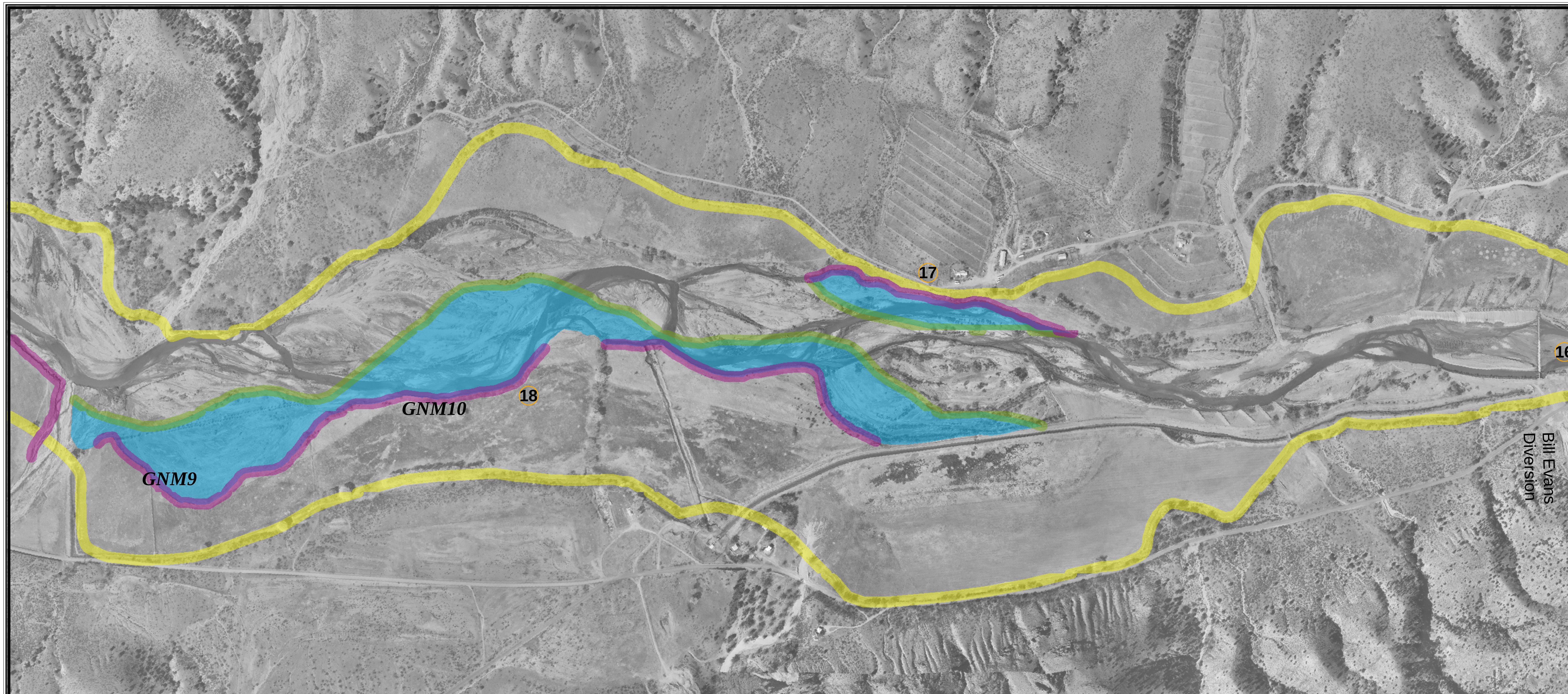

0 500 1,000 2,000 3,000 Feet

0 0.5 1 Miles

Map 5

Geomorphic Map of the Upper Gila River, NM

Upper Gila River Fluvial Geomorphology Study

Gila River Geomorphology

- Levee - present in 1980
- Bank - 1980
- Eroded Bank - older than several hundred years
- Geomorphic Limit
- # Geomorphic Analysis Location
- *GNM#* Soil Stratigraphy Description Sites
- Property Loss
- Tributary Alluvial Fan

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Orthophoto images created using a 40m DEM and 1:10,0000 scale aerial photography
Photography dated March 2001
New Mexico State Plane West Zone - NAD 83
Maps printed October 2003

