TECHNICAL SERVICE CENTER
DENVER, COLORADO

UPPER GILA RIVER FLUVIAL GEOMORPHOLOGY STUDY

STREAM CORRIDOR ASSESSMENT
ARIZONA

US Department of the Interior
Bureau of Reclamation

WATER RESOURCES MANAGEMENT.....FOR THE FUTURE

MARCH 5, 2004

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

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GRAHAM COUNTY, ARIZONA

COST SHARE AGREEMENT 00-GI 32-0054

Graham County, Arizona, 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 Graham County.

UPPER GILA RIVER FLUVIAL GEOMORPHOLOGY STUDY

STREAM CORRIDOR ASSESSMENT
ARIZONA

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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, and sedimentation.

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INTRODUCTION

The Stream Corridor Assessment synthesizes findings of the Background Information report, Catalog of Historical Changes, Flood Frequency and Flow Duration Analyses report, Geomorphic Map, Geomorphic Analysis, and Stable Channel Analysis. Combined, these studies provide a framework for understanding the physical processes that shape the Gila River upstream of the San Carlos Reservation.

The Background Information report is an annotated bibliography of the fluvial geomorphology of the upper Gila River. The Catalog of Historical Changes traces changes in the Gila River plan form from 1935 to 2001. Flood Frequency and Flow Duration Analyses analyze historical stream flow and rainfall data for trends. The Geomorphic Map and Geomorphic Analysis analyze the fluvial geomorphic changes in the river and determine causative factors for the changes. The Geomorphic Map and Geomorphic Analysis also document major historical geomorphic change along the river primarily related to the construction and subsequent failure of levees, the construction of diversion dams, bridges, and to a lesser degree, the influence of native and invasive riparian vegetation. The Stable Channel Analysis forms a quantitative basis for understanding Gila River sediment transport and channel stability. When combined, these studies cover historical changes in river plan form, historical trends in hydrology, historical and pre-historical sediment flux from the upstream drainage basin, the causes of major historical geomorphic change along the river, and channel stability and sediment transport.

Systemically, the Gila River active channel widens and narrows on a decadal time scale in response to cyclical changes in basin hydrology, sediment flux, riparian vegetation life cycles, as well as other factors. The widening and narrowing process is partly a natural response to cycles of basin hydrology. However, encroachment into the active channel by agriculture and invasive riparian vegetation accelerates channel narrowing, while widening appears to be in response to increases in frequency and magnitude of annual peak flows. The combined analyses of this study indicate that, on a local basis, constriction of the channel by levee construction and subsequent failure of significant lengths of levee, and the installation and operation of diversion dams, are the probable causes for the most significant land resource losses along the Gila River in the study reach. The findings of these analyses do not suggest that there is a system-wide instability in the Gila River system due to changes in sediment flux from the upper basin.

SCOPE OF REPORT

This report is a synthesis of the Background Information report, the Catalog of Historical Changes, Flood Frequency and Flow Duration Analyses report, Geomorphic Analysis, Geomorphic Map, and the Stable Channel Analysis. The goal of this study is to gain an understanding of the physical processes that control the fluvial geomorphology of the Gila River in the Safford and Duncan Valleys. The complexity of historical alteration of the Gila River led to a study that is broad in scope, seeking to understand the major processes that control the observed fluvial geomorphology. Through this understanding, it is possible to make informed choices about future river management.

It is possible that some factors of geomorphic change are not accounted for in this analysis. When considering any modification of the river or bounding structures, it would be prudent to contrast the intended purpose of the modification with the findings outlined and supported in this and the other study reports.

STUDY AREA & REACHES

The downstream limit of the study area is the San Carlos Reservation. The upstream boundary of the study is the Arizona-New Mexico State line. Figure 1 shows the study area and several landmarks, tributaries, towns, and highways. The analyses exclude the Gila Box area.

The length of river channel in the study area, including the Gila Box, is roughly 102 miles. There are two primary reaches in the study area under analysis, an upper and lower reach, separated by the Gila Box. The upper reach includes the river reach between the Highway 191 Bridge and the New Mexico State line. The lower reach includes the river reach between the downstream end of the Gila Box, near the Brown Canal diversion, and the San Carlos Reservation. Some of the analyses in this study further divided these primary reaches further into sub reaches.

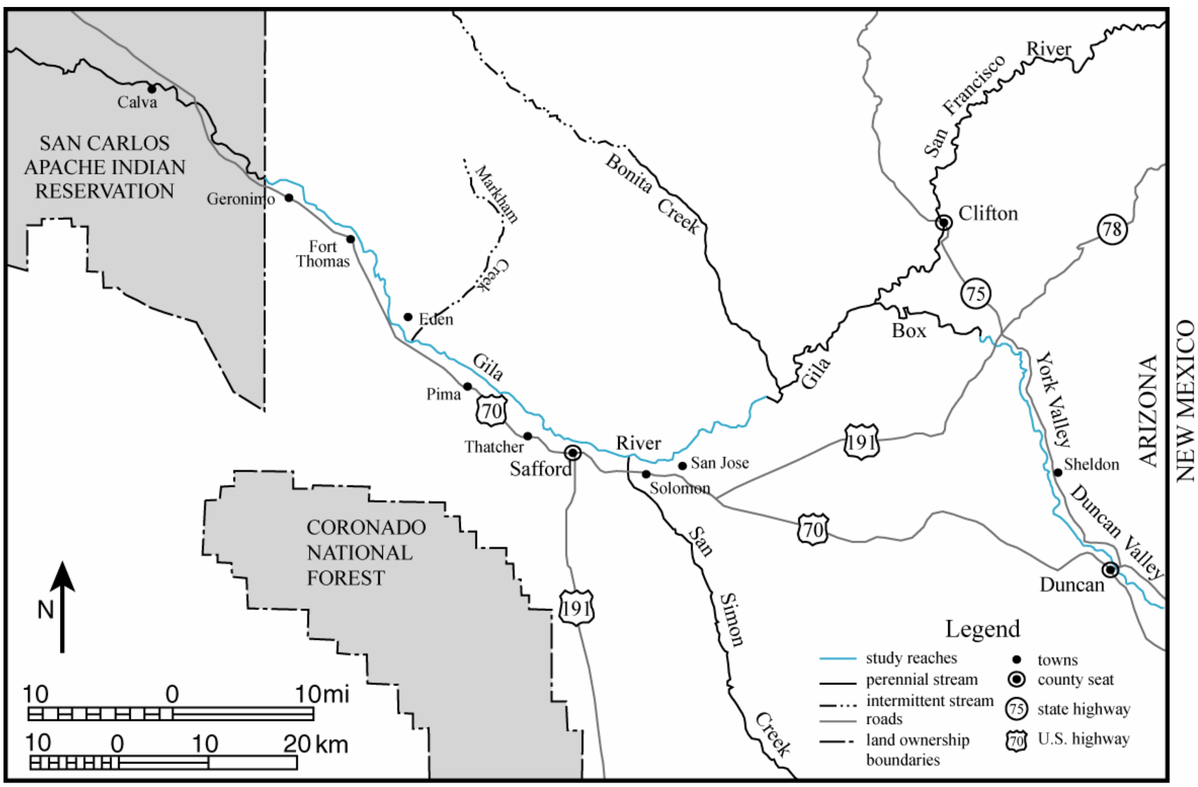


Figure 1. Study area between the San Carlos Reservation and the State of New Mexico.

CONCLUSIONS OF STUDY REPORTS & ANALYSES

This section presents the conclusions of the preceding study reports, including:

- Catalog of Historical Changes – Arizona
- Flood Frequency and Flow Duration Analyses – Arizona
- Geomorphic Analysis – Arizona
- Stable Channel Analysis – Arizona

In addition, this report presents the Arizona Geomorphic Map and a summary of the Arizona Background report.

BACKGROUND – ARIZONA

This document reviews existing studies that contain information that may be useful in the present study of the upper Gila River. The references include, but are not limited to, hydrologic and geologic data, accounts of floods and precipitation events, studies of channel change and erosion, sedimentation in San Carlos Reservoir, water resources documents, scour studies of bridges on the Gila River, links between flood records and climate, floods and vegetation, land use planning, water quality, and ground water. The document is in two parts: (1) an annotated bibliography that summarizes references that may be pertinent to the present study, and (2) a bibliography of related references that include water quality data, hydrogeologic data, fisheries studies, vegetation studies, soils data, and other miscellaneous information that is helpful for background information. This document is subject to amendment as other references become available during the course of the study.

GEOMORPHIC MAP – ARIZONA

A geomorphic map portrays surficial features or landforms that record geologic processes on the earth's surface. In fluvial geomorphology, these processes include erosion and deposition of sediment. Geomorphic landforms such as stream terraces and alluvial fans record sedimentary processes in a river system and are the basis for the delineations on the Geomorphic Map. For the Upper Gila River Fluvial Geomorphology Study, the Geomorphic Map illustrates geomorphic features that will aid in understanding recent channel changes of the Gila River.

The objective of the geomorphic map is to provide a picture of long-term river behavior in the Safford Valley and the Duncan Valley. Understanding long-term river behavior is useful for providing a comprehensive picture of river processes, placing recent channel changes into a long-term context, identifying causes of channel change and property loss in the historical period, and defining the extent of channel migration. The accompanying maps present basic geomorphic data on black and white orthophotographs. The Geomorphic Map, along with the Catalog of Historical Changes (Task 7C), fieldwork, and laboratory analyses, are combined in the Geomorphic Analysis (Task 10), a compilation of all geomorphic data developed in the Upper Gila River Fluvial Geomorphology Study.

The emphasis in this task was on defining the extent of lateral channel migration and assessing channel change. Geomorphic features that provide information on lateral migration and channel change include flood-modified surfaces, bedrock, alluvial fans, and older floodplain surfaces. Infrastructure is also a major factor in channel position and behavior of the Upper Gila River (Klawon, 2001). Thus, the maps include levees, diversion dams, and bridges.

The Geomorphic Map combines aerial photo interpretation, field mapping of geomorphic features, soil/stratigraphic descriptions, laboratory analyses, and use of previously published soil surveys to provide a long-term picture of river behavior. The maps are produced on 1:4800 scale digital orthophotographs and display geomorphic features and infrastructure important in the recent lateral movement of the Gila River channel.

CATALOG OF HISTORICAL CHANGES – ARIZONA

The Catalog of Historical Changes documents changes in the alluvial channel of the Upper Gila River, Arizona from 1935 to 2000. The objective of the Catalog is to quantify variability in channel width during the historical period and identify reaches of high variability. Measurements of channel width made from historical aerial photography and qualitative observations of lateral migration provide the data necessary for an analysis of trends in channel behavior and lateral stability of river reaches.

CONCLUSIONS

General trends in channel changes from this study parallel those described by Burkham (1972). The early 1900's experienced several extreme floods, causing channel widening to 1935 (Burkham, 1972; Olmstead, 1919). This early information was gathered for Safford Valley and may or may not apply to Duncan Valley. From 1935 to the early 1960's, the channel narrowed by sedimentation, vegetation growth, and levee, dike, and agricultural development. From the late 1960's to 2000, the channel widened in response to large floods and is approximately the same width on average as it was in 1935. In most cases, flood flow widths at specific channel locations are variable, but not unprecedented in the historical record.

This study has shown that although high variability exists in channel width and position in both Safford Valley and Duncan Valley, many channel positions are not new and channel widths are similar or smaller than 1935 channel widths for the Gila River during the period of study. In many of the case studies, the channel simply reoccupied old channel positions from earlier in the historical period. Average flood widths also show that by 2000, the river channel had reached an average flood width similar to the 1935 average flood width. Some channel changes; however, in recent decades do seem to be unprecedented in the period of study. Examples of such cases include the channel changes near Whitefield Wash, where erosion between 1992 and 1997 caused lateral migration of the left and right banks and greatly increased the sinuosity in the reach. Another dramatic area of channel change occurs downstream of the San Jose Diversion, where lateral movement of the channel toward the right bank has been observed on photograph years of 1981, 1992 and 1997.

The impact of floods on the Gila River channel is evident based corresponding large channel changes following flood years. In Duncan Valley, the most changes in flood width occurred following the 1978 flood and the floods in the 1990's. In Safford Valley, changes occurred following the 1972, 1983, and 1993 floods. The analysis of change using flood flow widths for Duncan Valley and Safford Valley show that Safford Valley has experienced many more perturbations in the period of study than Duncan Valley. This is shown best by the presence of several long, stable reaches in Duncan Valley, compared to a few short stable reaches in Safford Valley. Major channel changes generally occurred following large floods; this highlights the important point that the largest floods in the Gila River system have lasting effects that can be observed in channel morphology for decades following their occurrence.

FLOOD FREQUENCY AND FLOW DURATION ANALYSES – ARIZONA

This report summarizes flood frequency and flow duration for sites within the Gila River basin from approximately the Arizona-New Mexico State line to San Carlos Reservoir. These estimates were completed as part of Task 9 of the Upper Gila River Fluvial Geomorphology Study. The primary basis for the flood frequency and flow duration estimates are U.S. Geological Survey peak discharge and mean daily flow records. The data and results presented herein are appropriate for detailed hydraulic and geomorphic studies and analyses.

The Upper Gila River basin is located in the southeast corner of Arizona and southwestern New Mexico. The area in Arizona is called the Central Highlands physiographic province. Within the study area, the river flows generally westward from its headwaters in the Gila Wilderness area in Grand County, New Mexico to the San Carlos Indian Reservation, Arizona. The main tributaries in New Mexico enter the

Gila River upstream of Cliff, New Mexico. The major tributaries in Arizona upstream of Coolidge Dam are the San Francisco River, Eagle Creek, Bonita Creek, and the San Carlos River, which drain from the mountains on the north side of the basin, and the San Simon River, which drains from the south. Elevations in the drainage basin range from 5,650 feet at the western boundary of the study area (San Carlos Indian Reservation) to 11,000 feet in the mountains of the Gila Wilderness area (New Mexico).

The U.S. Geological Survey has published stream flow records from many gaging stations located in the Gila River basin upstream from San Carlos Reservoir into New Mexico (e.g., Pope et al., 1998). There are many active gaging stations in the Upper Gila River. This study focuses on using data from long-term gaging stations located on the Gila and San Francisco Rivers. A list of basin, flood and climatic characteristics for these sites are presented in Pope et al. (1998).

There are two main objectives of this study: (1) estimate flood peak frequencies; and (2) estimate flow durations at selected locations within the Upper Gila River basin, for application in subsequent fluvial geomorphic and hydraulic analyses.

CONCLUSIONS

Flooding in the Gila River basin is caused primarily by rains from fall and winter storm systems. These storms are generally cold frontal systems colliding with warm, moist air or tropical storms. Extreme flood-producing storms are widespread and generally 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. The largest floods have occurred in water years 1891, 1907, 1941, 1973, 1979, and 1984.

The log-Pearson Type III distribution was fit to annual peak discharge estimates at the five 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 5,210 ft^3/s and 9,650 ft^3/s at the five locations. The 100-year flood ranges between 44,800 ft^3/s and 175,000 ft^3/s at the five locations.

A period-of-record Flow Duration Curve for the water year indicated that mean daily flows are typically less than about 1,000 ft^3/s for 90 percent of the time at all five sites. 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 Gila River at Calva.

GEOMORPHIC ANALYSIS – ARIZONA

The Geomorphic Analysis synthesizes geomorphic information about the Gila River and compares results of the analysis to other tasks performed for the Upper Gila River Fluvial Geomorphology Study. The goal of the geomorphic analysis is to provide an understanding of the fluvial geomorphology and to explain recent geomorphic change on the Gila River in Safford and Duncan Valleys. Methods used for the Geomorphic Analysis include geomorphic mapping, soil descriptions and laboratory analysis. Soil maps developed by Poulson and Youngs (1938) and Poulson and Stromberg (1950) for Safford Valley and Duncan Valley, respectively, provided critical information for developing the Geomorphic Map. In addition to soil surveys, soil and stratigraphic characteristics were described for 30 sites with actively eroding banks along the Gila River in Duncan and Safford valleys. This information, along with radiocarbon analysis, aerial photography and soil surveys, was used to delineate geomorphic features.

CONCLUSIONS

In Safford and Duncan Valleys, the most substantial geomorphic changes in the Gila River in recent decades is due to changes in the magnitude and frequency of annual peak floods, as well channel straightening and flood interaction with levees and diversion dams. Using soil/stratigraphic information and lab analyses, geomorphic mapping in these valleys indicates that the Gila River has migrated within the Pima Soil boundary for the last several hundred years and within the Geomorphic Limit for at least the last 1,000 years. Areas of lateral change are indicated where historical floods eroded banks that are mapped as part of the Geomorphic Limit or Pima Soil Boundary.

The majority of property loss has occurred in areas of young alluvium, which is part of the active channel migration zone. Within this zone, lateral migration is common and it is not unexpected for areas to be eroded during large floods. Several areas with unusual channel geometries and erosion of banks older than several hundred years are clues that other factors are important in creating the current (year 2000) channel morphology. The Catalog of Historical Changes and the Geomorphic Map reveal the close correlation between the construction of man-made features and subsequent land resources loss during large floods along the Gila River in Arizona. Human factors that cause lateral instability include levee encroachment into the flood or active channel, diversion dams, and channel straightening. Vegetation and alluvial fan development may also act as controls on channel position in these reaches. The Catalog of Historical Changes shows that the majority of erosion occurs during high flow events such as the flood of October 2-3, 1983, and that channel widening is a geomorphic response to large floods. The local factors mentioned above appear to cause minimal geomorphic change during low to moderate flows but are the catalysts of substantial geomorphic change during large floods of recent decades.

STABLE CHANNEL ANALYSIS – ARIZONA

This report presents an analysis of the stability of the Gila River between the San Carlos Reservation and the lower end of the Gila Box, and between the upper end of the Gila Box and the Arizona-New Mexico state line. Stability, in an alluvial channel, according to Mackin (1948), "occurs when, over a period of time, the slope is adjusted to provide, with available discharge and the prevailing channel characteristics, the velocity required to transport sediment supplied from the drainage basin." Lane (1953) defines alluvial stability as "an unlined earth channel which carries water, the banks and bed of which are not scoured objectionably by the moving water, and in which objectionable deposits of sediment do not occur." Chien (1955) contends that "…the equilibrium state of an alluvial channel is attained by adjusting the dimensions of the cross section and the slope of the channel to the natural conditions imposed on the channel by the drainage basin."

This analysis utilizes an analytical tool named RISAD, a module of SAM, developed by the US Army Corps of Engineers, to analyze the channel roughness, sediment transport, and discharge in four reaches of the Gila River in the study area. Input into RISAD includes hydraulics produced by the HEC-RAS backwater model, bed material gradation data gathered during the Field Data Collection portion of the Upper Gila Fluvial Geomorphology study, and hydrology analyzed for this report based upon US Geological Survey stream gaging data collected at several gaging stations in the study area. The analysis uses hydrological data from water years 1965-2000.

This analysis indicates that the results of the stable channel modeling are consistent with the geometry of the Gila River in the study area. The modeling indicates that the river is moderately unstable at the effective discharge in many sub-reaches, mostly in the area downstream of Safford and upstream of Sheldon. The modeling shows that the river is stable in a few sub-reaches, mostly between York and Sheldon, possibly due to the lack of levees in this area. The instability is greatest with respect to the width and sinuosity of the stream. In general the channel has widened in response to an increase in the magnitude and frequency of floods since 1965. Without large floods in the future, the channel will narrow and may locally aggrade, similar to the 1935-1965 period.

CONCLUSIONS

This analysis indicates that the results of the stable channel modeling are consistent with the geometry of the Gila River in the study area. The modeling indicates that the river is moderately unstable at the effective discharge in many sub-reaches, mostly in the area downstream of Safford and upstream of Sheldon. The modeling shows that the river is stable in a few sub-reaches, mostly between York and Sheldon, possibly due to bed-rock controls in the area. The instability is greatest with respect to the width and sinuosity of the stream. In general the channel has widened in response to an increase in the magnitude and frequency of floods since 1965. Without large floods in the future the channel will narrow and may locally aggrade, similar to the 1935-1965 period.

Lower Reaches 1 & 2

Model results show that Lower Reach 1 and Lower Reach 2 are relatively unstable. Some sections in Lower Reach 2 might be stable. The channel in the Safford Valley is nearly the same as in 1935, the widest measured over the period of 1935-1997 (Klawon, 2001). Model results indicate that if the channel trends towards the minimum slope on the stable channel curve, Lower Reach 2 will experience the most channel narrowing. The process may include an increase in sinuosity causing widespread bank instability and retreat. Hypothetically, and separate from the stable channel analysis, a typical geomorphic response might include invasion of non-native vegetation, followed by bank encroachment and channel narrowing. The stable channel analysis indicates that Lower Reach 1 may to be overly steep. If the channel reduces its slope by increasing sinuosity, bank instability and retreat will result. However, local observations indicate that the channel may be aggrading in the reach below Fort Thomas. More modeling and geomorphic investigation is necessary to determine the channel trends in this area.

Lower Reaches 3 & 4

Model results show that both Lower Reach 3 and Lower Reach 4 are relative stable by virtue of the distribution of points about the stable channel curve. There has been significant lateral movement of the stream in several areas, due both to channel straightening projects and the river response to those and the hydrologic regime since the mid 1960's. Lower Reach 3 may undergo the most channel narrowing following invasion by non-native vegetation and bank encroachment.

Upper Reach

Model results show that most of the sections in the Upper Reach are in the degradational range of the stable channel plot. Geomorphic evidence indicates that the river is in a period of degradation following a period of aggradation. There are ample observations of that phenomenon in the Virden and Duncan areas. There are several bedrock areas and hydraulic controls that are not alluvial in nature, invalidating the stable channel analysis in those reaches.

ABSTRACTS OF STUDY REPORTS & ANALYSES

CATALOG OF HISTORICAL CHANGES – ARIZONA

The Catalog of Historical Changes documents changes in the alluvial channel of the Upper Gila River, Arizona from 1935 to 2000. The objective of the Catalog is to quantify variability in channel width during the historical period and identify reaches of high variability. Measurements of channel width made from historical aerial photography and qualitative observations of lateral migration provide the data necessary for an analysis of trends in channel behavior and lateral stability of river reaches.

DATA SOURCES

Data for this analysis derive mainly from aerial photography flown by U.S. government agencies and private aerial survey companies (Table 1). At least one aerial photograph set was acquired for each decade, with exception of the 1940s, and following extreme floods on the Gila River. The sets include photographs from 1972, 1978, 1983 and 1993. Prior to 1935, General Land Office Cadastral Land Surveys, and earlier literature reviews were used to evaluate the nature and position of the river channel. Photograph sets used for Duncan Valley include: 1935, 1953, 1958, 1967, 1978, 1978 Flood, 1981, 1992, 1997, and 2000. Photograph sets used for Safford Valley include: 1935, 1953, 1958, 1967, 1972 Flood, 1973, 1978, 1981, 1983 Flood, 1992, 1993 Flood, 1997, and 2000. In this analysis, the numbers of channel width measurements total over 2,000 for Duncan Valley and Safford Valley.

Table 1. List of Aerial Photographs.

DATE	SOURCE	SCALE
1935	Fairchild Aerial Surveys, Inc.	~1:30,000
1953	Army Map Service	1:54,000
1958	U.S. Department of Agriculture	1:20,000
1967	U.S. Department of Agriculture	1:20,000
1972	Arizona Department of Transportation	1:12,000
1973	U.S. Department of Agriculture	1:22,000
1978	Bureau of Land Management	1:24,000
1978	Natural Resources Conservation Service	1:24,000
1981	U.S. Geological Survey	1:38,000
1983	Cooper Aerial Survey	1:20,000
1983	Natural Resources Conservation Service	1:6,000
1985	Natural Resources Conservation Service	1:12,000
1992	U.S. Geological Survey	1:40,000
1993	Natural Resources Conservation Service	1:6,000
1997	U.S. Geological Survey	1:40,000
2000	Bureau of Reclamation	1:10,000

DATA COLLECTION

Measurements of channel width for the Gila River were made on the aerial photographs with a digital caliper and measured to a hundredth of a millimeter (0.01 mm), which corresponds to an actual ground distance of 0.1 m to 0.6 m (0.3 ft to 2 ft) depending on the scale of the photographs. On the large-scale photograph sets, which include year 2000 and 1983 post-flood photographs, measurements were recorded to a half-millimeter (0.02 inches) using a ruler. This corresponds to a ground distance of 2.0 m to 2.8 m (6.6 ft to 9.2 ft) for the 2000 and 1983 photographs, respectively.

Conversions to ground distance from the aerial photograph distance were made by measuring corresponding distances on USGS 7.5 minute topographic maps and aerial photographs creating conversion factors. This option was chosen because the scale of the photographs was not always known and to account for minor changes in camera position and distortion from the camera lens on the unrectified photographs. Several distances of varying lengths and orientations were measured and the average taken for the conversion factor for each set of aerial photographs. A test of precision was also conducted by measuring the same point multiple times.

Channel width measurements provide a quantitative measurement for comparison of the Gila River channel between aerial photography from different years. Channel width measurements were made approximately every kilometer (~0.6 mile) by establishing points from which a width measurement was made perpendicular to flow direction. Sixty-two measurement points were established in Safford Valley; thirty-nine points were established for Duncan Valley. For each point, not including flood photographs, two channel width measurements were made:

1. Active channel or recent flow width: that part of the channel that was being reworked by recent flows at the time the photographs were taken.
2. Flood flow width: that part of the channel that was clearly inundated by high magnitude flows. These widths appeared to be the actual channel width during floods, not the result of lateral migration. In some cases where levees were built to protect structures or land from erosion and damage, the allowable width between levees was considered the flood flow width. This measurement should be considered a minimum value, as shallow inundation may not be visible long after a flood. In some cases, plowing of fields following floods obscured the evidence of flooding. Sometimes flood flow width could be inferred from adjacent plots that had not been obscured. In the case of photographs following major floods, the actual width of inundation was measured, independent of structures in the river.

In addition, qualitative assessments of lateral change were also made by analyzing photographs for differences in channel position over the time period considered, which spans 1935 to 2000.

GENERAL TRENDS

AVERAGE WIDTH DATA: COMPARISON OF FLOOD YEARS

The 1935 channel was the widest channel recorded. From 1935 to 1967, channel width decreased, with the magnitude of change being larger for the active channel width measurements. This decrease is concurrent with a period of relatively few large floods (see Figure 2). From 1967 to 1978, channel width increased, with a spike in the 1973 flood width measurements, corresponding to the 1972 flood. From 1978 to 1997, flood channel width gradually increases in the flood width measurements and approaches the flood width of 1935. The recent flow width set had a slight decrease in width from 1981 to 1997 and was actually much wider by 1997 than the 1935 channel. Year 2000 photographs show a decrease in average recent flow width from that of 1997 for both flood flow and recent flow widths.

The average width data for Duncan Valley show similar trends to that of Safford Valley. From 1935 to 1958, there was a general decrease in both recent flow channel width and flood width, especially from 1953 to 1958. This decrease followed a period of fewer and smaller magnitude floods. From 1958 to 1981, channel width increased, most likely due to the 1965, 1972 and 1978 floods in Duncan Valley. From 1981 to 1992, widths decreased slightly for the recent flows and increased for the flood flows, the latter of which may be associated with the 1984 flood, which is the second largest peak in the record at the Gila River near Clifton gaging station. From 1992 to 1997, average flood width appears to have remained constant and reached the average flood width of 1935 measurements in 2000. Recent flow width increased from 1992 to 2000.

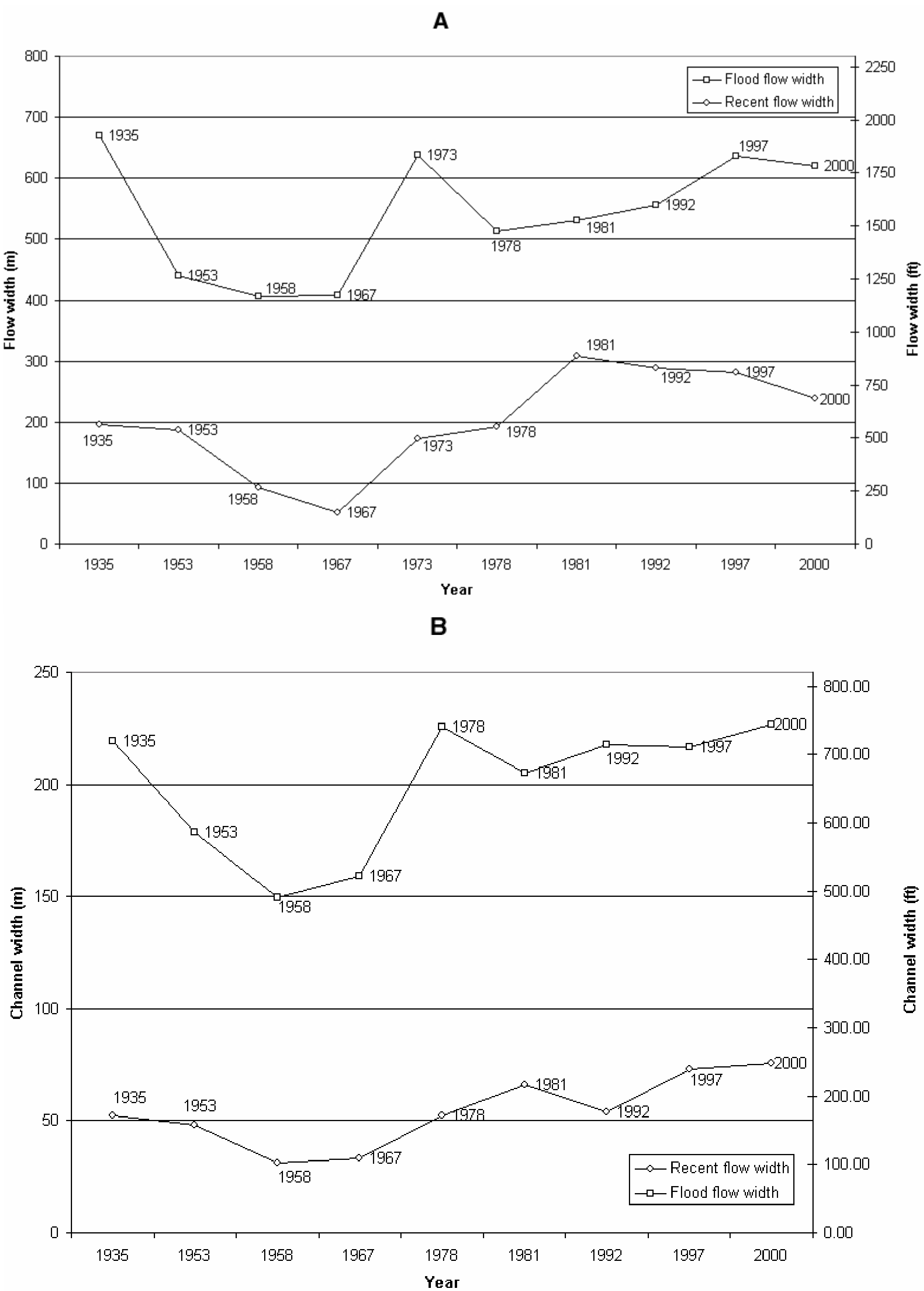


Figure 2. Average width by year in A. Safford Valley; B. Duncan Valley.

PHOTOGRAPH YEAR COMPARISON

ANALYSIS OF CHANNEL CHANGES

The statistical analysis of channel change identifies the reaches of greatest variability in flood channel width and also those of intermediate and small variability over the period measured (Figure 3). The standard deviation of the widths for all non-flood years at each measurement point was compared relative to other points so that reaches with high variability could be identified. This analysis only includes results for the flood width measurements, although the same could be performed for active channel width measurements. Flood width measurements appear to be the more important variable to analyze, as these are the measurements that reflect the greatest change in the river system.

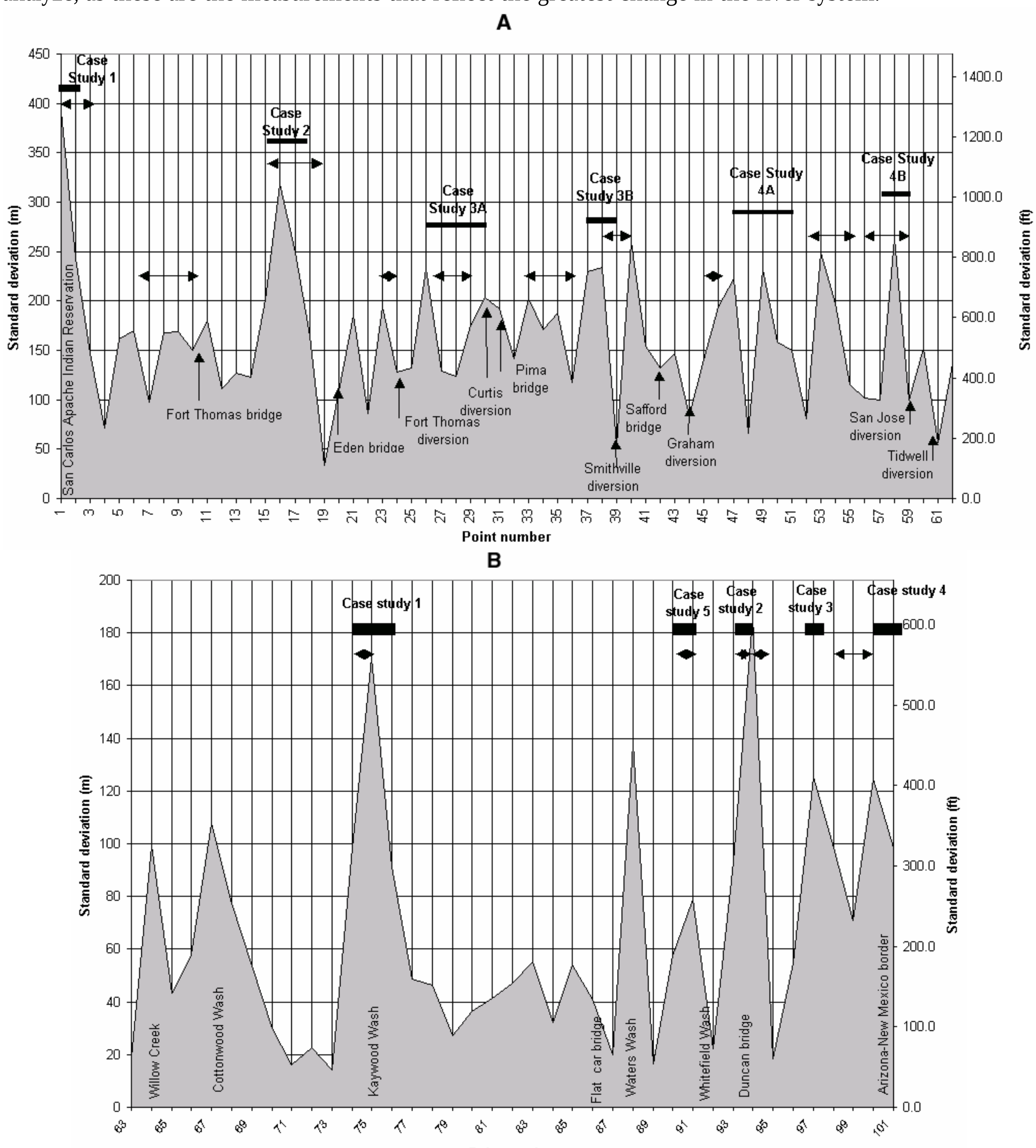


Figure 3.Standard deviation of channel widths measured at each point in A.) Safford Valley and, B.) Duncan Valley.

Low points of the curve in Figure 3 reflect low variance in flood width measurements, while high points reflect high variance in flood width measurements. The information contained on this chart does not correspond to narrow or wide points in the channel, but rather those points that experienced very little change in width and those points in the channel that experienced a high variability in width over the period measured. Several Case Studies were made in the reaches of greatest variability.

Reaches of high variability are more numerous in Safford Valley than in Duncan Valley. In Duncan Valley, the reaches of smallest variability are much longer than any reaches that have high variance. This suggests that channel change in Duncan Valley has been minimal with the exception of a few select reaches. Qualitative information gathered by evaluating photograph sets prior to measurement confirms the nature of channel behavior in reaches of great variability and also those of small variability.

CASE STUDIES

In the Catalog of Historical Changes, reaches with high variability in channel width were selected as case studies to illustrate the types of changes that occurred along the Gila River channel during the historical period. Two case studies are included in this document

CASE STUDY 5: WHITEFIELD WASH LEVEES

This reach is generally similar throughout most of the period of record, but exhibits major channel changes between 1992 and 1997 (Figure 4 and Figure 5). The 1935 channel exhibited more sinuous channel morphology, but was generally similar to subsequent years. This difference is most likely due to the construction of levees in 1953, which forced the channel to conform to a particular pattern. This pattern persisted through 1981, where levees were constructed in a slightly different arrangement and with greater length. This was probably in response to the 1978 flood, in which inundation is apparent behind the levees on reoccupied farmland on the 1981 photograph set. The 1992 channel had a similar configuration, although some levees had been eroded in the intervening years. In 1997, the left bank levee had been eroded where it was built up after the 1978 flood, and a new right bank meander cut into the floodplain that was previously a part of the flood width in 1935. In sum, although a seemingly new channel was created, high flows between 1992 and 1997 cut into areas that were previously part of the inundation area.

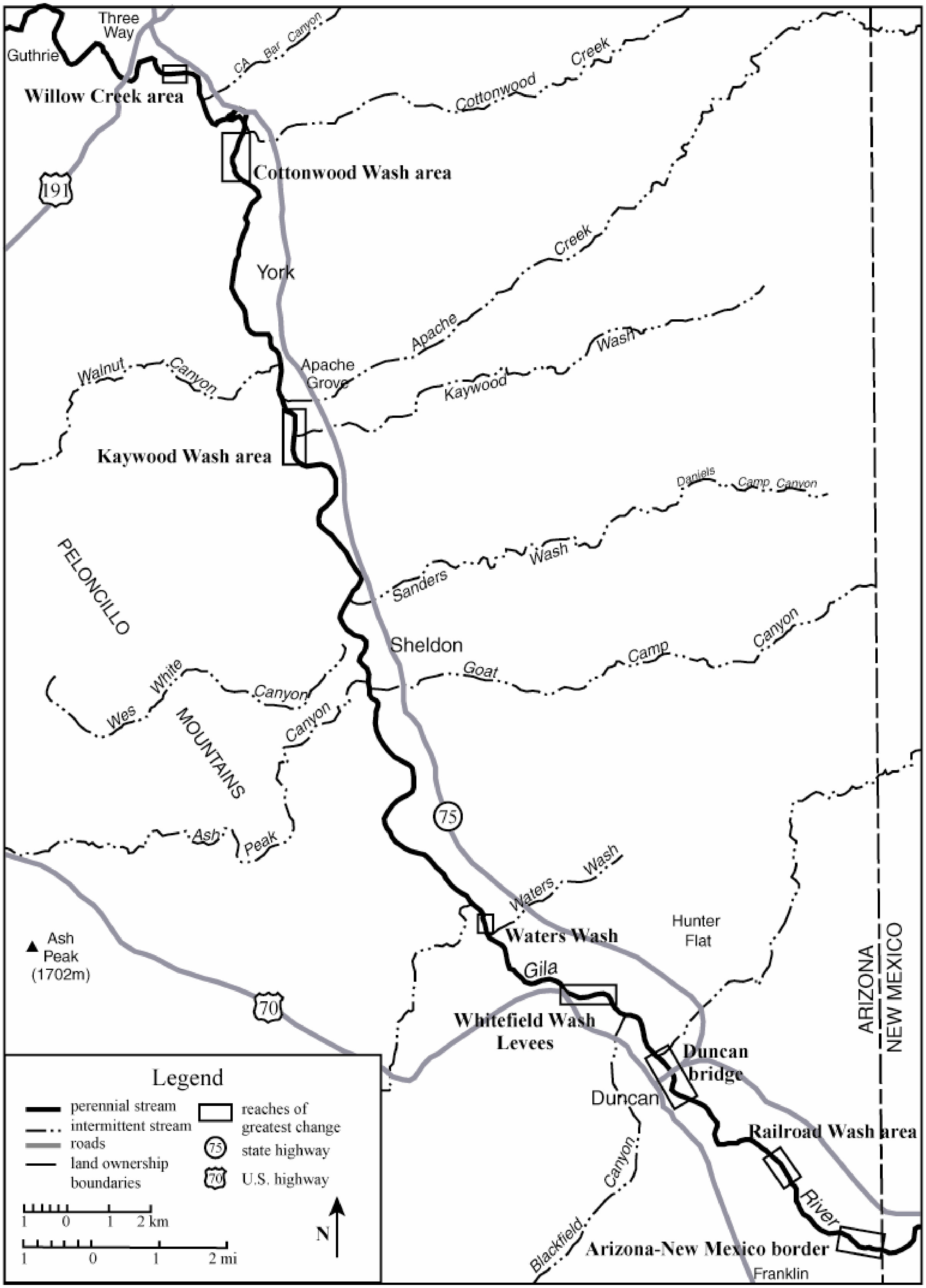
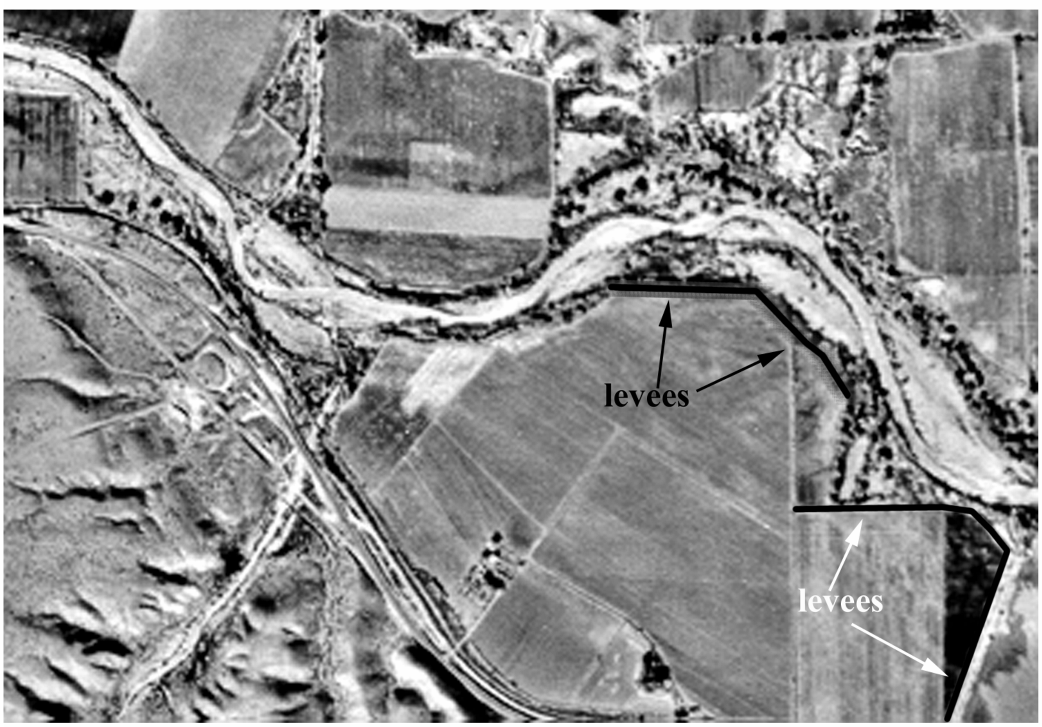