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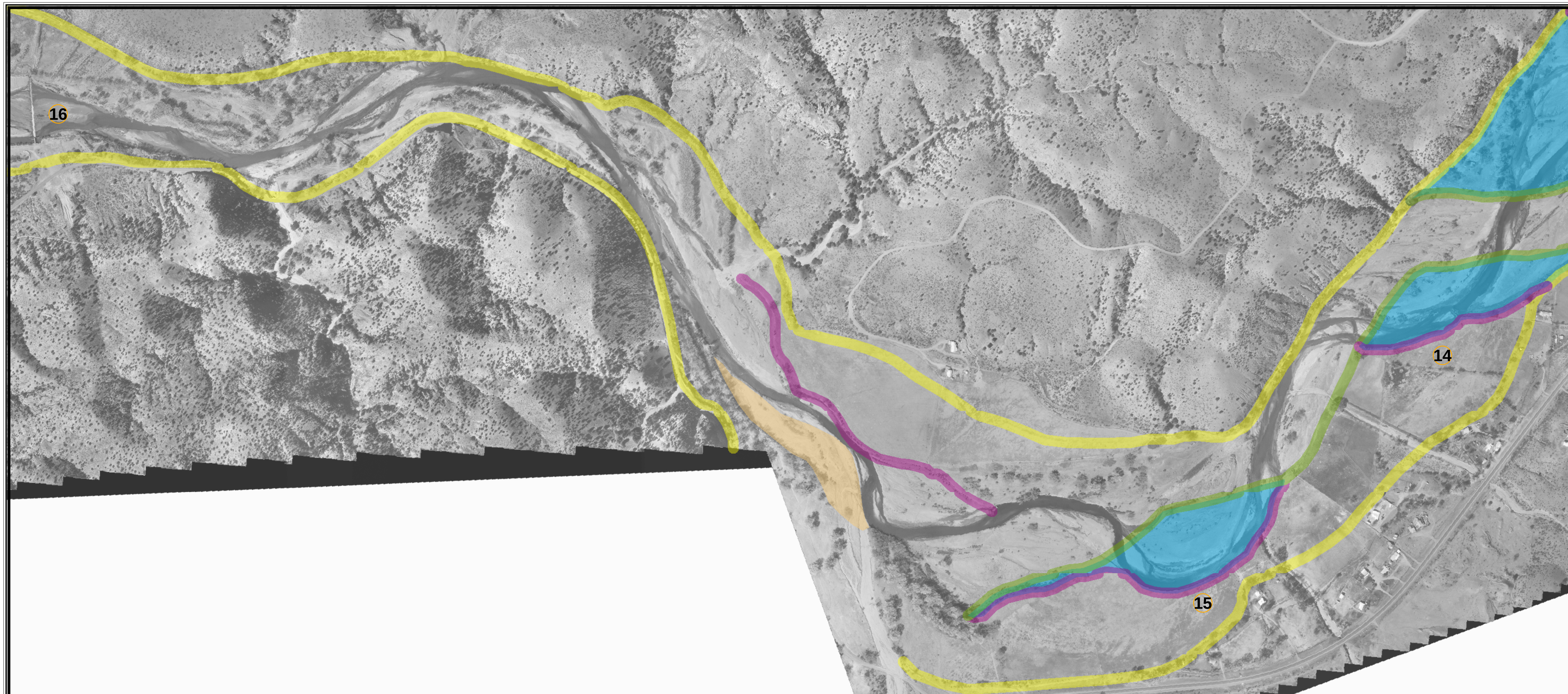


0 500 1,000 2,000 3,000 Feet

0 0.5 1 Miles

Map 6

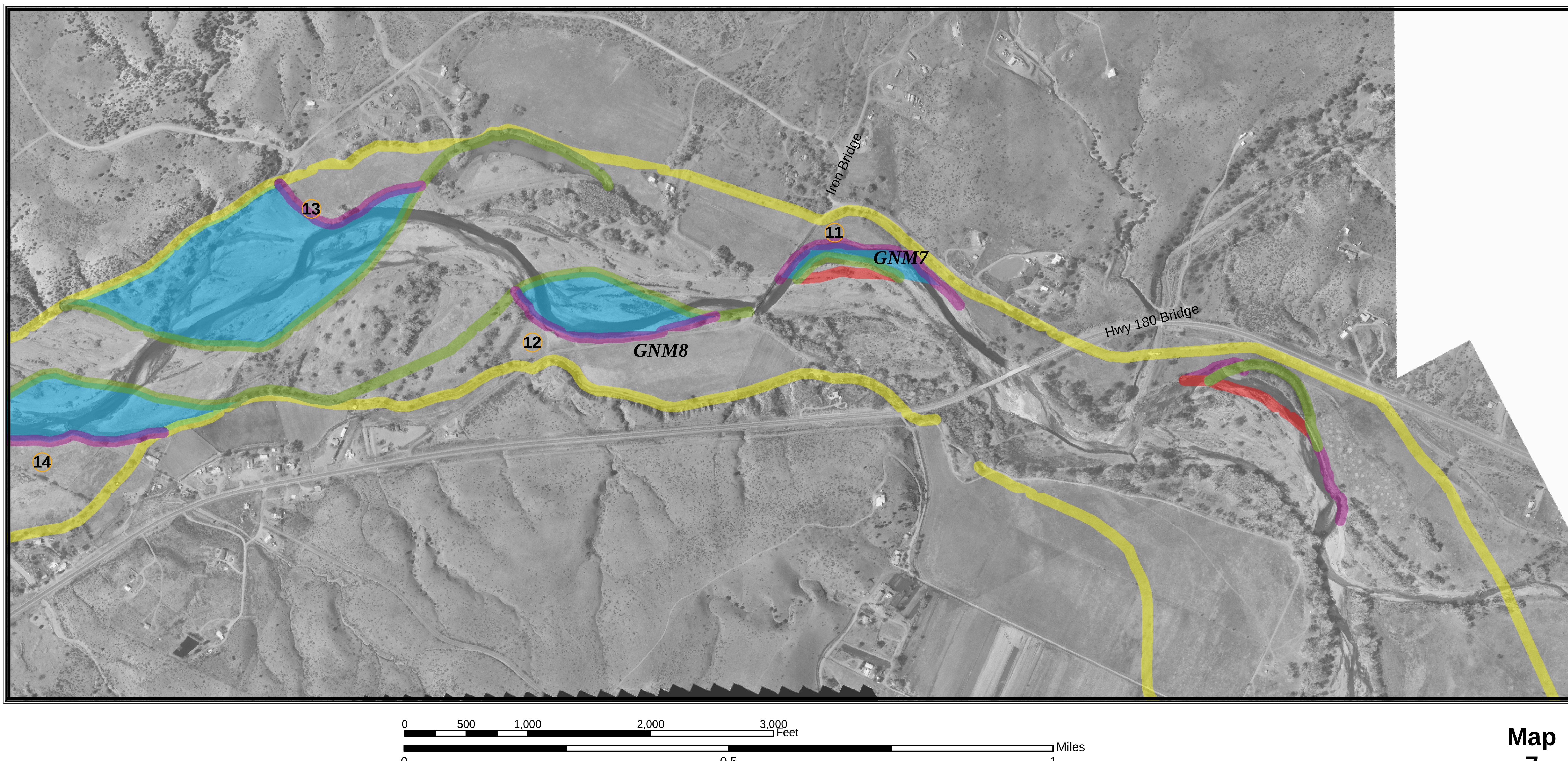
Geomorphic Map of the Upper Gila River, NM

Upper Gila River Fluvial Geomorphology Study

Gila River Geomorphology

Levee - present in 1980
Bank - 1980
Eroded Bank - older than several hundred years
Geomorphic Limit
Geomorphic Analysis Location
GNM# Soil Stratigraphy Description Sites
Property Loss
Tributary Alluvial Fan

Maps Produced by the Bureau of Reclamation - Technical Service Center
Orthophoto images created using a 40m DEM and 1:10,0000 scale aerial photography
Photography dated March 2001
New Mexico State Plane West Zone - NAD 83
Maps printed October 2003



Map 7

Geomorphic Map of the Upper Gila River, NM

Upper Gila River Fluvial Geomorphology Study

Gila River Geomorphology

- Levee - present in 1980
- Bank - 1980
- Eroded Bank - older than several hundred years
- Geomorphic Limit
- \# Geomorphic Analysis Location
- *GNM#* Soil Stratigraphy Description Sites
- Property Loss
- Tributary Alluvial Fan