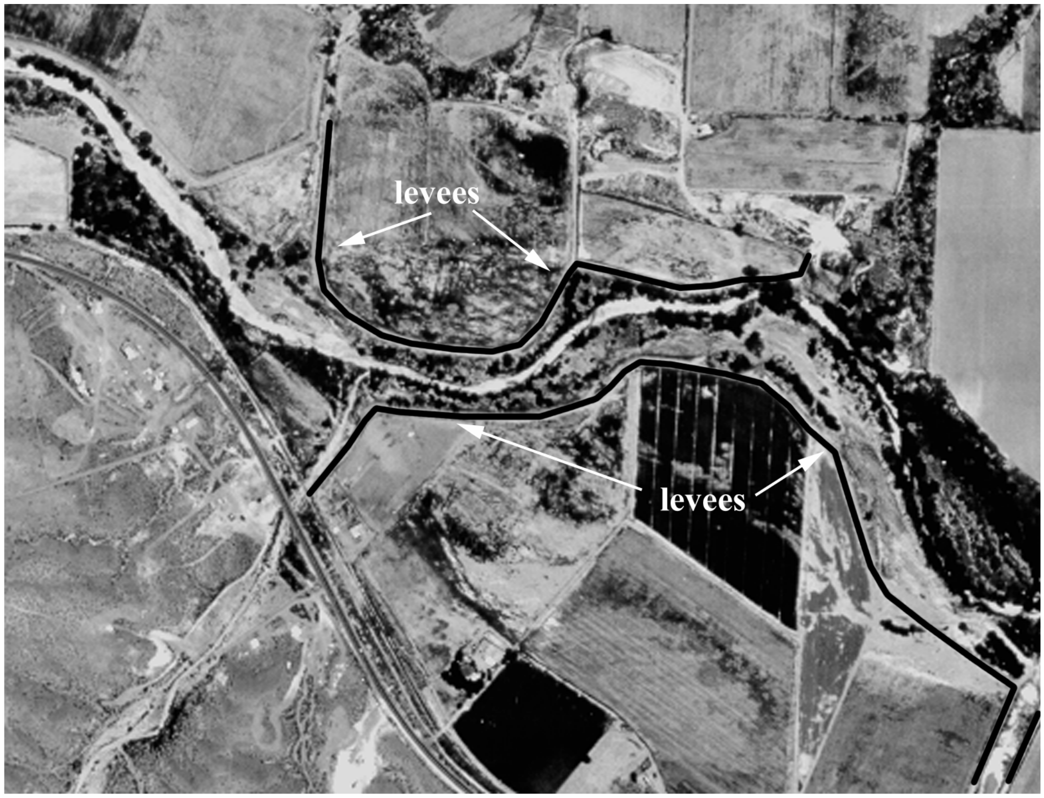
Figure 4. Reaches of greatest change: Duncan Valley indicated by the boxed in reaches of the Gila River.

(a) 1935

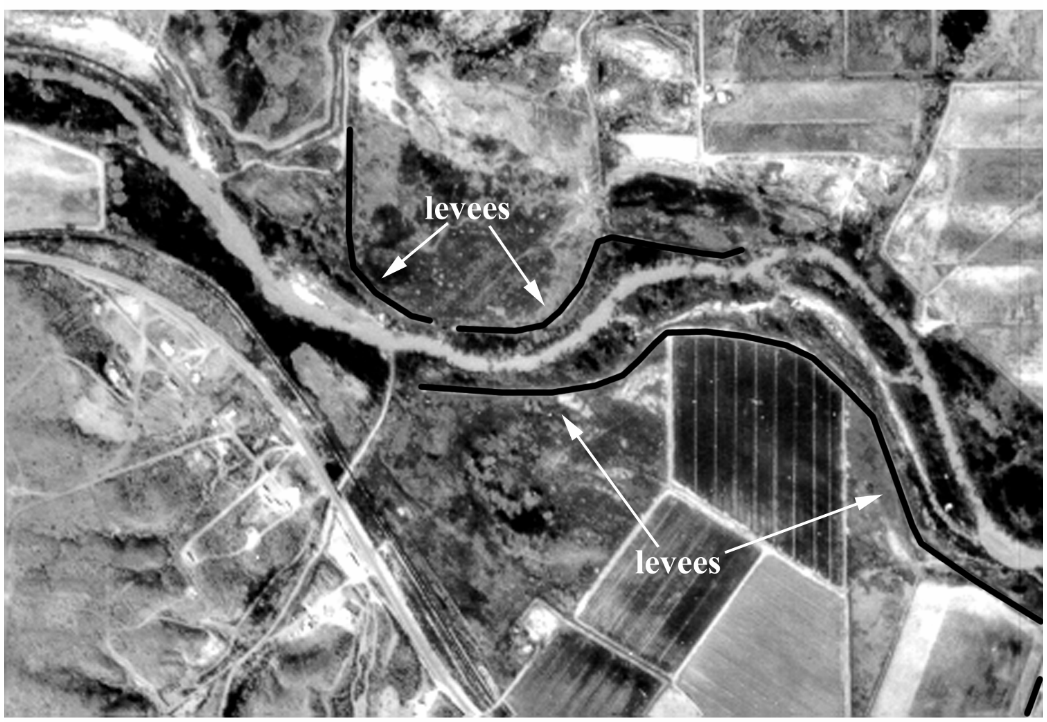


(b) 1953

Figure 5. Case Study 5: Whitefield Wash levees. Levees imposed on the left bank caused changes in channel morphology from (a) 1935 to (b) 1953. Flow is from right to left.



(c) 1981



(d) 1992

Figure 5 (cont.) (c) Additional levees constructed by 1981 on the right and left banks imposed further restrictions on the channel and by (d) 1992, some of these levees had been eroded and not replaced. The majority of the erosion probably occurred during the 1984 flood. Flow is from right to left.

(e) 1997

Figure 5 (cont.) (e) In 1997, the majority of the left bank levee and parts of the right bank levee had been eroded and a new right bank meander had been cut into the floodplain that was previously part of the flood channel in 1935. Flow is from right to left.

CASE STUDY 1: NEAR THE SAN CARLOS RESERVATION

The overall channel pattern in this reach over the period of study is similar; however, channel narrowing and widening appears to be related to levees in the study reach (Figure 6 and Figure 7). The 1935 channel was the widest channel recorded in the period of measurement. By 1953, the channel has narrowed by approximately 25%. By 1997, the channel pattern had changed dramatically to a more sinuous channel with nearly 90-degree bends from bank to bank. This pattern is associated with erosion into right and left bank levees and channel modification.

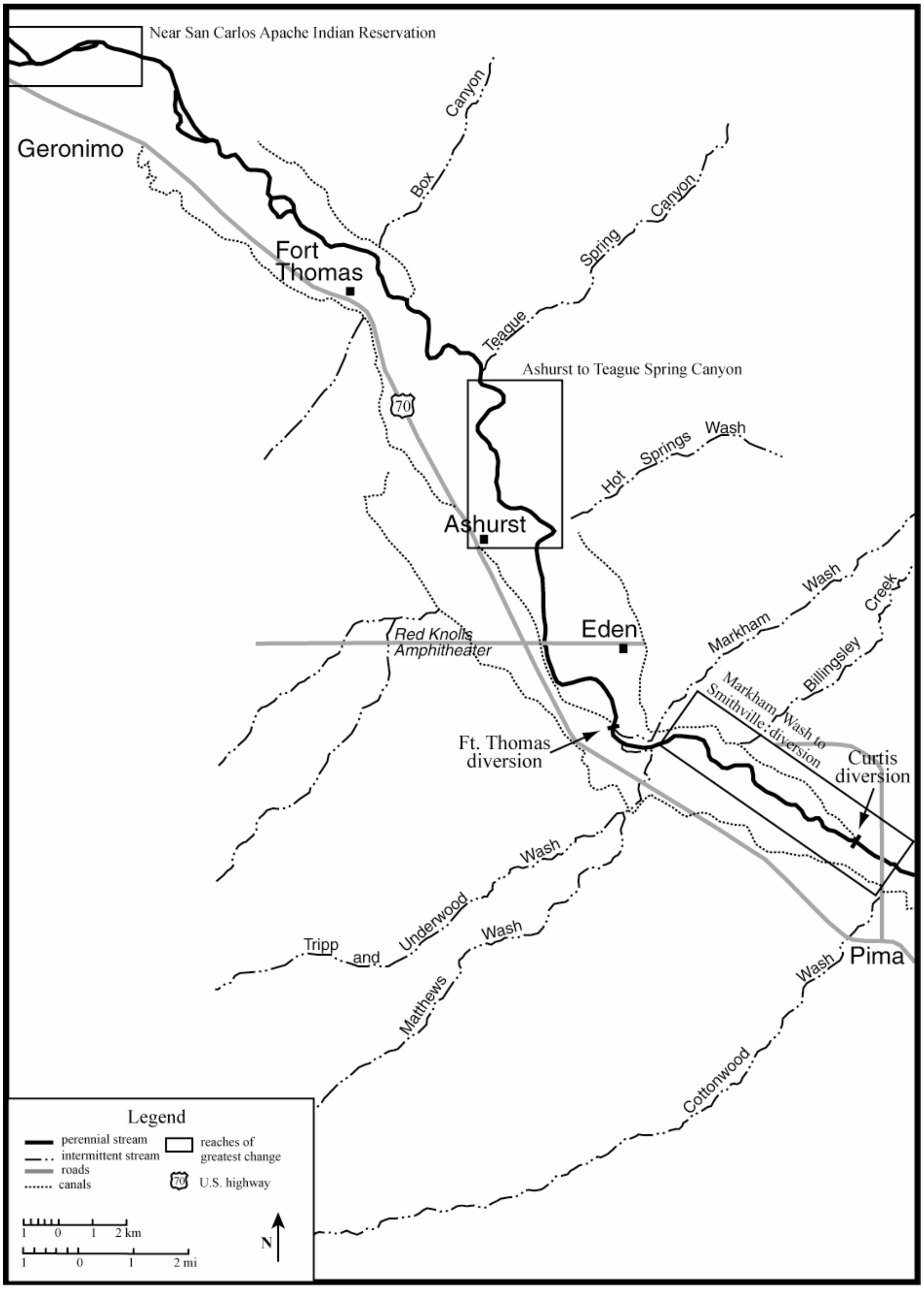
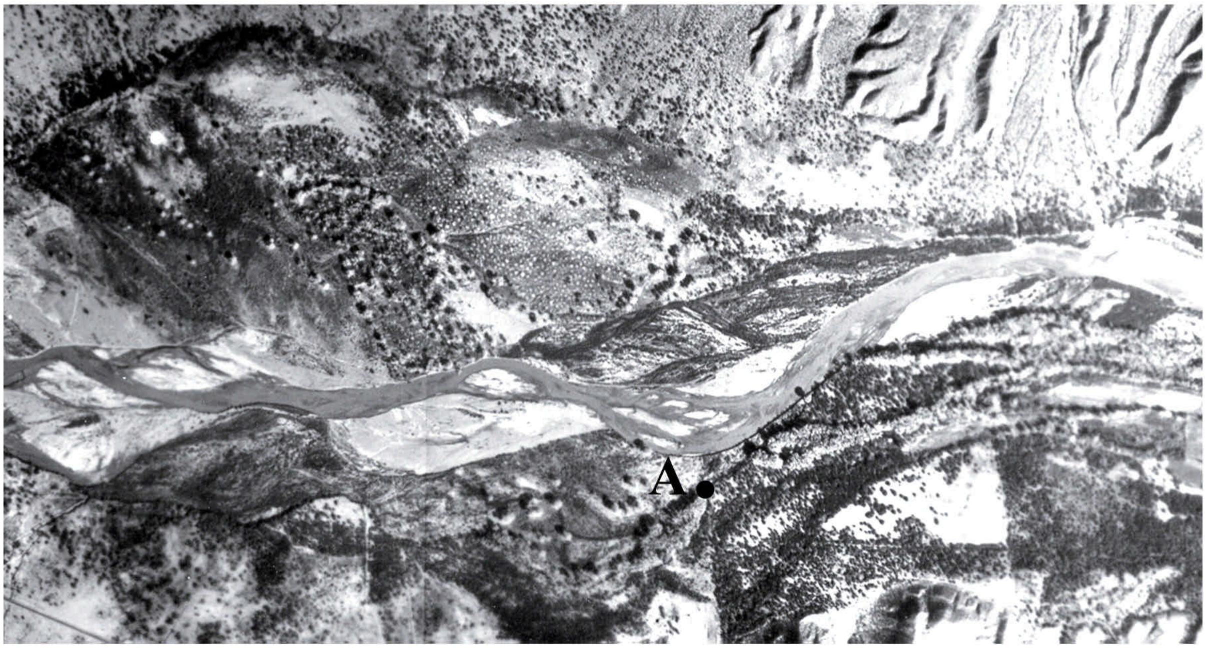


Figure 6. Location figure showing reaches of high variability, including the reach near the San Carlos Reservation.



(a) 1935

(b) 1953

Figure 7.Case Study 1: Near San Carlos Reservation. From (a) 1935 to (b) 1953, channel width had decreased significantly in the study reach. See point A for reference. Flow is right to left.

(c) 1967

(d) 1978

Figure 7 (cont.) Levees built at A in (c) 1967 further restrict the channel; by (d) 1978, these levees have disappeared.

(e) 1992

(f) 1997

Figure 7. (cont.) By (e) 1992, the Gila River channel had reoccupied the left bank channel downstream of point A. By (f) 1997, the channel pattern had changed dramatically to a more sinuous channel with nearly 90-degree bends from bank to bank. This pattern is associated with erosion into right and left bank levees and channel modification. Flow is from right to left.

CONCLUSIONS

General trends in channel changes from this study parallel those described by Burkham (1972). The early 1900's experienced several extreme floods, causing channel widening to 1935 (Olmstead, 1919; Burkham, 1972). This early information was gathered for Safford Valley and may or may not apply to Duncan Valley. From 1935 to the early 1960's, the channel narrowed by sedimentation, vegetation growth, and levee, dike, and agricultural development. From the late 1960's to 2000, the channel widened in response to large floods and is approximately the same width on average as it was in 1935. In most cases, flood flow widths at specific channel locations are variable, but not unprecedented in the historical record.

This study has shown that although high variability exists in channel width and position in both Safford Valley and Duncan Valley, many channel positions are not new and channel widths are similar or smaller than 1935 channel widths for the Gila River during the period of study. In many of the case studies, the channel simply reoccupied old channel positions from earlier in the historical period. Average flood widths also show that by 2000, the river channel had reached an average flood width similar to the 1935 average flood width. Some channel changes; however, in recent decades do seem to be unprecedented in the period of study. Examples of such cases include the channel changes near Whitefield Wash, where erosion between 1992 and 1997 caused lateral migration of the left and right banks and greatly increased the sinuosity in the reach. Another dramatic area of channel change occurs downstream of the San Jose Diversion, where lateral movement of the channel toward the right bank has been observed on photograph years of 1981, 1992 and 1997.

The impact of floods on the Gila River channel is evident based on corresponding large channel changes following flood years. In Duncan Valley, the most changes in flood width occurred following the 1978 flood and the floods in the 1990's. In Safford Valley, changes occurred following the 1972, 1983, and 1993 floods. The analysis of change using flood flow widths for Duncan Valley and Safford Valley show that Safford Valley has experienced many more perturbations in the period of study than Duncan Valley. This is shown best by the presence of several long, stable reaches in Duncan Valley, compared to a few short stable reaches in Safford Valley. Major channel changes generally occurred following large floods; this highlights the important point that the largest floods in the Gila River system have lasting effects that can be observed in channel morphology for decades following their occurrence.

FLOOD FREQUENCY AND FLOW DURATION ANALYSES

This report summarizes flood frequency and flow duration for sites within the Gila River basin from approximately the Arizona-New Mexico State line to San Carlos Reservoir. These estimates were completed as part of Task 9 of the Upper Gila River Fluvial Geomorphology Study. The primary bases for the flood frequency and flow duration estimates are U.S. Geological Survey peak discharge and mean daily flow records. The data and results presented herein are appropriate for detailed hydraulic and geomorphic studies and analyses.

The Upper Gila River basin is located in the southeast corner of Arizona and southwestern New Mexico. The area in Arizona is called the Central Highlands physiographic province. Within the study area, the river flows generally westward from its headwaters in the Gila Wilderness area in Grand County, New Mexico to the San Carlos Indian Reservation. The main tributaries in New Mexico enter the Gila River upstream of Cliff, New Mexico. The major tributaries in Arizona upstream of Coolidge Dam are the San Francisco River, Eagle Creek, Bonita Creek, and the San Carlos River, which drain from the mountains on the north side of the basin, and the San Simon River, which drains from the south. Elevations in the drainage basin range from 5,650 feet at the eastern boundary of the study area (San Carlos Indian Reservation) to 11,000 feet in the mountains of the Gila Wilderness area.

The U.S. Geological Survey has published stream flow records from many gaging stations located in the Gila River basin upstream from San Carlos Reservoir into New Mexico (e.g., Pope et al., 1998). There are many active gaging stations in the Upper Gila River. This study focuses on using data from long-term gaging stations located on the Gila and San Francisco Rivers. A list of basin, flood and climatic characteristics for these sites are presented in Pope et al. (1998). A brief summary is listed in Table 2.

There are two main objectives of this study: (1) estimate flood peak frequencies; and (2) estimate flow durations at selected locations within the Upper Gila River basin, for application in subsequent fluvial geomorphic and hydraulic analyses.

Table 2. Basin characteristics for long-term gaging stations in the Upper Gila River Basin.

USGS Gaging Station Name	Gila River below Blue Creek near Virden, NM	Gila River near Clifton, AZ	San Francisco River at Clifton, AZ	Gila River at head of Safford Valley near Solomon, AZ	Gila River at Calva, AZ
USGS Gaging Station No	09432000	09442000	09444500	09448500	09466500
Drainage Area	3,203 mi^2	4,010 mi^2	2,766 mi^2	7,896 mi^2	11,470 mi^2
Latitude	32°38’53”	32°57’57”	33°02’58”	32°52’06”	33°11’08”
Longitude	108°50’43”	108°18’35”	109°17’43”	109°30’30”	110°13’10”
Mean Basin Elevation	6,690 ft.	6,250 ft.	6,880 ft.	6,360 ft.	5,650 ft.
Mean Annual Precipitation	16.2 in.	15.4 in.	18.1 in.	16.7 in.	15.5 in.
24-hour, 2 day precipitation	1.6 in.	1.6 in.	1.6 in.	1.7 in.	1.7 in.

STREAMFLOW DATA SOURCES AND DISCUSSION

The precipitation source for eastern Arizona and western New Mexico, including the Upper Gila River basin, is from prevailing westerly Pacific moisture, subtropical Pacific moisture, and some Gulf and subtropical Atlantic moisture (Brazel, 1991). Annual precipitation in the Central Highlands province ranges from about 15 to 30 inches. Major storms that result in heavy precipitation and large-magnitude flooding in the Gila River basin usually occur in the fall and winter (October through March). These storms are generally cold frontal systems colliding with warm, moist air or tropical storms (Brazel, 1991; Hirschboeck, 1985). Extreme flood-producing storms are widespread and generally cover the majority of the Gila basin, including many western tributaries such as the Salt and Verde Rivers (e.g., Aldridge and Hales, 1984). River basin drainage area, elevation and mean annual precipitation are the most significant physical characteristics for estimating floods. In this study, stream flow data are used to estimate flood magnitude and frequency.

STREAMFLOW DATA

Three data sources from the U.S. Geological Survey were used to characterize stream flow in the Gila River basin:

- Annual peak discharge estimates at gaging stations;
- Daily mean discharge estimates at gaging stations; and
- Qualitative information from USGS Water-Supply Papers and other reports.

Stream flow data from five gaging stations were used for peak discharge frequency and flow duration analyses. The period of record and largest flood at each site are summarized in Table 3.

Table 3. US Geological Survey stream flow gaging stations utilized in this study.

USGS Gaging Station No.	Station Name	Drainage Area	Period of Record (Water Years)	Maximum Discharge and Date
09432000	Gila River below Blue Creek near Virden, NM	3,203 mi^2	1927-1997, 1999	58,700 ft^3/s 12/19/1978
09442000	Gila River near Clifton, AZ	4,010 mi^2	1911-1917, 1928-1946, 1948-1999	57,000 ft^3/s 12/19/1978
09444500	San Francisco River at Clifton, AZ	2,766 mi^2	1891, 1905-1907, 1911-1999	90,900 ft^3/s 10/02/1983
09448500	Gila River at head of Safford Valley near Solomon, AZ	7,896 mi^2	1914-1999	132,000 ft^3/s 10/02/1983
09466500	Gila River at Calva, AZ	11,470 mi^2	1916, 1930-1999	150,000 ft^3/s 10/03/1983

The U.S. Geological Survey has been collecting stream flow data in Arizona and the Gila River basin since the early 1900s. Arizona stream flow records prior to 1954 are summarized in Smith and Heckler (1955). Since that time, records have been summarized in Water-Supply Papers and are now listed in annual Water Resources Data reports and summaries (e.g., Pope et al., 1998). Peak and mean daily discharge estimates for the Gila River basin gages listed in Table 3 are obtained from these sources. These sources indicate that there are major gaps in stream gaging in the Gila River basin through about 1927. Records are particularly fragmentary in the basin prior to about 1910. Historical information (discussed below) is used to supplement peak discharge estimates and extend record lengths.

The largest observed floods in the gaging station records in the Upper Gila River basin, in terms of instantaneous peak discharge, occurred in December 1978 and October 1983. These storms and floods are documented in Aldridge and Hales (1984), Roeske et al. (1989) and Hjalmarson (1990). The December 18-20, 1978 flood on the Gila River upstream of the San Francisco River had its source area in the wilderness area in New Mexico and in mountainous areas between Wilderness and Cliff, New Mexico. A persistent series of low-pressure centers off the southwest coast of California caused the flood (Aldridge and Hales, 1984). The estimated recurrence interval for this flood was greater than 100 years. Precipitation from the storm of September 27-October 3, 1983 was the result of the interaction of a high-altitude, low-pressure trough with moist tropical air. On September 30, tropical Storm Octave arrived and brought additional moisture to the region. The most intense rainfall occurred on October 1 with most stations recording more than 2 inches of rain; a total maximum of 11 inches fell during the 7-day storm period (Roeske et al., 1989). Several gages set records for volume of runoff and peak discharge magnitude (Table 3). Many other major floods have been documented in the Upper Gila River basin, including water years 1891, 1905, 1906, 1907, 1906, 1915, 1916, 1941, 1966 and 1973. The floods are summarized in Burkham (1970); data are provided in Pope et al. (1998).

HISTORICAL FLOOD DATA

There is a relative abundance of readily available information that documents historical (pre-gaging station) flooding, and periods of no flooding, in the Gila River basin. The major sources of historical information and data used in this report were obtained from Olmstead (1919), Smith and Heckler (1955), Burkham (1970), Aldridge and Hales (1984), and Hjalmarson (1990). The historical information in the Gila River basin, which includes large floods outside the period of record, helps to extend the record length, and place extreme floods within the record in their proper context. A longer record provides more assurance for peak discharge probability model selection and reduced variance of estimated quantiles.

Censored data methods (e.g., Cohn et al., 1997; England, 1998) were used to ‘fill in’ unobserved peak discharge estimates for the five stations in the Gila River basin (Table 3). In this context, the term ‘censored data’ means that some observations are missing or unknown. Instead of estimating a peak discharge for each of the unobserved floods at the five sites, data and information were analyzed to document that the unobserved (unmeasured) peak discharges were ‘less than’ or did not exceed some level. This level for each gaging station is called a discharge threshold.

The historical information and data indicate large floods occurred in the basin in water years 1833, 1869, 1884, 1891, 1905, 1906, 1907, and 1916. Storm summaries for many of these floods and others are in Durrenberger and Ingram (1978). Unfortunately, knowledge of historical information is inconsistent throughout the basin. There is good information in and near the Safford Valley; some data indicate the historical record extends back to 1861. However, there is little information to document large floods and the lack of floods in the Gila basin upstream from the San Francisco River (Aldridge and Hales, 1984). In addition, some of the information is conflicting in terms of flood occurrence and ranking. There are also discrepancies in peak discharge estimates for the historical floods in water years 1891, 1905, 1906, 1907, and 1916. These discrepancies were unable to be resolved for this study. Data as published in Pope et al. (1998) were used for peak discharge estimates. Interpretations were made from information presented in Aldridge and Hales (1984, pp. 19-21) and from Pope et al. (1998) to determine: (1) the length of the historical period; (2) a discharge threshold; and (3) number of floods exceeding the threshold.

The data for the historical period at each site are summarized in Table 4. Three types of data are typically presented in the U.S. Geological Survey reports: (1) dates, stages and sometimes discharges of observed floods prior to the gaging station period of record; (2) a large flood during the period of record that is known to be the ‘maximum stage and discharge since at least’ some historic date; and (3) a large flood during the period of record that is known to be the ‘maximum stage and discharge since’ some historic date. The information provided in (2) and (3) sometimes only refers to either stage or discharge, depending on the observation or estimate made. In addition, there is a very subtle difference between the information provided in (2) and (3). Data provided as (2) indicate one does not have information on any flood discharges or stages prior to the date stated. One does have knowledge of a flood in the historical year stated in (3). The information for cases (1) and (3) is typically stored in electronic format in the U.S. Geological Survey NWIS database. The data are generally summarized in two columns: discharge codes, where a '7' indicates that the discharge is a historic peak, and a 'highest since' column, where the historic year is listed. These data need to be evaluated on an individual basis to estimate the historical period *h* and discharge threshold Q_o.

The estimates for each station were derived based on the available data and information in the basin. Peak discharge time series including historical data for each gage are shown in Figure 8 through Figure 12. Because it was known when large floods occurred, the historical period at most sites was started one year after a major flood if the magnitude of that flood was unknown. For example, the 1942 flood on the Gila River near Virden was known to be *the largest since* 1891 (Pope et al., 1998 p. 243). Because the 1891 flood magnitude was unknown, the historical period was started in 1892. This was also done for the Gila River gages near Clifton, near Solomon, and at Calva. Discharge threshold levels were estimated directly from the discharge associated with historical information listed in Pope et al. (1998). For example, the 12/03/1906 flood on the San Francisco River (70,000 ft^3/s) was known to be the largest since 1870; this discharge was selected as the discharge threshold (Figure 10).

Based on the information and interpretations presented above, the historical flood observation period for the Gila River basin commences in 1870 to 1907, depending on the gage. It is assumed that unobserved floods in this time period were lower in magnitude than the discharge threshold at each site. Currently, there is insufficient flood data in this basin (less than 130 years) to reliably estimate extreme flood probabilities greater than about 1 in 200.

Table 4. Historical data summary for long-term gaging stations in the Upper Gila River Basin.

USGS Gaging Station Name	Gila River below Blue Creek near Virden, NM	Gila River near Clifton, AZ	San Francisco River at Clifton, AZ	Gila River at head of Safford Valley near Solomon, AZ	Gila River at Calva, AZ
USGS Gaging Station No	09432000	09442000	09444500	09448500	09466500
Systematic Record Length (s)	72 years	78 years	93 years	86 years	71 years
Historical Record Length (h)	35 years (1892-1926)	30 years (1892-1947)	37 years (1870-1910)	7 years (1907-1913)	23 years (1907-1929)
Total Record Length (n)	107 years	108 years	130 years	93 years	94 years
Discharge Threshold (Q_o)	41,700 ft^3/s (09/29/1941 peak)	33,000 ft^3/s (10/21/1972 peak)	70,000 ft^3/s (12/03/1906 peak)	100,000 ft^3/s (09/29/1941 peak)	100,000 ft^3/s (09/29/1941 peak)
Number of Floods Equaling or Exceeding Q_o	2	4	2	3	4

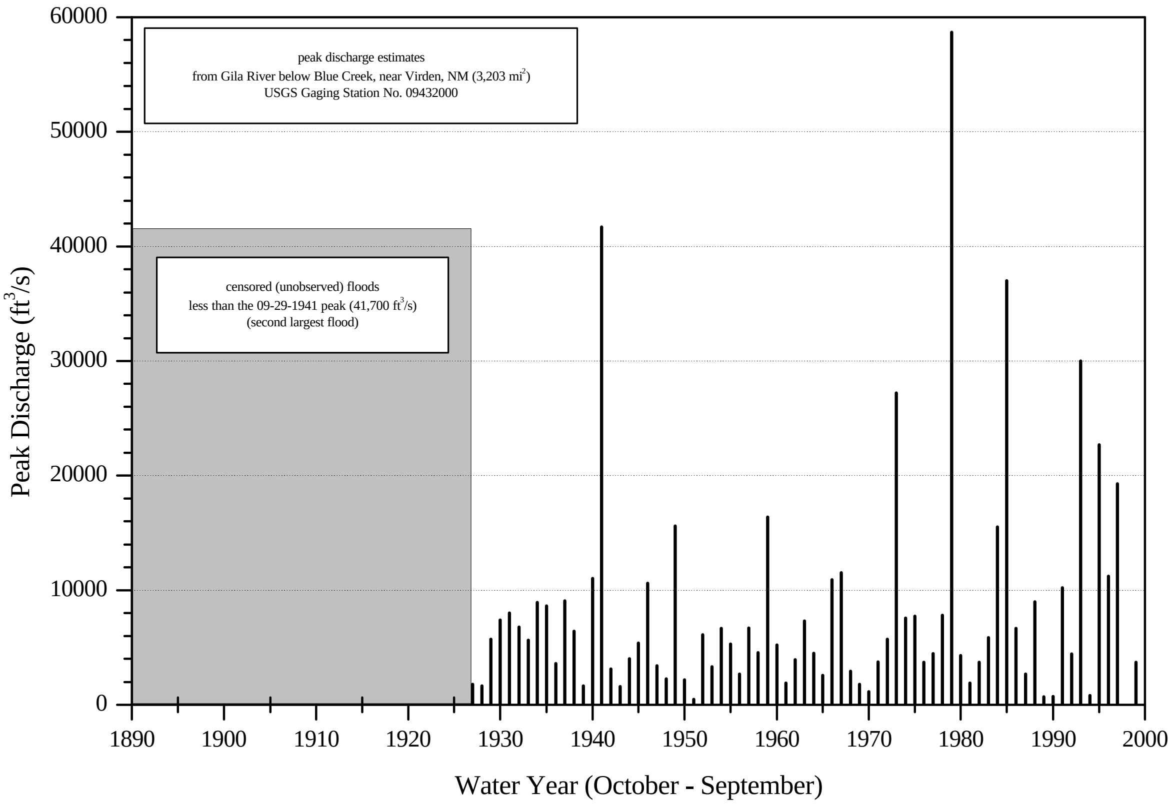


Figure 8. Peak discharge time series for the Gila River below Blue Creek near Virden, NM

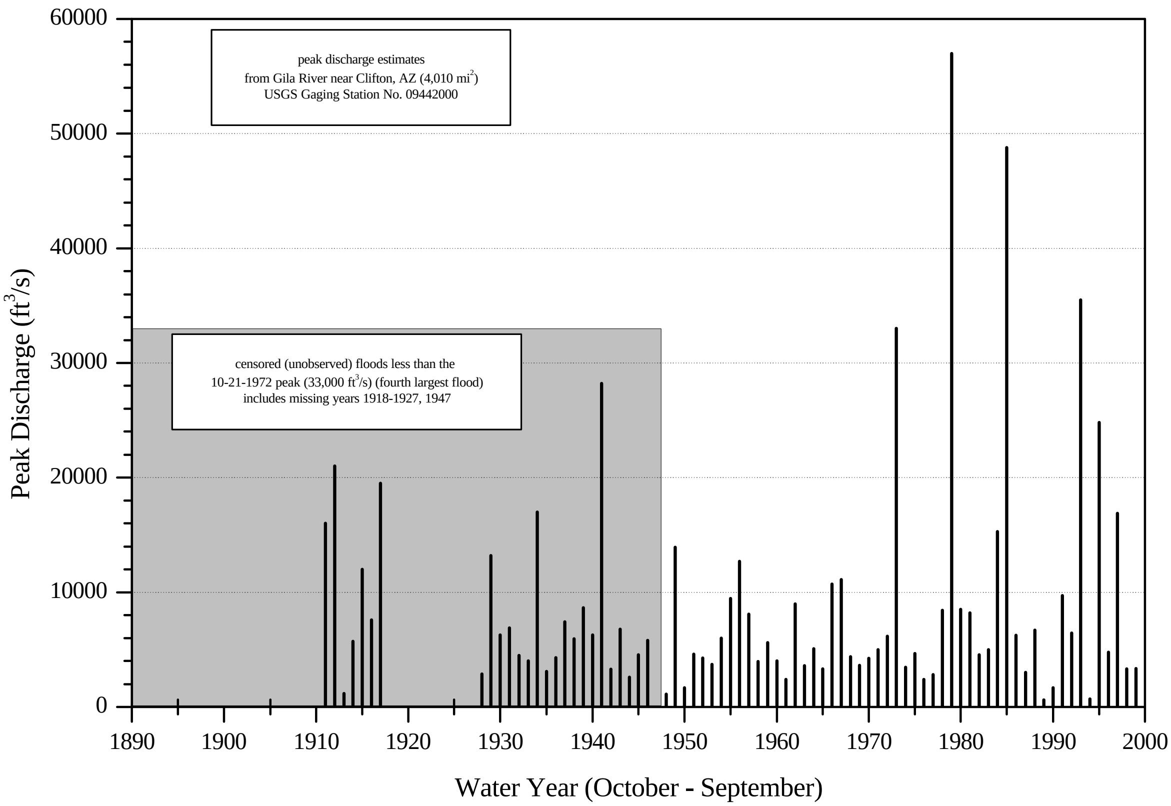


Figure 9. Peak discharge time series for the Gila River near Clifton, AZ.

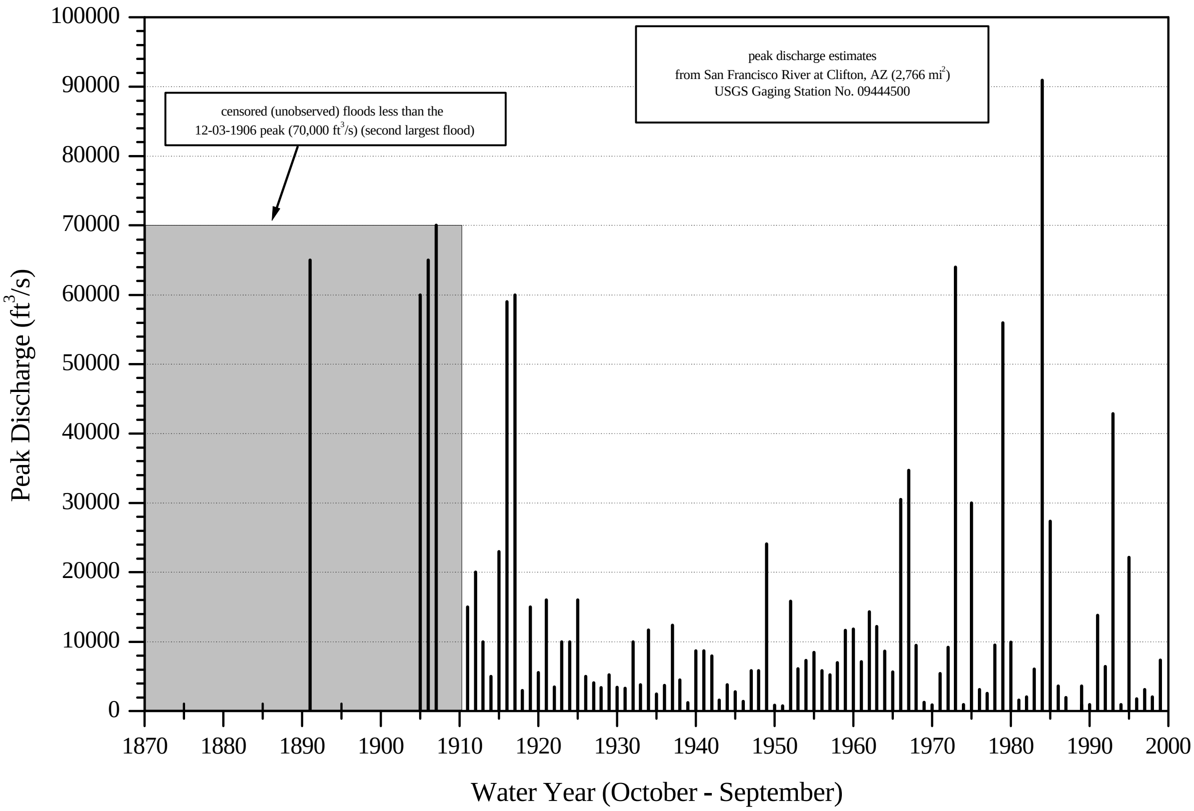


Figure 10. Peak discharge time series for the San Francisco River at Clifton, AZ.

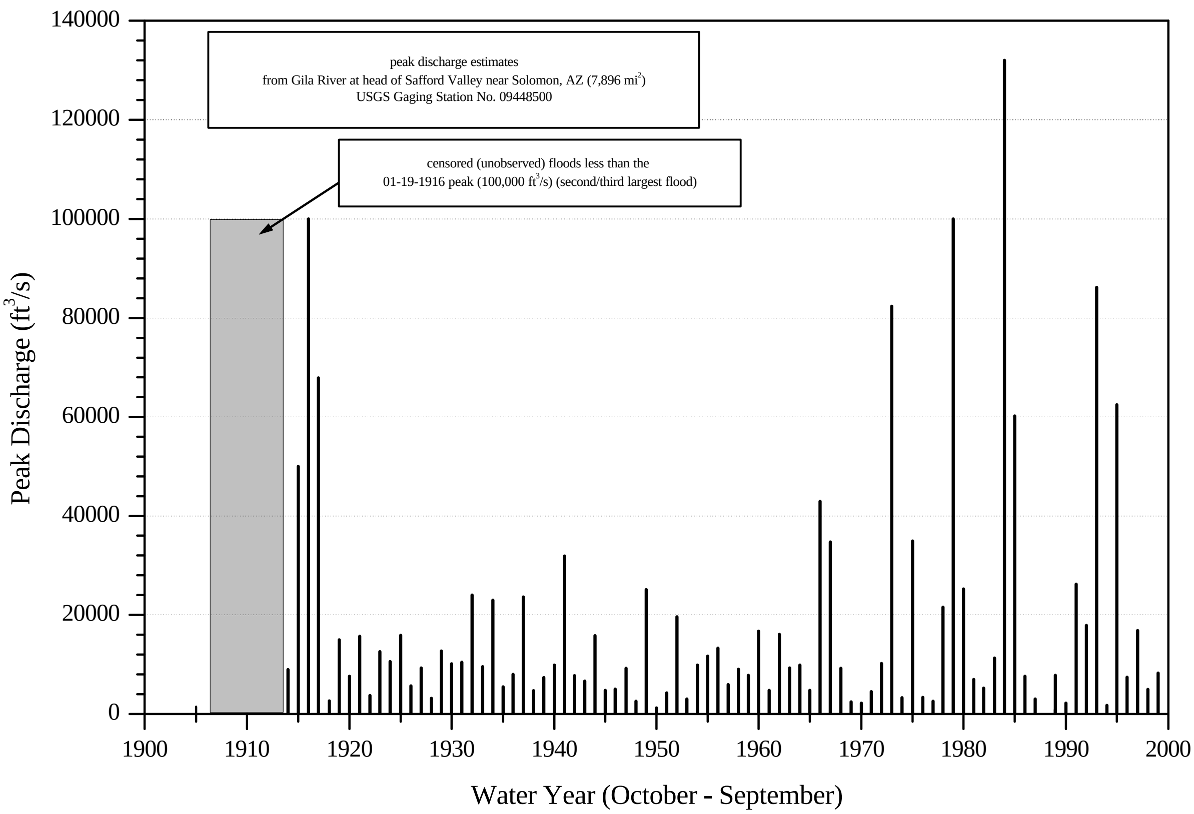


Figure 11. Peak discharge time series for the Gila River at the head of Safford Valley near Solomon, AZ.