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Orthophoto images created using a 40m DEM and 1:10,0000 scale aerial photography
Photography dated March 2001
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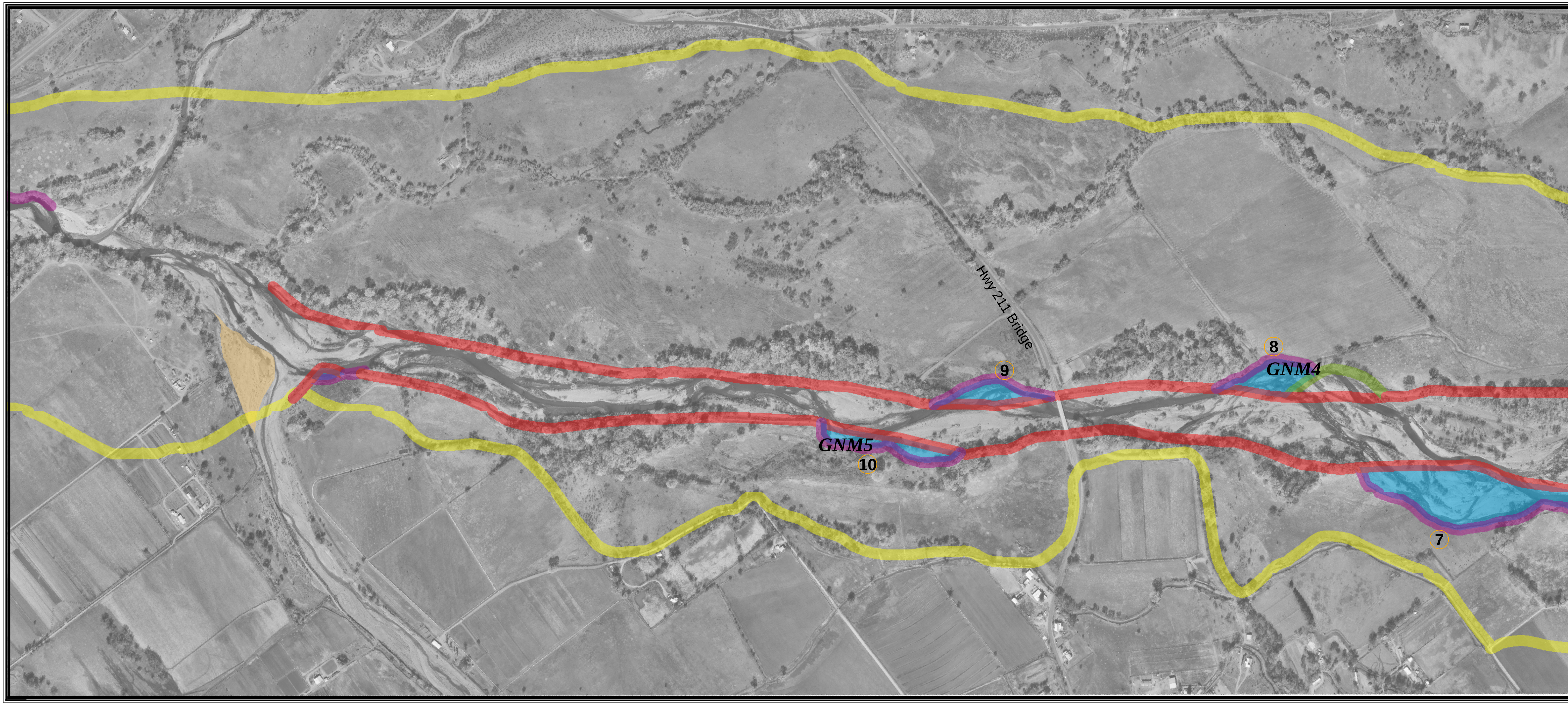
Maps printed October 2003

N



0 500 1,000 2,000 3,000 Feet

0 0.5 1 Miles

Map 8

Geomorphic Map of the Upper Gila River, NM

Upper Gila River Fluvial Geomorphology Study

Gila River Geomorphology

- Levee - present in 1980
- Bank - 1980
- Eroded Bank - older than several hundred years
- Geomorphic Limit
- # Geomorphic Analysis Location
- *GNM#* Soil Stratigraphy Description Sites
- Property Loss
- Tributary Alluvial Fan