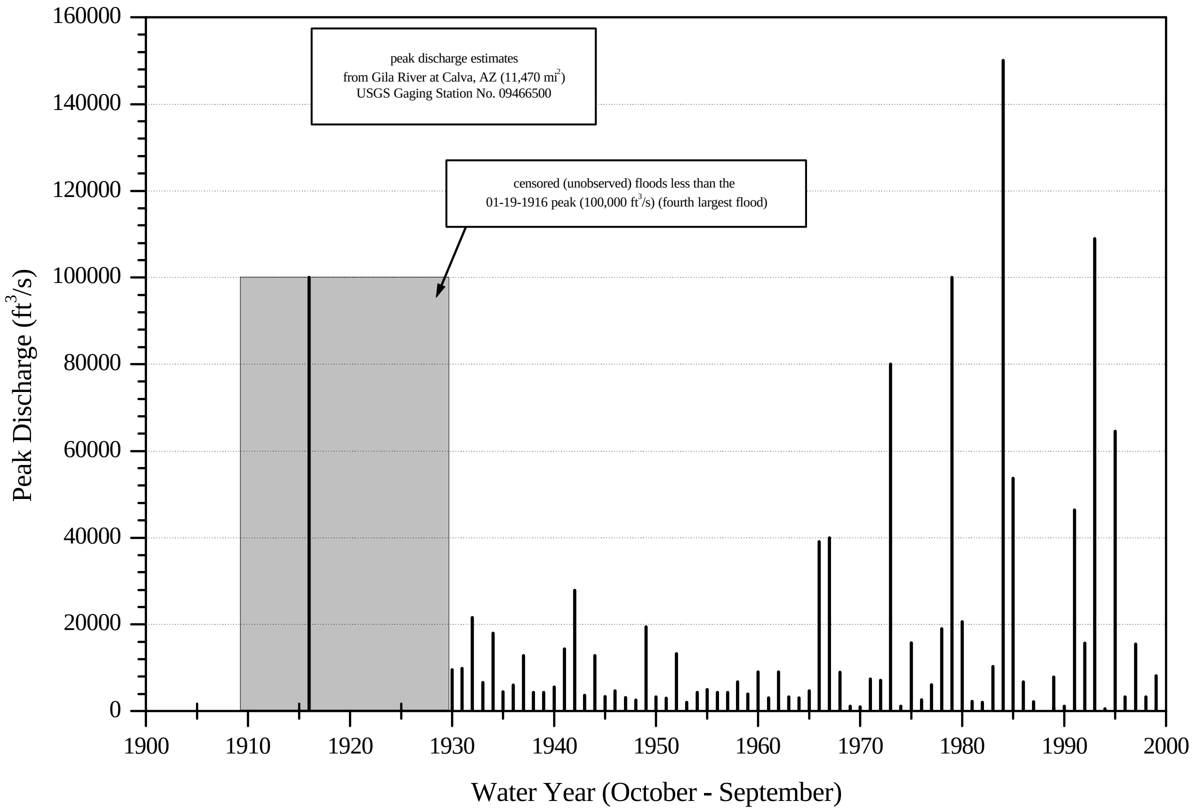


Figure 12. Peak discharge time series for the Gila River at Calva, AZ.

HYDROLOGIC ANALYSIS METHODS

Two analysis techniques were utilized for the Upper Gila River fluvial geomorphology study: (1) frequency analysis of flood peak discharge estimates at a site; and (2) mean daily flow-duration estimates. In the context of the Upper Gila River fluvial geomorphology study, peak flow frequency estimates can be used for estimating stream bed shear stress and stream power (e.g., Costa and O'Connor, 1995). Flow-duration curves can be used to infer median river flow in a 'typical' or 'hypothetical' year, determine instream flow requirements for habitat (e.g., Milhous et al., 1990), or estimate effective discharge (e.g., FISRWG, 1998).

FLOOD FREQUENCY

Flood frequency estimates were made for three variables: annual instantaneous peak discharge estimates, annual maximum mean daily flows, and annual maximum 3-day mean flows. The data were assumed to follow a log-Pearson Type III (LP-III) distribution. The method of moments was used to estimate the LP-III parameters for peak discharge estimates using Expected Moments Algorithm (EMA) techniques (Cohn et al., 1997; England, 1999). The EMA procedure is an alternate method to IACWD (1982) for treating historical peak discharge information. Cohn et al. (1997) and England (1998) showed that the EMA estimator is an improvement over IACWD historical procedures. Confidence intervals were estimated using the approach in Cohn et al. (2001). Because the record lengths were long, no skew weighting was performed. At-site estimates of the station skewness coefficients were used in the analysis.

As discussed above, peak discharge data utilized to estimate flood frequency consist of annual peaks and historical data shown in Figure 8 through Figure 12. The data are sufficient to define flood frequency relations to the 1 in 100 annual exceedance probability (100-year flood); the model and confidence intervals are tentatively extrapolated to 1 in 200.

FLOW DURATION

Mosley and McKerchar (1993, p. 8.27) provide a definition for flow duration: "A flow-duration curve (FDC) plots cumulative frequency of discharge, that is, discharge as a function of the percentage of time that the discharge is exceeded. It is not a probability curve, because discharge is correlated between successive time intervals, and discharge characteristics are dependent on the season of the year." Searcy (1959) and Vogel and Fennessey (1994) describe the theory and methods to construct flow-duration curves (FDCs). Flow-duration curve applications are presented and reviewed by Searcy (1959) and Vogel and Fennessey (1995).

Two types of simple FDCs were constructed: period-of-record FDCs and seasonal FDCs. The period-of-record FDC is constructed using flow data for all the years (entire period) that the gaging station is in operation. The seasonal FDC is constructed from all the data from the period of record for a particular season. Two seasonal FDCs were estimated: for the November-April winter season, and for the July through October summer season (Burkham, 1970). Thus, these FDCs are dependent on the period used. In a strict sense, the flow-duration curve applies only to the period for which data were used to develop the curve (Searcy, 1959 p. 2).

Instead of using the bin method to construct the FDC empirical probability distribution function (as suggested by Searcy, 1959), the cumulative distribution function (CDF) of the FDC is estimated directly via techniques outlined in Vogel and Fennessey (1994). The period-of-record FDC is estimated using three steps:

1. Separate out the s mean daily flows for each season and year i of the n years of record ($i = 1, ..., n$);
2. Combine the s seasonal flows for each year i into a single series (ns) and rank the entire seasonal mean daily flow $q(j)$ series ($j = 1, ..., ns$), from largest to smallest magnitude; and
3. Utilize a plotting position (equation 1) to estimate the percentage of time $p(j)$ a particular flow $q(j)$ was equaled or exceeded.

$$p(j) = \left(\frac{j}{ns+1}\right)100; \qquad j = 1,\ldots,ns \tag{1}$$

Note that $q(1)$ is the largest observation and $q(ns)$ is the smallest mean daily stream flow observation. Likewise, $p(1)$ and $p(ns)$ are the smallest and largest percent exceedances, respectively.

RESULTS AND DISCUSSION

PEAK DISCHARGE

A peak discharge frequency curve was constructed for each of the gages listed in Table 3 and data presented above. The peak discharge LP-III model estimates may be used to estimate exceedance probabilities from 0.95 to 0.01 (1 in 100). The flood frequency results indicate that the LP-III model adequately fits the data. Results for each site are summarized in Figure 13 through Figure 18 and Table 5 through Table 9. These results are considered to be statistically indistinguishable with those presented in Pope et al. (1998). There are minor differences in magnitudes for given probabilities at various sites. Overall, the empirical distributions (data plotted as solid squares) are similar at the five sites, with the exception of the San Francisco River. It appears that both the upper and lower tails at this site are somewhat different than the surrounding stations. It was not possible to investigate this potential difference at this level of study. Hirschboeck (1985) classified causative mechanisms of floods in the Gila basin. Unfortunately, the period of record that was used in the classification was from 1950 to 1980, and excludes the largest four observations and eight out of the top ten largest peaks on the San Francisco River. The fifth largest peak (10/20/1972) and the ninth largest peak (12/19/1978) were classified as a cutoff low and front, respectively.

Because the records at all five sites are relatively long, the distributions are fairly well behaved over the magnitudes of interest. There is higher variability for the larger (50- and 100-year) return periods. For fluvial geomorphic analyses, the 2-year and 10-year flood estimates are well-defined at all five sites. The 2-year flood ranges from 5,210 to 9,650 ft^3/s at the five locations. There is a noticeable decrease in flood frequency estimates between the head of Safford Valley and Calva for more frequent floods. The 100-year flood estimates increase from upstream to downstream locations, and ranged from 44,800 to 175,000 ft^3/s.

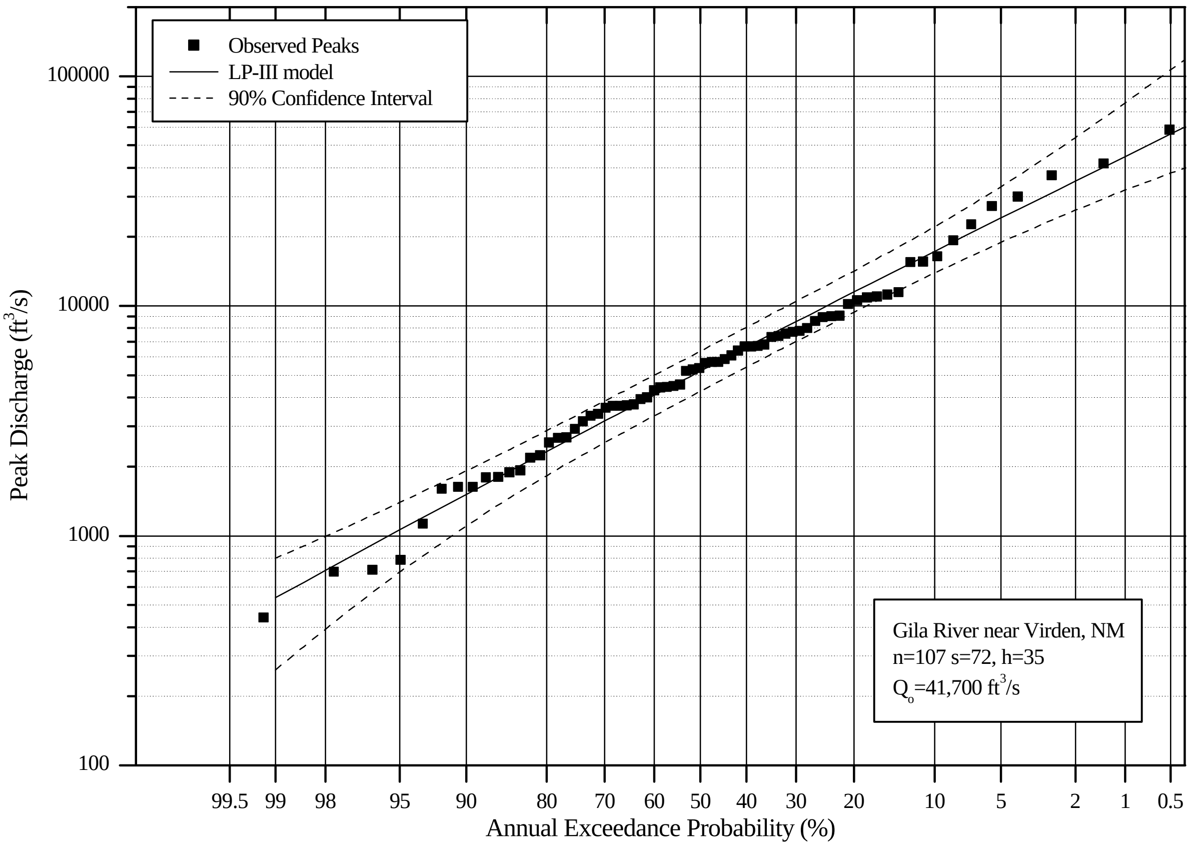


Figure 13. Annual peak discharge frequency curve for the Gila River near Virden, NM.

Table 5. Peak discharge frequency estimates for the Gila River near Virden, NM.

Annual Exceedance Probability (%)	Return Period (years)	Peak Discharge (ft^3/s)		
		Model Estimate	5% Confidence Limit	95% Confidence Limit
50	2	5,210	4,260	6,360
20	5	11,500	9,400	14,200
10	10	17,300	13,900	22,100
4	25	26,600	20,600	37,400
2	50	35,100	26,200	54,200
1	100	44,800	32,000	76,700

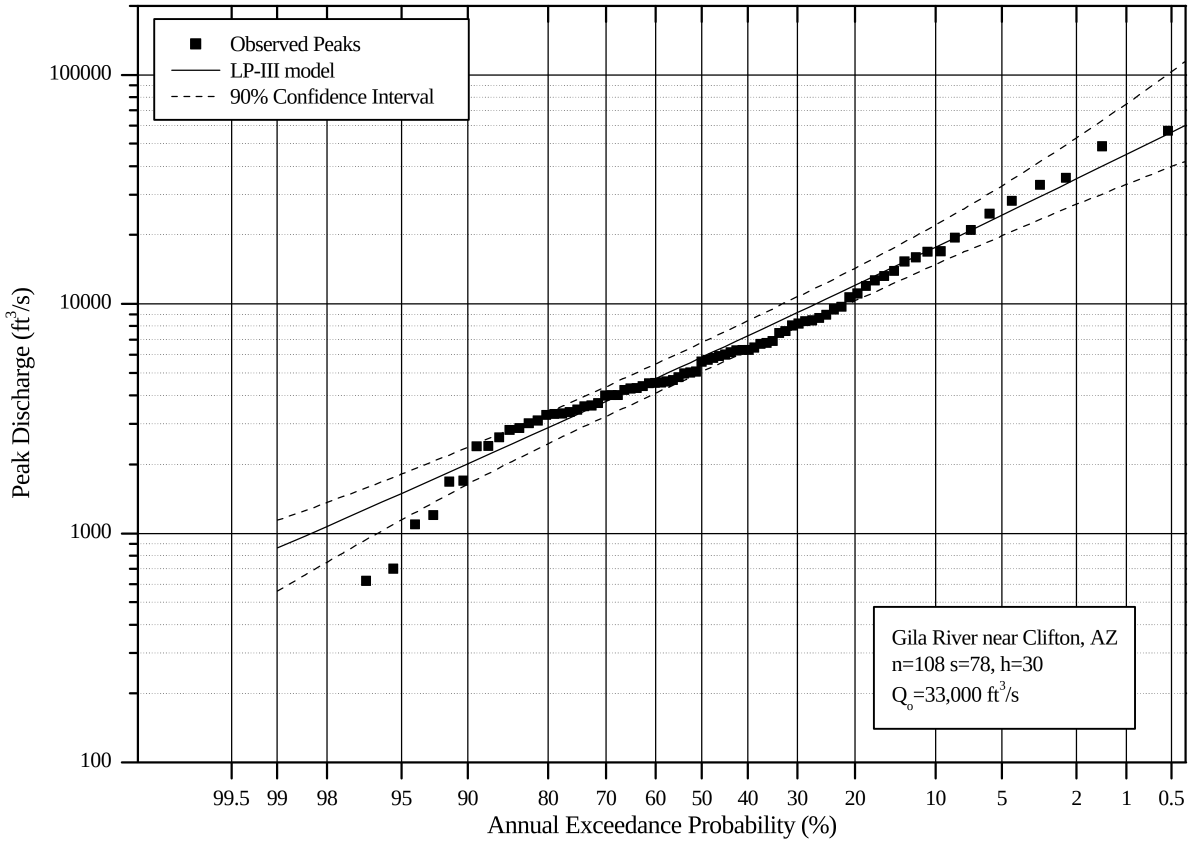


Figure 14. Annual peak discharge frequency curve for the Gila River near Clifton, AZ.

Table 6. Peak discharge frequency estimates for the Gila River near Clifton, AZ.

Annual Exceedance Probability (%)	Return Period (years)	Peak Discharge (ft^3/s)		
		Model Estimate	5% Confidence Limit	95% Confidence Limit
50	2	5,860	5,060	6,790
20	5	12,100	10,300	14,300
10	10	17,700	14,900	22,100
4	25	26,800	21,600	37,000
2	50	35,200	27,200	53,100
1	100	44,900	33,300	74,600

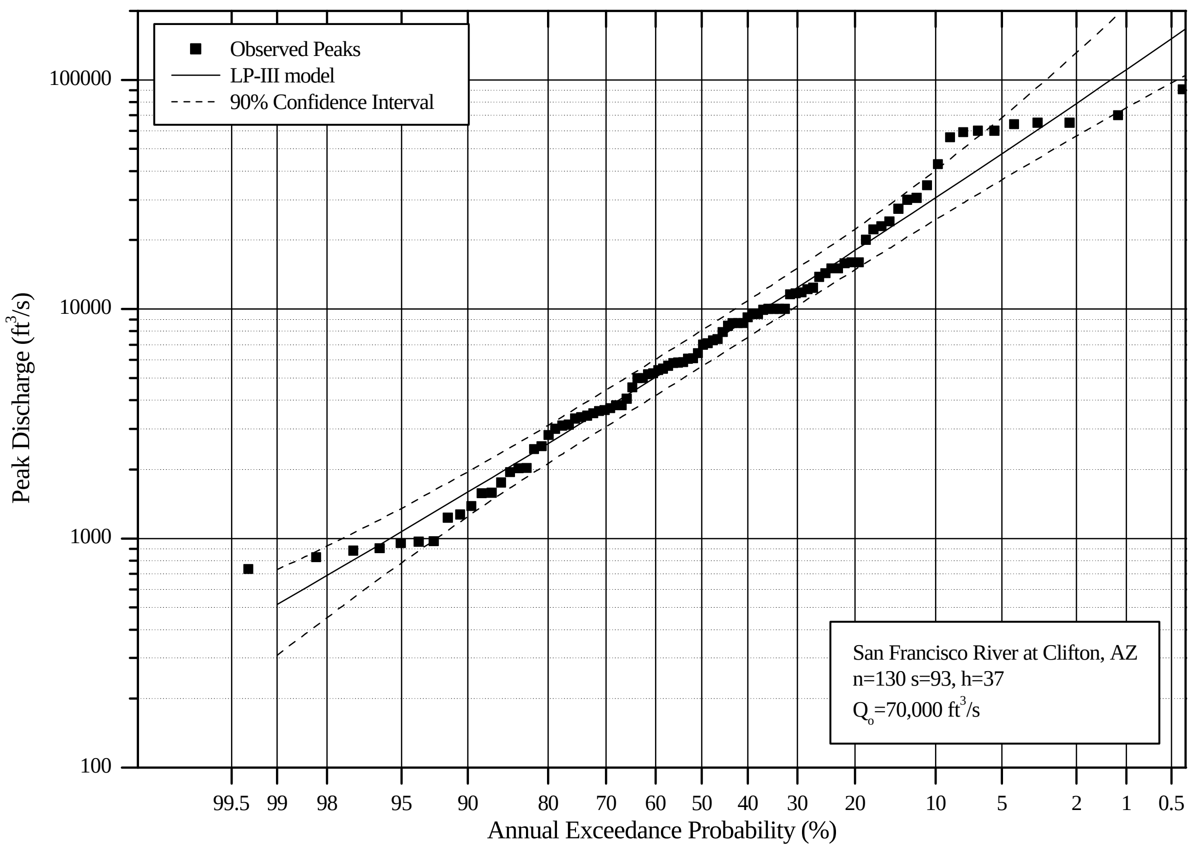


Figure 15. Annual peak discharge frequency curve for the San Francisco River at Clifton, AZ.

Table 7. Peak discharge frequency estimates for the San Francisco River at Clifton, AZ.