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Orthophoto images created using a 40m DEM and 1:10,0000 scale aerial photography
Photography dated March 2001
New Mexico State Plane West Zone - NAD 83
Maps printed October 2003

N

0 500 1,000 2,000 3,000 Feet

0 0.5 1 Miles

Map 9

Geomorphic Map of the Upper Gila River, NM

Upper Gila River Fluvial Geomorphology Study

Gila River Geomorphology

- Levee - present in 1980
- Bank - 1980
- Eroded Bank - older than several hundred years
- Geomorphic Limit
- # Geomorphic Analysis Location
- *GNM#* Soil Stratigraphy Description Sites
- Property Loss
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Photography dated March 2001
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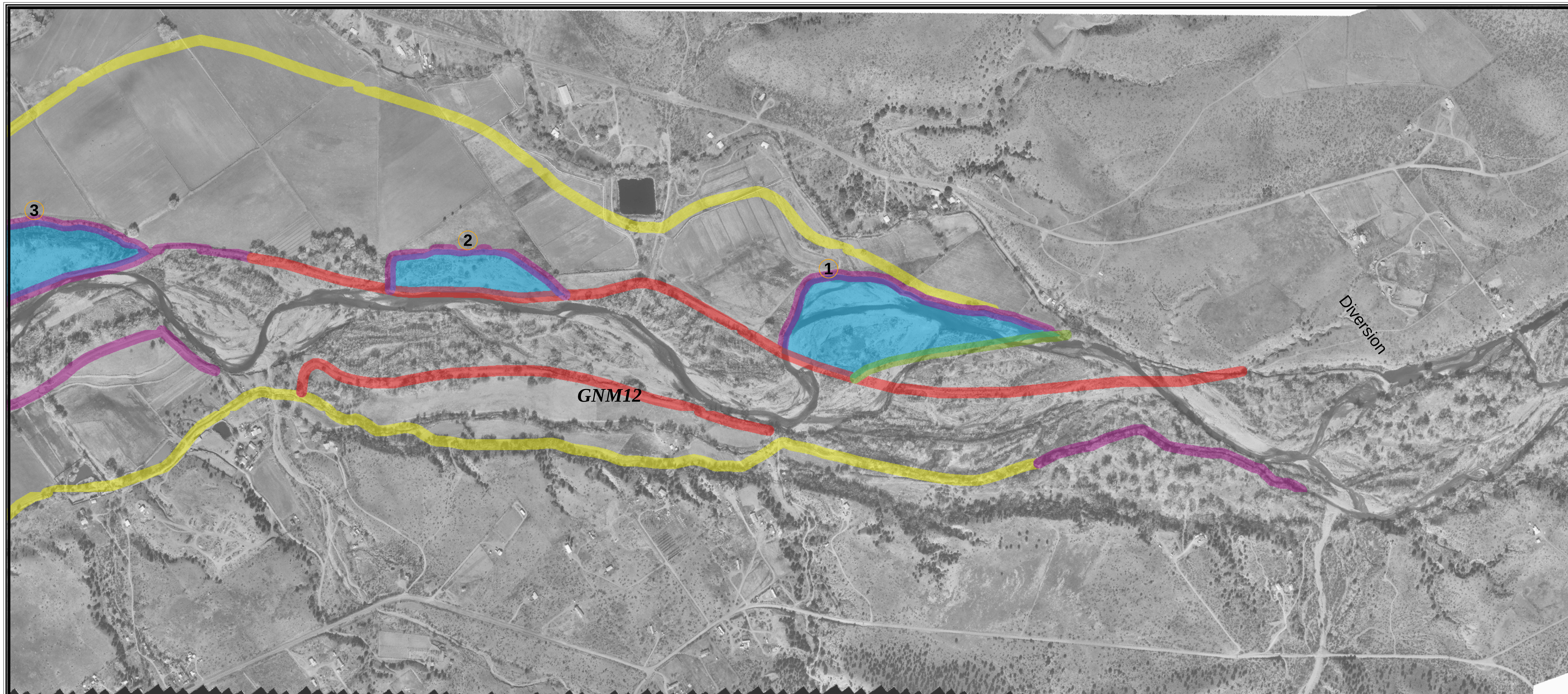
Maps printed October 2003



0 340 680 1,360 2,040 Feet

0 0.35 0.7 Miles

Map 10