Annual Exceedance Probability (%)	Return Period (years)	Peak Discharge (ft^3/s)		
		Model Estimate	5% Confidence Limit	95% Confidence Limit
50	2	6,740	5,630	8,090
20	5	18,100	14,900	22,400
10	10	30,600	24,600	40,300
4	25	54,200	41,200	80,700
2	50	78,900	56,900	131,000
1	100	111,000	75,400	207,000

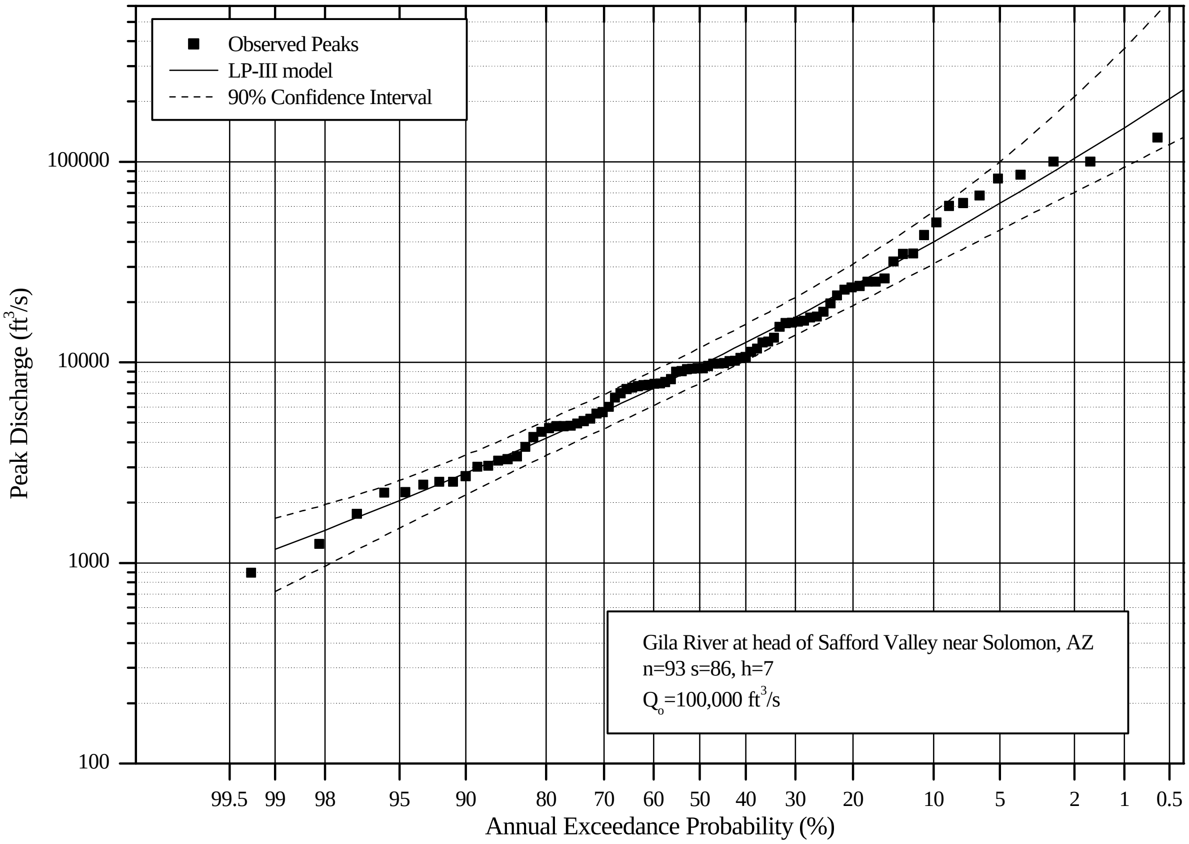


Figure 16. Annual peak discharge frequency curve for the Gila River at head of Safford Valley near Solomon, AZ.

Table 8. Peak discharge frequency estimates for the Gila River at head of Safford Valley near Solomon, AZ.

Annual Exceedance Probability (%)	Return Period (years)	Peak Discharge (ft^3/s)		
		Model Estimate	5% Confidence Limit	95% Confidence Limit
50	2	9,650	7,870	11,820
20	5	24,000	19,300	31,000
10	10	40,000	31,000	56,400
4	25	70,800	51,200	121,000
2	50	104,000	70,600	212,000
1	100	148,000	94,100	367,000

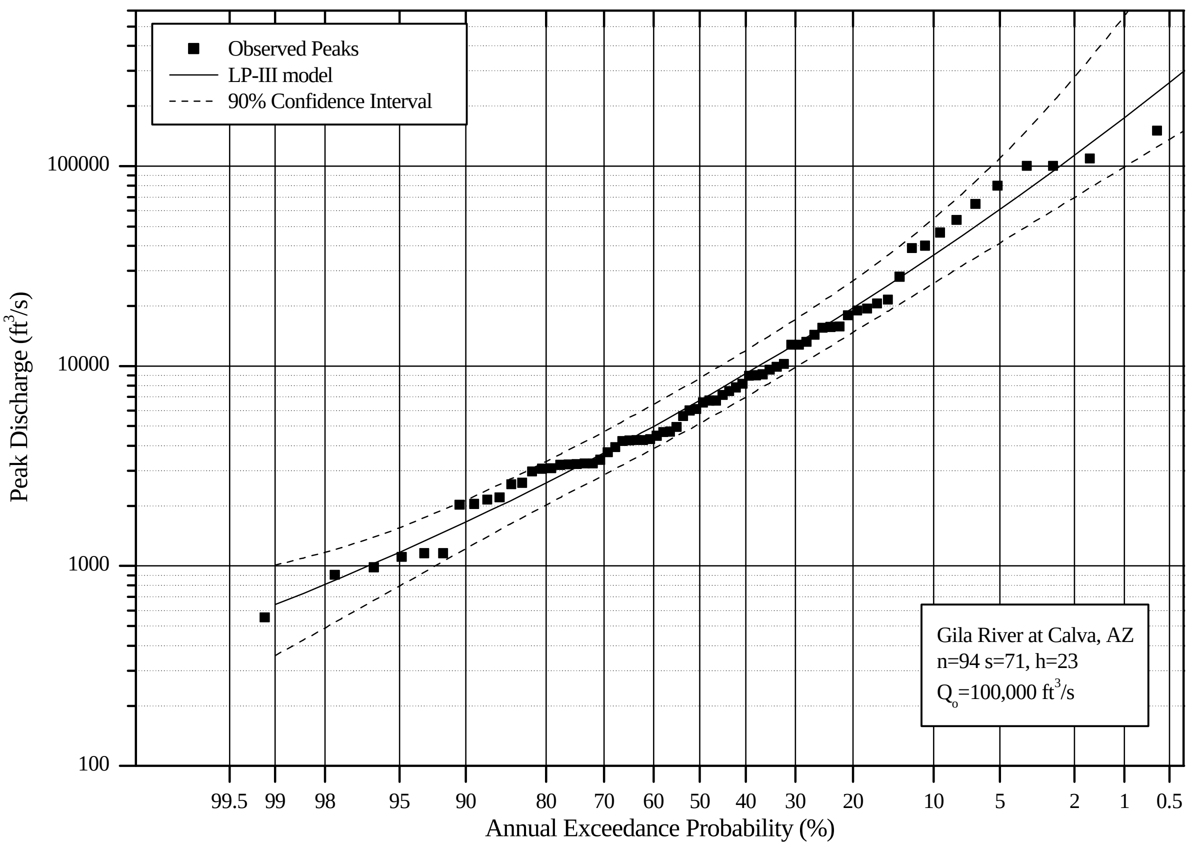


Figure 17. Annual peak discharge frequency curve for the Gila River at Calva, AZ.

Table 9. Peak discharge frequency estimates for the Gila River at Calva, AZ.

Annual Exceedance Probability (%)	Return Period (years)	Peak Discharge (ft^3/s)		
		Model Estimate	5% Confidence Limit	95% Confidence Limit
50	2	6,730	5,170	8,710
20	5	19,600	14,800	26,800
10	10	35,900	26,000	54,600
4	25	71,300	47,400	138,000
2	50	113,000	69,900	278,000
1	100	175,000	99,100	562,000

FLOW DURATION

Two sets of flow-duration curves were made: a period-of-record annual FDC, and seasonal FDCs for winter (November-April) and summer (July-October) flows at each site. The period-of-record annual FDC (Figure 18) shows that mean daily flows are less than about 10,000 ft^3/s about 99.7 percent of the time, and less than 1,000 ft^3/s 90 percent of the time for all sites. The median flows (50 percent) range from about 60 to 200 ft^3/s for the water year. Because there are significant water diversions upstream of the Calva gage, mean daily flows are zero about 10 percent of the time (Figure 18, Table 10). Mean daily flows for the November-April winter season are nearly always greater than the summer season (Figure 19 and Figure 20). In some cases, the winter FDCs are higher than the annual FDCs for approximately 0.5 percent of time. Specific FDC percentiles of daily mean discharge for the period of record are summarized for each site in Table 10.

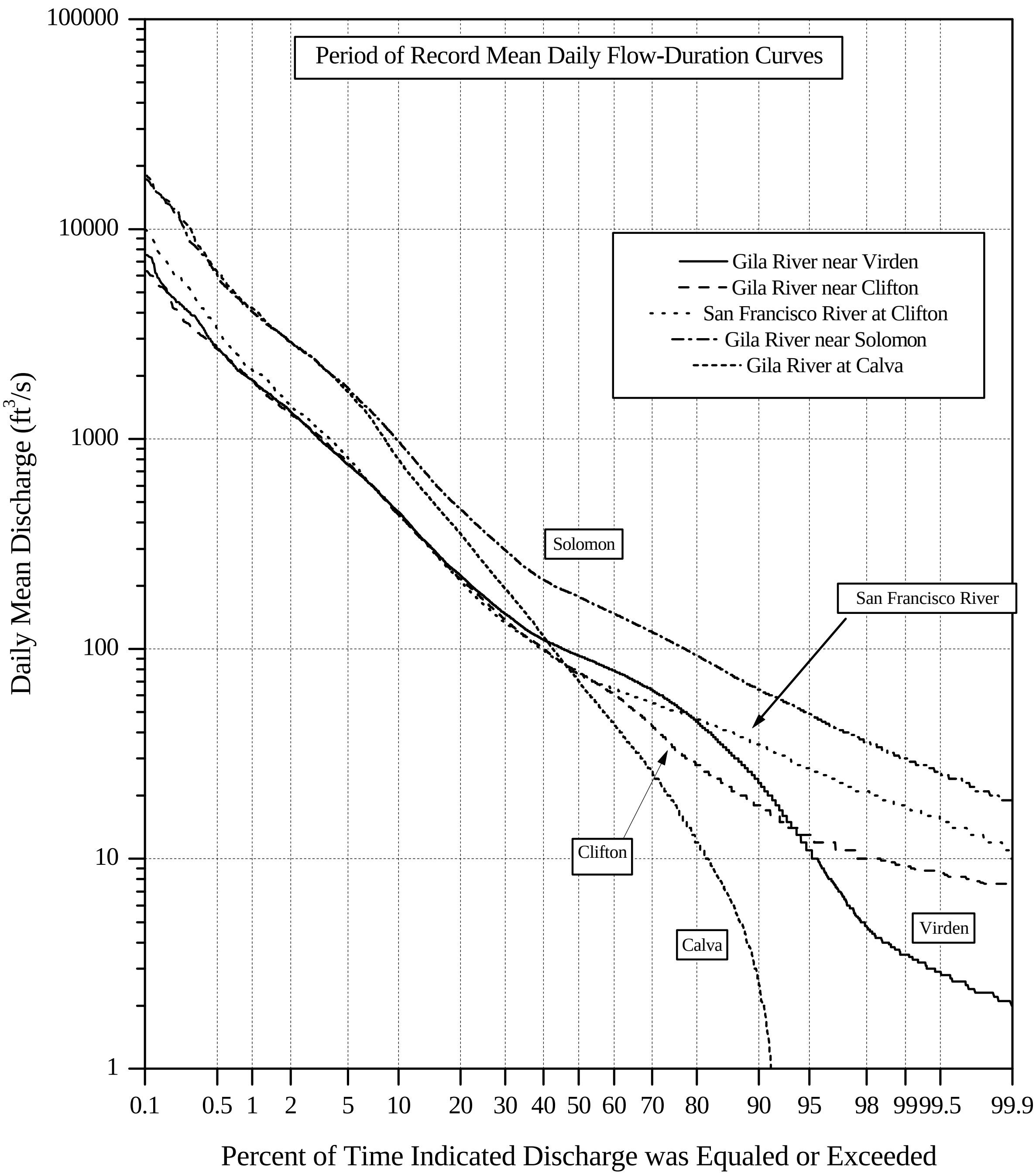


Figure 18. Period of record mean daily flow duration curves for five stations in the Upper Gila River basin.

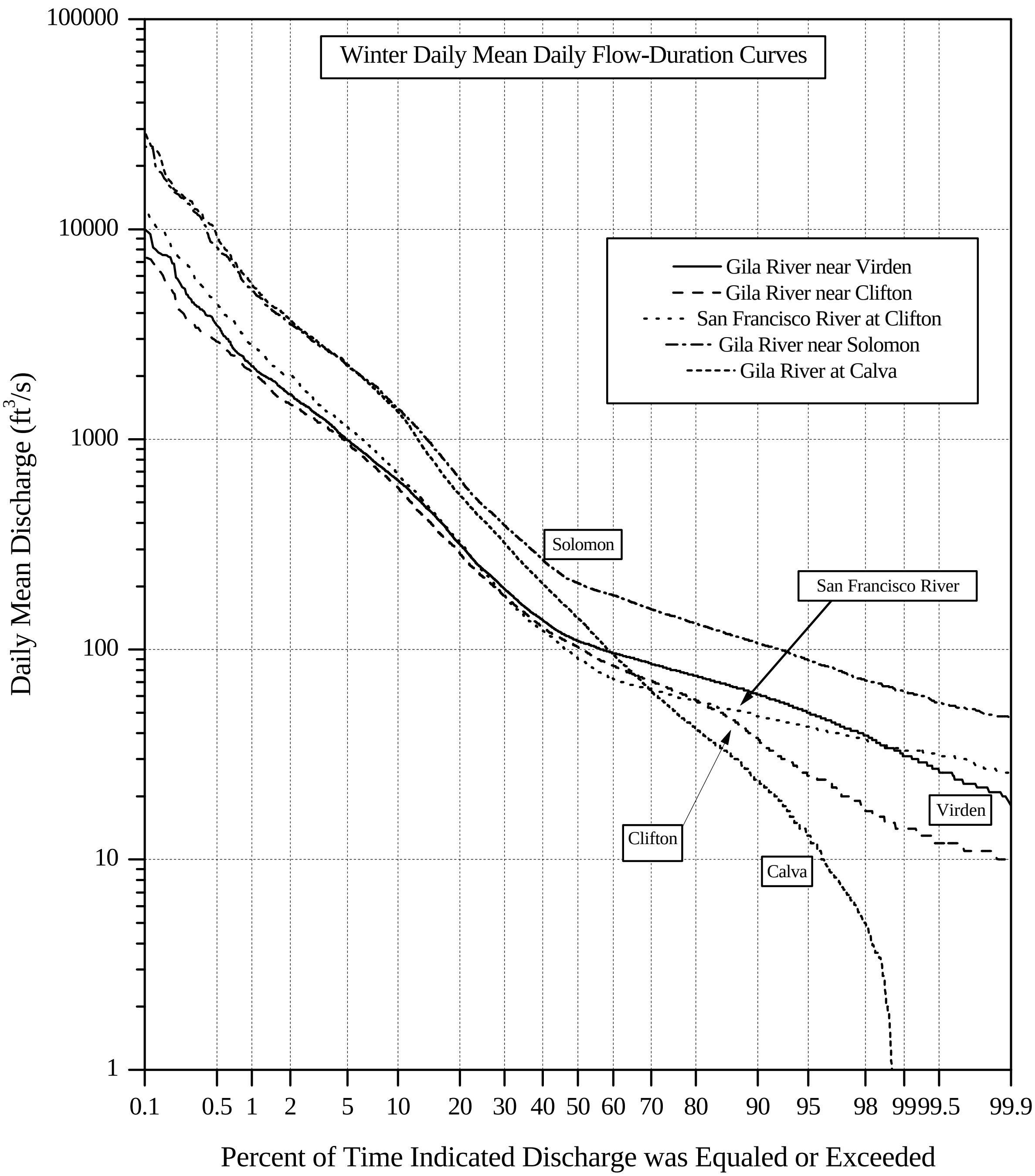


Figure 19. Winter season mean daily flow duration curves for five stations in the Upper Gila River basin.

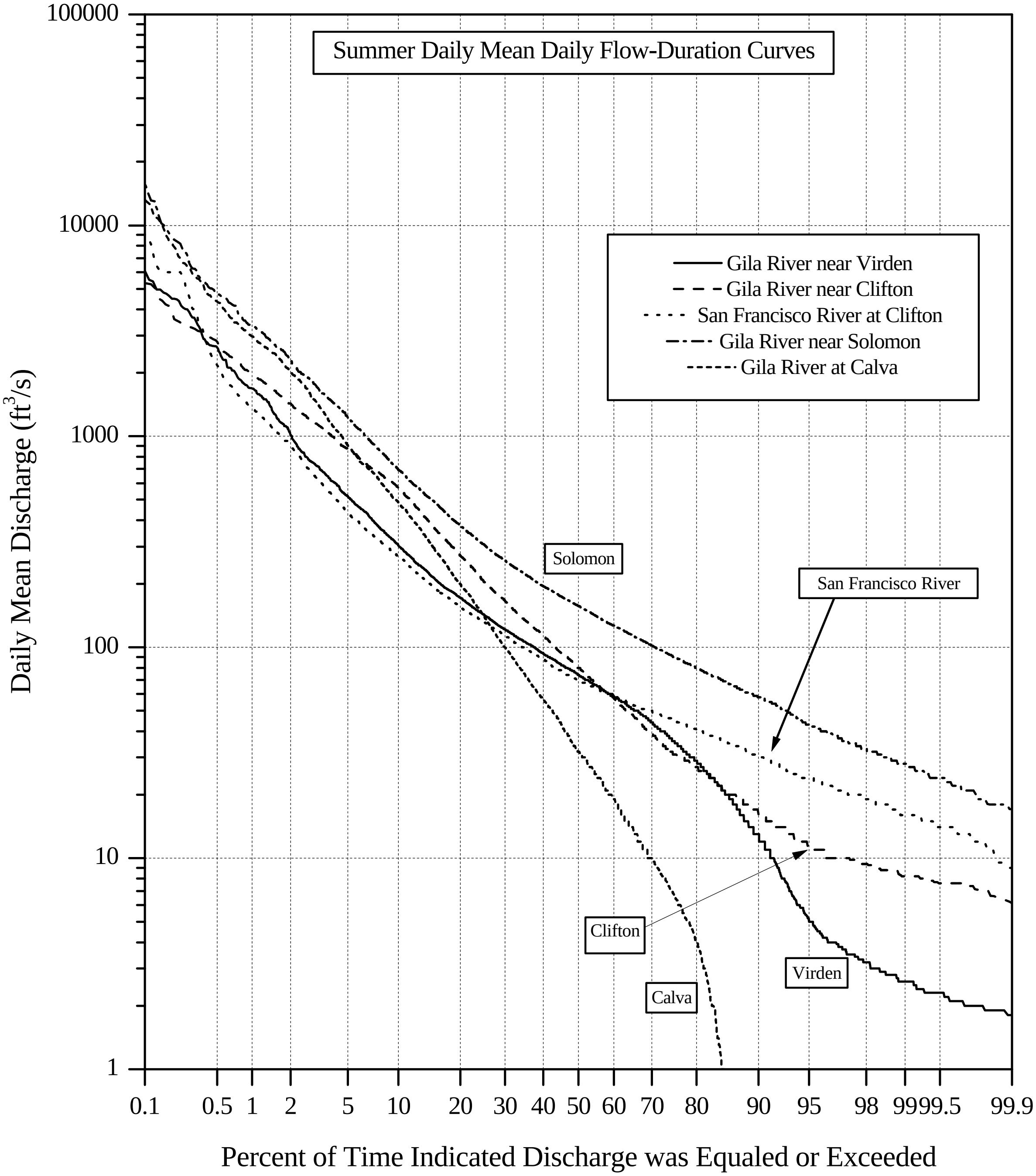


Figure 20. Summer season mean daily flow duration curves for five stations in the Upper Gila River basin.

Table 10. Period of record mean daily flow duration statistics for five stations in the Gila River basin.

Parameter	Location				
	Gila River near Virden	Gila River near Clifton	San Francisco River at Clifton	Gila River near Solomon	Gila River at Calva
number of samples	26603	26207	28268	28278	25933
mean (ft^3/s)	212.114	198.597	222.898	461.518	378.794
standard deviation (ft^3/s)	581.923	533.2	800.52	1481.407	1697.87
minimum observation (ft^3/s)	1.7	3.7	6.1	13	0
99.99 percent exceedance (ft^3/s)	1.7	4.4	7.3	15	0
99.94 percent exceedance (ft^3/s)	1.9	6.5	8.5	17	0
99.7 percent exceedance (ft^3/s)	2.6	8.2	14	23	0
99 percent exceedance (ft^3/s)	3.5	9.3	18	30	0
96.75 percent exceedance (ft^3/s)	7.2	11	24	42	0
90 percent exceedance (ft^3/s)	23	18	35	64	2.6
80 percent exceedance (ft^3/s)	45	28	46	93	12
75 percent exceedance (ft^3/s)	55	34	51	107	19
70 percent exceedance (ft^3/s)	64	43	55	120	26
60 percent exceedance (ft^3/s)	79	61	65	147	44
50 percent exceedance (ft^3/s)	93	77	76	177	70
40 percent exceedance (ft^3/s)	111	100	99	214	115
30 percent exceedance (ft^3/s)	147	138	134	296	193
25 percent exceedance (ft^3/s)	178	170	162	362	256
20 percent exceedance (ft^3/s)	224	215	210	462	352
10 percent exceedance (ft^3/s)	448	434	438	969	798
3.25 percent exceedance (ft^3/s)	992	1,030	1,100	2,250	2,260
1 percent exceedance (ft^3/s)	1,900	1,900	2,140	4,040	4,200
0.3 percent exceedance (ft^3/s)	3,870	3,370	4,840	8,500	9,250
0.06 percent exceedance (ft^3/s)	10,400	8,330	13,350	25,516	33,200
0.01 percent exceedance (ft^3/s)	20,600	21,800	36,400	57,200	80,800
maximum observation (ft^3/s)	33,100	27,100	52,200	90,000	90,000

CONCLUSIONS

Flooding in the Gila River basin is caused primarily by rains from fall and winter storm systems. These storms are generally cold frontal systems colliding with warm, moist air or tropical storms. Extreme flood-producing storms are widespread and generally 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. The largest floods have occurred in water years 1891, 1907, 1941, 1973, 1979, and 1984. The log-Pearson Type III distribution was fit to annual peak discharge estimates at the five 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 5,210 and 9,650 ft^3/s at the five locations. The 100-year flood ranges between 44,800 and 175,000 ft^3/s at the five locations. A period-of-record FDC for the water year indicated that mean daily flows are typically less than about 1,000 ft^3/s for 90 percent of the time at all five sites. 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 Gila River at Calvin.

GEOMORPHIC MAP

A geomorphic map portrays surficial features or landforms that record geologic processes on the earth's surface. In fluvial geomorphology, these processes include erosion and deposition of sediment. Geomorphic landforms such as stream terraces and alluvial fans record sedimentary processes in a river system and are the basis for the delineations on the Geomorphic Map. For the Upper Gila River Fluvial Geomorphology Study, the Geomorphic Map illustrates geomorphic features that will aid in understanding channel changes of the Gila River.

The objective of the geomorphic map is to provide a picture of long-term river behavior. Understanding long-term river behavior is useful for providing a comprehensive picture of river processes, placing recent channel changes into a long-term context, identifying causes of channel change and property loss in the historical period, and defining the extent of channel migration. Appendix B presents the Geomorphic Map, geomorphic data on black and white orthophotographs. The Geomorphic Analysis combines the Geomorphic Map, the Catalog of Historical Changes, fieldwork, and laboratory analyses.

The emphasis in this task was on defining the extent of lateral channel migration and assessing channel change. Geomorphic features that provide information on lateral migration and channel change include flood-modified surfaces, bedrock, alluvial fans, and older floodplain surfaces. Infrastructure is also a major factor in channel position and behavior of the Upper Gila River (Klawon, 2001). Thus, the maps include levees, diversion dams, and bridges.

The Geomorphic Map combines aerial photo interpretation, field mapping of geomorphic features, soil/stratigraphic descriptions, laboratory analyses, and use of previously published soil surveys to provide a long-term picture of river behavior. The maps are produced on 1:4800 scale digital orthophotographs and display geomorphic features and infrastructure important in the recent lateral movement of the Gila River channel.

METHODS

Methods used to produce the geomorphic map of Safford Valley and Duncan Valley include a combination of aerial photograph interpretation, field mapping of geomorphic features, soil/stratigraphic descriptions, laboratory analyses, and use of previously published soil surveys. Historical aerial photography and soil surveys are instrumental in mapping those features obscured by recent land use. Aerial photography spanning 1935 to 2000 with various scales and the Catalog of Historical Changes (Klawon, 2001) was used to identify recent channel change during large floods. The photography was also used to map levees built during the historical period. Soil maps developed by Poulson and Youngs (1938) and Poulson and Stromberg (1950) for Safford Valley and Duncan Valley, respectively, provided critical information for obscured areas and for checking those areas mapped by aerial photo interpretation and fieldwork. The soils for Safford Valley are mapped at a 1:63,360 scale, while the soils of Duncan Valley are mapped at a 1:15,840 scale. Although more recent soil surveys were available (DeWall, 1981; Gelderman, 1970), they did not accurately reflect fluvial geomorphic processes. Approximately 30 soil/stratigraphic descriptions of bank exposures and laboratory analyses provide detailed information about areas that are currently being eroded. Soil and sedimentologic characteristics of bank exposures were described following USDA guidelines and standard sedimentary terminology (Tucker, 1981; Soil Survey Staff, 1993; Birkeland, 1999). For more detailed discussion of this terminology, please see the listed references. Laboratory analysis includes both radiocarbon analysis and macrobotanical analysis. Radiocarbon analysis provides quantitative estimates for the age of alluvium, while macrobotanical analysis identifies the charcoal prior to radiocarbon analysis. Features were initially mapped on 9x9 contact prints of aerial photography and then were transposed onto paper versions of the orthophotographs developed in Task 5 of the Upper Gila River Fluvial Geomorphology Study (Arizona). Delineations were then transferred onto the digital orthophotographs. The coordinate system was re-projected from an arbitrary projection to state plane coordinates.

FEATURES OF THE GEOMORPHIC MAP

The geomorphic map defines four major features: the Pima Soil boundary, geomorphic limit of flood evidence, levees of various ages from 1953 to 1992, and historical property loss along the river. Although not explicitly mapped, the Gila alluvium extends from the Pima Soil boundary to the active channel or from the Geomorphic Limit to the active channel (Figure 21).

The Gila alluvium is most commonly adjacent to the active channel and is part of the channel migration zone of the past several hundred years. The Gila alluvium is composed of weakly developed soils with a C-horizon commonly at the surface. Buried soils exist in many cases; some of these soils appear to be truncated with no A-horizon, while others consist of an A and C-horizon with no B-horizon development. The texture of the Gila alluvium is typically either a silt loam or sandy loam. The soils generally are formed on point bars, or on floodplain nearest to the river. The Gila Soil Series as described in Poulson and Stromberg (1950) is a clay loam and fine sandy loam formed on level to 2% slopes and is generally adjacent to the low flow channel and subject to frequent overflow. The surface is frequently channelized, or channelized scars are readily apparent on the surface. Radiocarbon dates obtained from charcoal samples range in age from 0 to 500 years old.

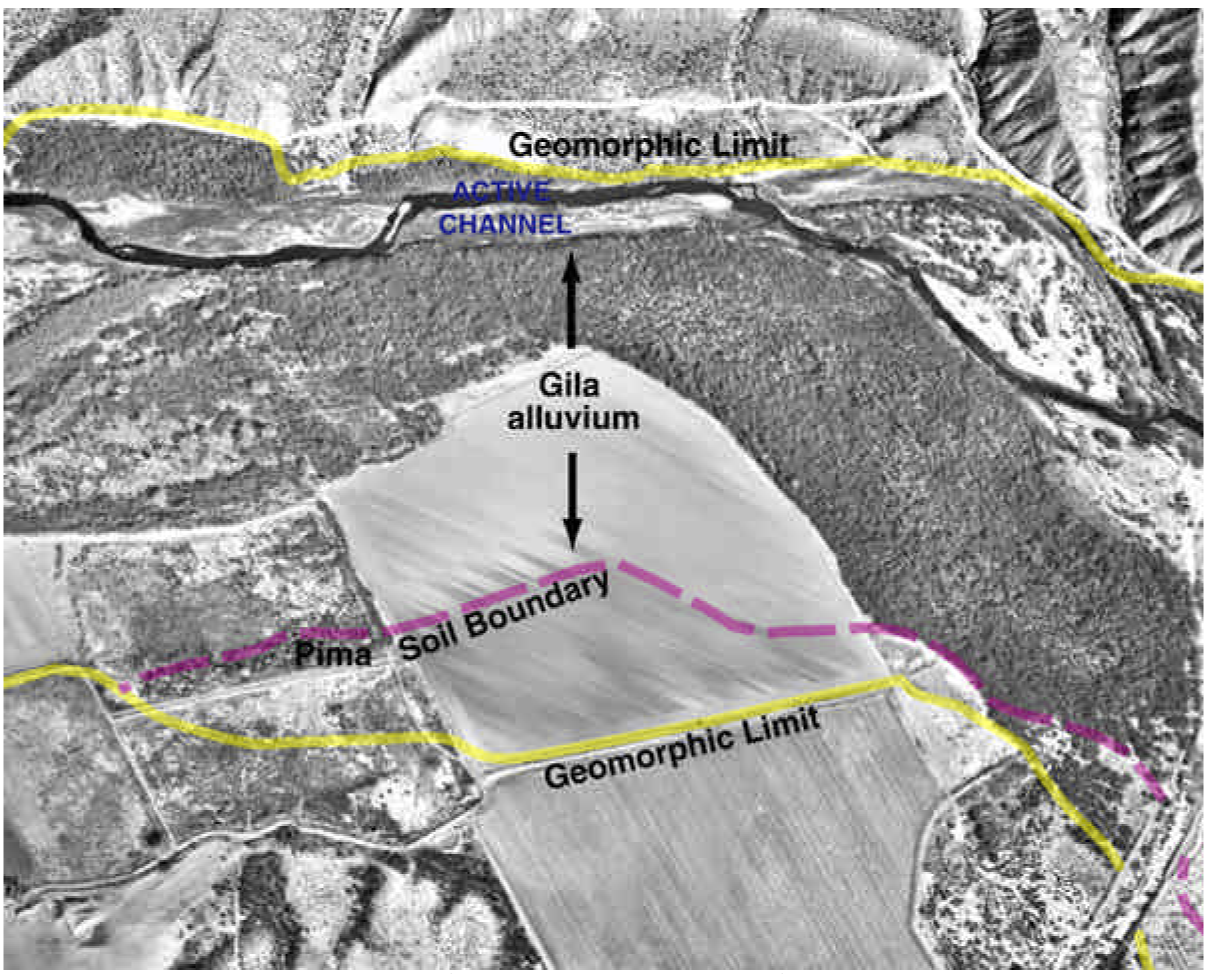


Figure 21. Sample map showing extent of the Gila alluvium and depiction of the Pima Soil and Geomorphic Limit.

PIMA SOIL BOUNDARY

This boundary defines the extent of the Pima Soil as shown on soil surveys and as identified in soil descriptions of bank exposures and observations of corresponding stream terraces. The Pima Soil Boundary is an important boundary because it defines the extent of lateral channel migration for the past several hundred years and is an indicator of channel instability where significant areas of this soil have been eroded. Surfaces with the Pima Soil are generally elevated above the active channel by 5 to 10 ft and appear to be formed on alluvium that is several hundred years old. The Pima Soil Series generally runs parallel to the river and is a deep, dark-colored soil formed on level to 2% slopes. Although there is no salt concentration in any particular layer, the soil is generally rich in salts. Stratified materials are present in the subsoil, which is lighter in color below a depth of 2-3 ft (Poulson, 1950). A typical soil consists of 15 inches of brownish gray granular silty clay loam underlain by brownish gray silty clay loam with irregular fine blocky structure to a depth of 24 inches. From 24 to 40 inches, the profile consists of stratified or laminated layers of pale brown to weak brown friable silty clay loam, loam, and clay loam with occasional sandy and silty seams. From 40 to 70 inches, the soil consists of friable stratified pale brown material ranging from fine sandy loam to silty clay loam. Coarser material is present below 70 inches (Poulson and Youngs, 1938). Surfaces with Pima soils are accessed by the river during flood flows and may be substantially modified in some cases. These soils are currently being eroded along the river in some locations where the active channel is adjacent to the Pima Soil.

In some areas, the boundary between the Pima Soil and younger alluvium along the river was well defined and could be drawn with an accuracy of ± 40 ft. In other areas, ground leveling obscured the boundary so that it could only be drawn with an accuracy of ± 200 ft. The two levels of uncertainty are depicted on the Geomorphic Map by a solid and dashed line, respectively.

GEOMORPHIC LIMIT OF FLOOD EVIDENCE

The geomorphic limit of flood evidence defines the boundary for surface modification by floods of the Gila River and indicates the extent of lateral channel migration for at least the past 1,000 years. Within the geomorphic limit, surfaces are channelized or have tonal signatures on aerial photography that suggest flooding in agricultural fields. Soils developed on surfaces within the geomorphic limit are poorly developed and labeled as the Gila Soil (see Poulson and Stromberg, 1950; Poulson and Youngs, 1938) or are moderately developed soils in the Pima Soil Series. Beyond the geomorphic limit, soils may be eroded along bank exposures, but are eroded much slower than other banks due to their consolidated nature. Geomorphic units beyond the geomorphic limit include bedrock, colluvium, high stream terraces, alluvial fans derived from a single tributary, and alluvial fan complexes on gently sloping piedmonts. These units provide information about the lateral movement along the Gila River because they are difficult to erode. Although several soil series are included in this unit, the soils generally contain higher percentages of gravel and are more sloping than soils of the Pima Series. The soils also typically have carbonate accumulations in a particular horizon in the form of coatings on gravels in gravelly sediments or nodules and filaments in fine-grained sediments. In many cases, these soils have a greater amount of clay when compared to the Pima soil (Poulson and Youngs, 1938). They are also further removed from the active channel where the Pima soil is present and occupy positions of higher elevation than the Pima soil. As with the Pima Soil Boundary, in some areas the geomorphic limit was easily observed and could be depicted with an accuracy of ± 40 ft. In other cases where the boundary was not readily observed and had to be transferred from soils information, it could only be depicted with an accuracy of ± 200 ft. The two levels of accuracy are shown on the Geomorphic Map as solid and dashed lines, respectively.

LEVEES

Levees from 1953 to 1992 were mapped that appeared to be important factors in property loss during large floods. Although many levees have been built that are not portrayed on the Geomorphic Map, they were not mapped because they did not appear to be catalysts for channel change on the Gila River. Table 11 lists the aerial photographs that were used in mapping levees from various years.

Table 11. Source data for mapped levees.

DATE	SOURCE	SCALE	FILM TYPE
1953	Army Map Service	1:54,000	Black & White
1967	U.S. Department of Agriculture	1:20,000	Black & White
1978	Bureau of Land Management	1:24,000	Color
1981	U.S. Geological Survey	1:32,800 to 1:34,000	Color Infrared
1992	U.S. Geological Survey	1:40,000	Black & White

PROPERTY LOSS

Property loss is defined as agricultural land eroded during large floods. Aerial photography from 1935-2000 was examined to determine property loss. Since the majority of land in Safford Valley was eroded between 1967 and 2000, 1967 was set as an arbitrary datum. The majority of erosion in Duncan Valley occurred between 1978 and 2000, so that pre-flood 1978 photography was used as the datum. Once the eroded property was identified, it was then outlined on the 2000 aerial photography.

GEOMORPHIC ANALYSIS

The Geomorphic Analysis synthesizes geomorphic information about the Gila River and compares results of the analysis to other tasks performed for the Upper Gila River Fluvial Geomorphology Study. The goal of the geomorphic analysis is to provide an understanding of the fluvial geomorphology and to explain recent geomorphic change on the Gila River in Safford and Duncan Valleys. Methods used for the Geomorphic Analysis include geomorphic mapping, soil descriptions and laboratory analysis. Soil maps developed by Poulson and Youngs (1938) and Poulson and Stromberg (1950) for Safford Valley and Duncan Valley, respectively, provided critical information for developing the Geomorphic Map. In addition to soil surveys, soil and stratigraphic characteristics were described for 30 sites with actively eroding banks along the Gila River in Duncan and Safford valleys. This information, along with radiocarbon analysis, aerial photography and soil surveys, was used to delineate geomorphic features.

COMPONENTS OF GEOMORPHIC INVESTIGATION

The Catalog of Historical Changes and Geomorphic Map form the main components of the Geomorphic Analysis. The Catalog of Historical Changes documents changes in the alluvial channel of the Upper Gila River, Arizona from 1935 to 2000. This task includes an analysis of trends in channel behavior and stability of river reaches based on lateral migration and changes in channel widths. Rather than repeating the research from previous literature, this study complements previous studies that document channel changes along this reach of the Gila River.

The Geomorphic Map combines aerial photo interpretation, field mapping of geomorphic features, soil/stratigraphic descriptions, laboratory analyses, and use of previously published soil surveys to provide a long-term picture of river behavior in the Safford Valley and the Duncan Valley. Understanding long-term river behavior is useful for providing a comprehensive picture of river processes, placing recent channel changes into a long-term context, identifying causes of channel change and property loss in the historical period, and defining the extent of channel migration. The maps are produced on 1:4800 scale digital orthophotographs and display geomorphic features and infrastructure important in the recent lateral movement of the Gila River channel.

OBSERVATIONS AND ANALYSIS

AGE OF SURFACES UNDERGOING ACTIVE EROSION

The geomorphic map provides evidence for lateral migration and stability along the Gila River. Understanding the age of alluvial deposits that bound a river provides a long-term perspective on the lateral migration 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 they would be actively eroding. That is not to say that rivers do not migrate laterally and erode older deposits. However, a river that is migrating laterally into many locations of older deposits, a low probability natural circumstance, indicates a general form of imposed instability.

The Gila River in Safford and Duncan valleys displays a typical sequence of alluvial deposits, where the age of surfaces increases with distance from the active channel. The majority of surfaces adjacent to the active channel are young alluvium, mapped as the Gila Soil. Radiocarbon ages and soil development indicate that these soils are less than 500 years old. Surfaces with the Pima Soil have been developing for at least several hundred years. Although floods from the Gila River may occasionally inundate these surfaces, flood sediment is incorporated into the developing soil based on stratigraphy of bank exposures in which the soil is not buried by young sediments. A major exception occurs upstream of the Duncan Bridge constriction where aggradation within the levees has resulted in breaching of the left bank levee downstream of Duncan Bridge and substantial sedimentation over the Pima Soil (Figure 22). The Geomorphic Limit of Flood Evidence is against bedrock and piedmont alluvium in some places, while in other areas the alluvium appears to be related to the Gila River. Soils found in these banks have been developing for at least 1,000 years. In comparing Safford Valley and Duncan Valley, the Geomorphic Limit is much closer to the active channel in Duncan Valley when compared to the Geomorphic Limit in Safford Valley. This seems logical since the size of the river is much smaller in Duncan Valley, whereas the San Francisco River greatly increases the size of peak discharges and therefore the width of the Gila River flood channel in Safford Valley. The Pima Soil is only preserved in wider reaches of Duncan Valley, where the flood channel does not frequently re-occupy the entire area within the Geomorphic Limit. In Safford Valley, the Pima Soil is more prevalent, paralleling the Gila River for the majority of its length in the study reach.

Figure 22. Surface morphology following the flood of December, 1978 at Duncan Bridge. White arrows show levee breaches, inundating Gila and Pima alluvium on the left bank downstream of Duncan Bridge. Photography dated Dec. 21, 1978. Flow is right to left.

The geomorphic map shows that majority of eroding banks are part of the Gila alluvium, or alluvium that is considered to be part of the historical channel migration zone. This lateral migration is typical for the Gila River as it shifts its channel in response to peak flows and sediment flux. The Gila River is currently eroding banks composed of Pima alluvium, which is hundreds of years old, in fewer locations than the Gila alluvium. Alluvium that is mapped as part of the Geomorphic Limit is currently being eroded in a few locations, the majority of which are in Duncan Valley (Figure 23). This alluvium is estimated to be at least 1,000 years old. This information confirms that as the age of the alluvium increases, the less likely it is to be currently eroding along the Gila River.

Figure 23. View looking downstream at 3 m (9.8 ft) bank of alluvium associated with geomorphic limit of the Gila River.

GEOMORPHIC EFFECTS OF FLOODS ON CHANNEL FORM

The majority of geomorphic change appears to have occurred during the floods of 1978 and 1993 in Duncan Valley and 1972, 1983, and 1993 in Safford Valley. This conclusion was made by qualitative observations of channel change as well as measurements of channel width on historical aerial photography. As shown by the Catalog of Historical Changes, floods widen the channel by eroding non-cohesive banks of the floodplain and semi-consolidated banks of older alluvium. Floods also tend to straighten the channel or decrease channel sinuosity. This behavior has been documented by numerous authors on the Gila as well on other semi-arid streams (e.g., Burkham, 1972; Baker, 1988) where floods tend to erode meander bends or simply cut off the meander bend to increase the efficiency of transport through the reach. Where channel sinuosity increases during large floods on the Gila River, it is a clue that other local factors may be influencing channel morphology.

PATTERNS OF LEVEE CONSTRUCTION AND PROPERTY LOSS

The Geomorphic Analysis reveals a close association between levee construction and geomorphic change during large floods along the Gila River in Arizona. In general, levees appear to cause minimal geomorphic change during low to moderate flows, but are the catalysts of substantial geomorphic change during the largest floods.

Levee failure causes catastrophic property loss because failure results in water flowing nearly perpendicular to the former flood channel. The reduction of flood plain storage and the decrease in flood channel sinuosity results in higher flood velocities. Since the levees artificially raise the stage of the floodwater, the water flowing from a levee breach generally has tremendous energy compared to normal overbank flows. Once behind the levee, the water must find a return path to the main channel. This return path also acts as an effective flow redirection and can propagate erosion and levee failure downstream. For example, levee failure in the Railroad Wash reach resulted in erosion of agricultural land. While this land was composed of young alluvium and was frequently inundated during large floods, the critical combination of the erosive nature of the 1993 flood and extensive levees enhanced the erosion of agricultural land (Figure 24). In the Whitefield Wash reach downstream of Duncan Bridge, the levees were breached, causing erosion of Pima alluvium behind the levees and propagation of erosion downstream into opposing stream banks. The exposed banks are mapped as part of the Geomorphic Limit (Figure 25). The Watson and Butler wash reach in Safford Valley shows a similar pattern, where a levee constructed upstream of Butler Wash following the 1978 flood is breached during subsequent floods. It is most probable that reentrant flow from behind the levee initiated the erosion of agricultural property on alternating banks and effectively increased channel sinuosity for approximately two miles downstream. The majority of this property is mapped as Gila alluvium, with the exception of land near the corner of Safford-Bryce road, which exposes the Pima soil (Figure 26).

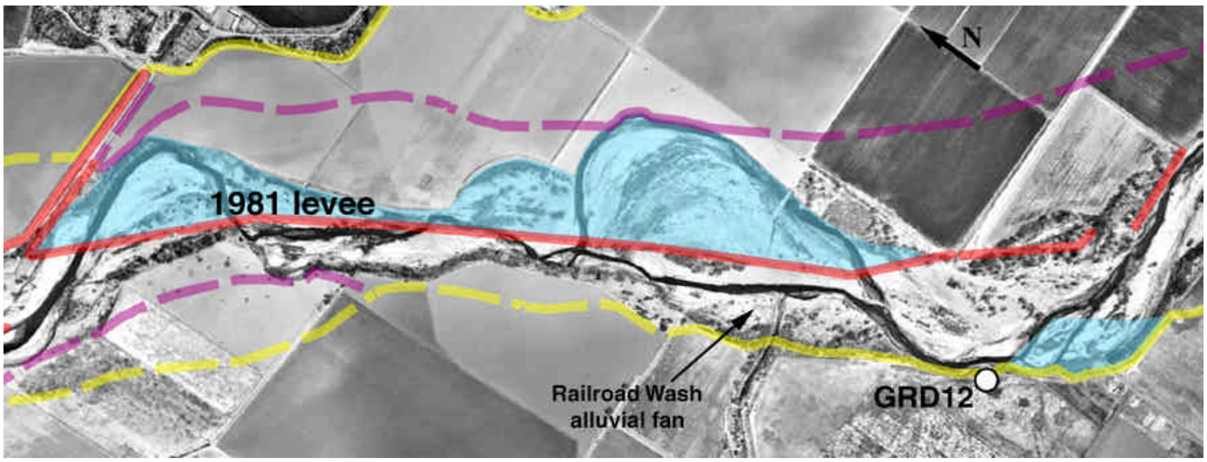


Figure 24. Geomorphic map of the Railroad Wash reach. Flow is from right to left.

Figure 25. Geomorphic map of the Whitefield Wash reach. Flow is from right to left.

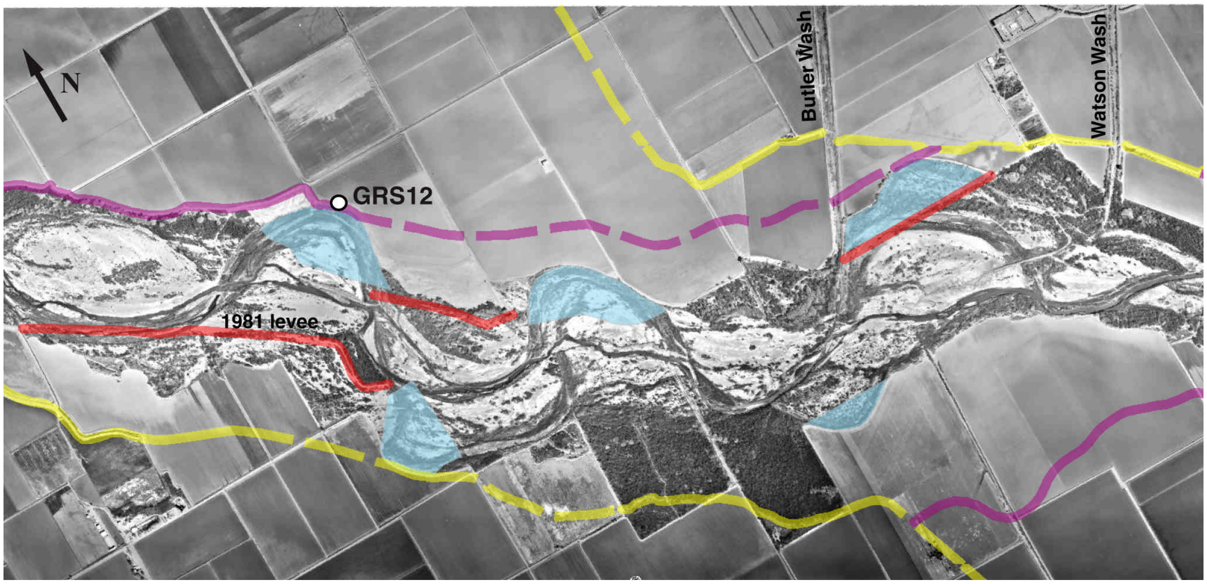


Figure 26. Geomorphic map of the Watson and Butler washes reach. Flow is from right to left.

IMPACT OF DIVERSION STRUCTURES

Six diversion dams were constructed throughout the historical period in Safford Valley, and exert influence on channel morphology both upstream and downstream of the structure itself. Downstream, the orientation of the diversion dam may act in concert with extreme floods by directing flow toward river banks located opposite of the structure. For instance, the orientation of San Jose Diversion appears to have accentuated erosion downstream of the diversion by directing flood flow over the diversion and into the right bank. Upstream, sediment storage to the height of the diversion and extending upstream to a similar elevation creates local changes in base level and slope that lead to aggradation and lateral instability of the river channel and cause changes in channel topography that redirect the low flow channel around the diversion rather than over it (Figure 27). Reduced sediment transport through the reach acts to increase sinuosity and accentuate bank erosion. Attempts to straighten reaches in order to maintain flow over the dam, or direct flow downstream of the dam, become ineffective when large floods caused lateral erosion of banks, and destroyed levees or the straightened channels.

At Smithville Diversion, for example, multiple large asymmetrical meanders show the lateral erosion of the surrounding floodplain upstream of the diversion (Figure 28). Straightened reaches, although effective during low to moderate flows, do not appear to facilitate flow through the flood channel but rather are obliterated during large flows. Large floods overtop and erode the banks of the straightened channel and flow toward the banks of the floodplain and terraces, causing lateral erosion and uncharacteristic channel morphology. Lateral erosion between Curtis Diversion and Fort Thomas Diversion is also apparent and occurs through a reach that was straightened primarily during the 1970's. Reduced sediment transport through this reach appears to have caused the lateral instability that has led to the exaggerated meanders on both sides of the river (see Figure 28).

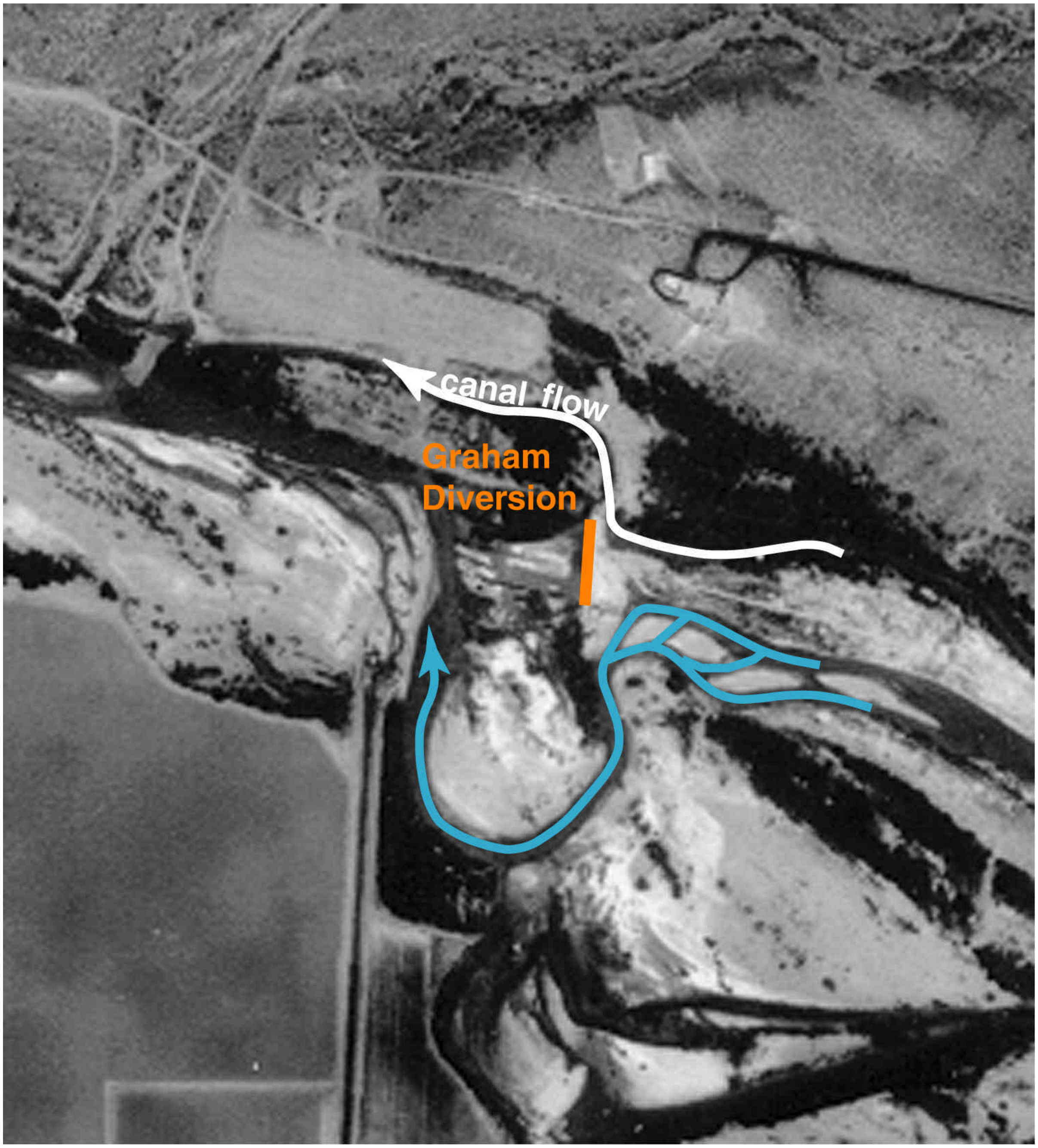
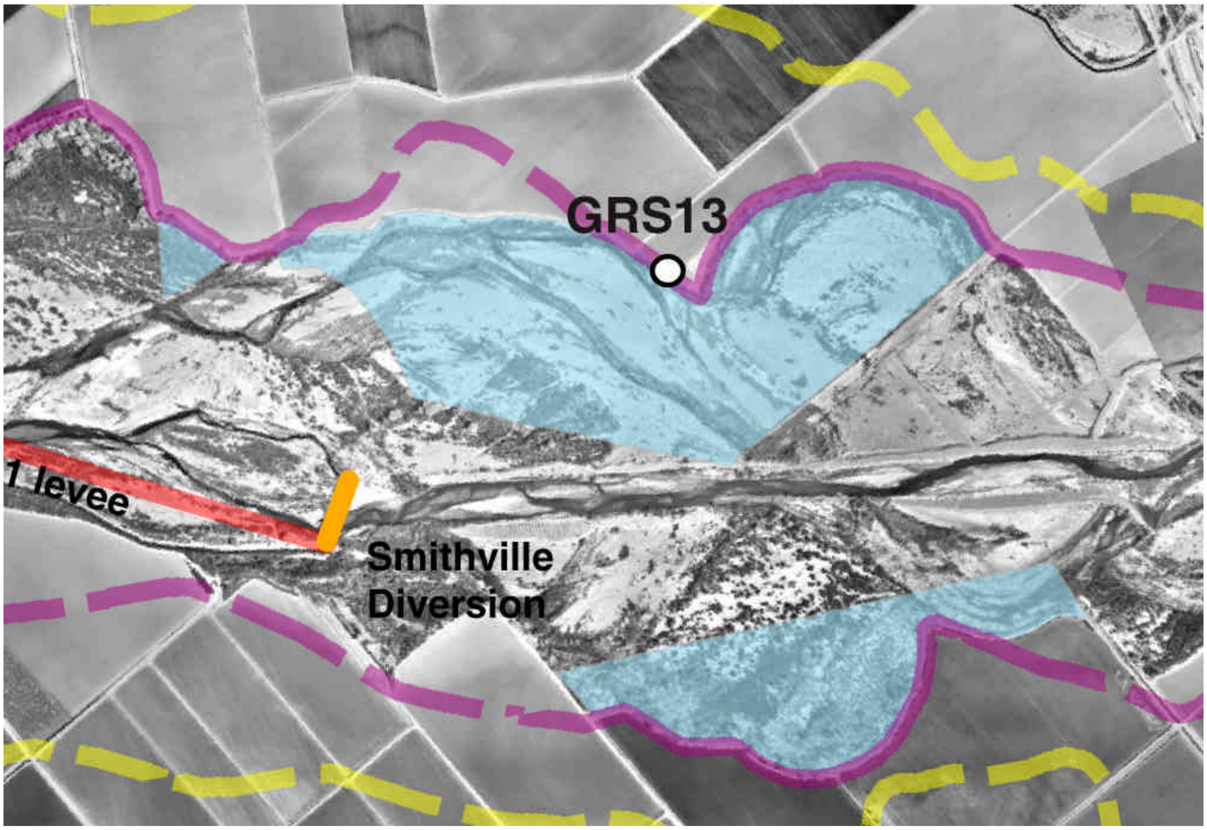


Figure 27. Redirection of low flow around Graham diversion (blue flow lines), resulting in erosion of the left bank. Aerial photograph dated 1999.

A



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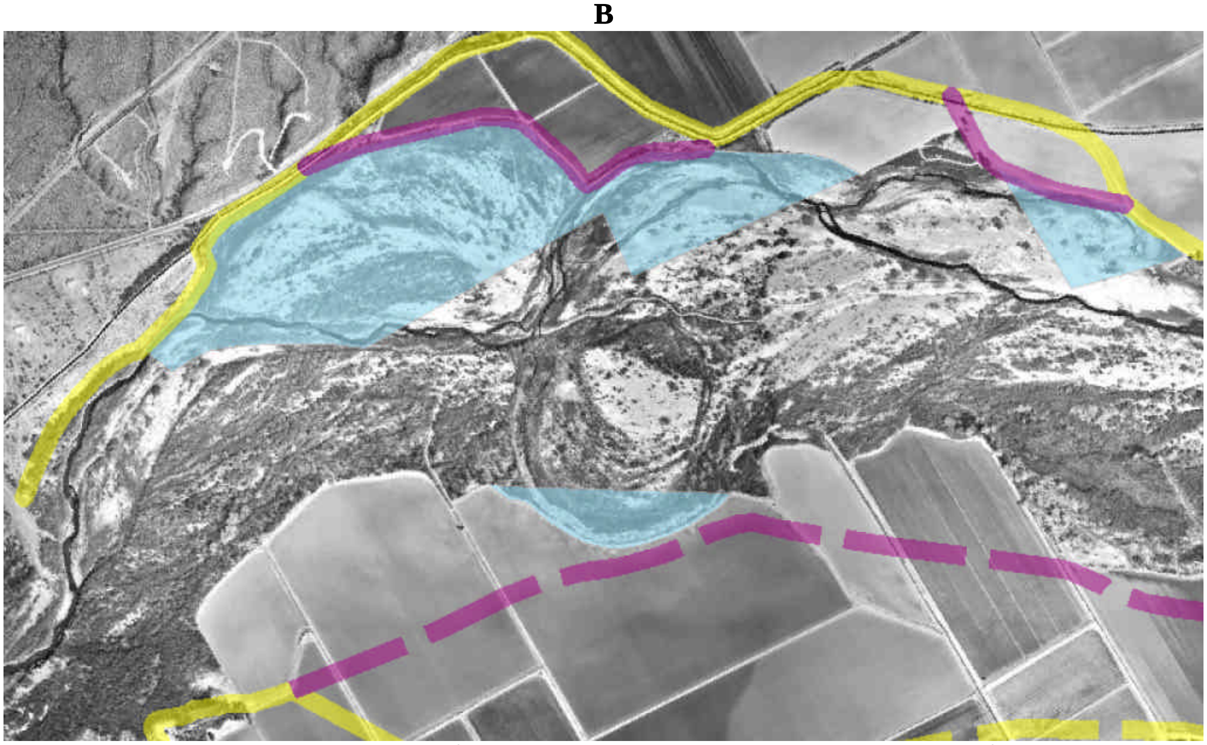

Figure 28. A.) Lateral erosion upstream of Smithville Diversion; B.) Lateral erosion downstream of Curtis Diversion

IMPACT OF BRIDGES

In Duncan and Safford valleys, bridges act as constrictions along the Gila River. The most obvious effect from bridge construction along the Gila River is the reduction in sediment transport through the bridge opening and subsequent aggradation of the bed upstream. At Duncan Bridge this effect is apparent, evidenced by a wedge of sediment that is thickest near the bridge and thins with distance upstream (Figure 29). It is important to note, however, that levees and embankments constructed to focus flow under the Duncan bridge opening also may be partly responsible for the aggradation.

Figure 29. Photograph of the right bank upstream of Duncan Bridge showing wedge of sediment. We submit that this sediment aggraded due to bridge and levee/embankment construction.

In Safford Valley, it is not clear that bridges have played a major role in causing channel change during large floods. Instead, large floods generally overtop the abutments, causing damage to the structure as well as to agricultural fields. Bridges and their abutments are generally located within the Gila alluvium, where the channel is expected to migrate over the short term. It is therefore not surprising for the channel to laterally erode the abutments or reoccupy areas of former channel that were leveled for agriculture near bridges. These channel changes can obviously be problematic in maintaining a constant channel position underneath the bridge opening.

ALLUVIAL FAN FORMATION

Tributary alluvial fans appear to play an important role in channel position and recent geomorphic change. In some cases, deposition of alluvial material in the active channel redirects the channel toward the opposite bank (i.e., Railroad Wash). In other cases, the position of old fans exerts a long-term control on channel position, where channel geometry is clearly related to the alluvial fan. Examples of this scenario occur in Duncan Valley near Apache Peak and Kaywood Wash. In Safford Valley, Day Mine Wash and Markham Wash are two fans that exert important controls on channel geometries. Other authors have attributed similar importance to the capacity of alluvial fans to influence channel geometries on the Gila River (i.e., Burkham, 1972; Levish, 2003). Burkham's study in Safford Valley extends from the Gila River's confluence with the San Simon River to Calva, Arizona. Burkham states that alluvial fans are an important influence from Fort Thomas to Calva, where numerous steep gradient tributaries deposit coarse sediment in the form of an alluvial fan along the Gila River. Upstream of Fort Thomas progressive fan building on the north side of the river forced the river toward the opposite bank, causing the erosion of agricultural land. During large floods, alluvial fans may also be eroded and reformed, creating a dynamic environment for channel change. Levish and Wittler (2003) document several alluvial fans deposited at the mouths of straightened tributaries in Virden Valley that have caused erosion of opposite banks in a manner similar to that described by Burkham. Levish and Wittler also note the presence of several large alluvial fans that exert a long-term control on channel positions, such as at Winn Canyon in the Cliff-Gila valley and at Greenwood Canyon near Riverside, NM.

VEGETATION ENCROACHMENT

Recent vegetation encroachment in the floodplain appears to be most dense from Pima to the San Carlos Indian Reservation. This factor should also be considered as a control on active channel morphology and as an agent of geomorphic change during floods. Attributing channel change to vegetation may be difficult due to the complex interaction among interdependent variables such as stream flow, vegetation, and sediment. The invasion of non-native phreatophytes during the 1930's to 1950's and floodplain formation certainly were important in narrowing the channel and increasing the sinuosity of the active channel. This is documented by Turner (1976) in the reach near Calva. Thick vegetation may act as a barrier to flow and cause erosion of banks with less vegetation during floods and increase channel sinuosity (Hooke, 1996). Avulsions also appear to be more prevalent in this downstream reach during floods, where flood flow exits in an area that is less vegetated and flows behind the dense vegetation, reentering several miles downstream. It also is possible, however, that other factors such as slope are important in causing this change in behavior rather than vegetation or that a combination of factors are important.

CAUSE OF HISTORICAL GEOMORPHIC CHANGE

In Safford and Duncan Valleys, geomorphic change along the Gila River in recent decades appears to be primarily controlled by large floods and exacerbated by the construction of man-made features such as levees and diversion dams. Other factors such as vegetation and alluvial fan formation appear to be less important overall, but in some cases, exert important controls on channel morphology. Previous sections document instances where each of these factors has been a catalyst for geomorphic change along the Gila River.

With the exception of floods, these factors are local characteristics of reaches along the Gila River rather than factors that are external to the study reach. There has been much speculation that the cause of historical geomorphic change along the Gila River was initiated by changes in hydrology or land use changes in the upper basin. This study has produced no information that would lend support to this hypothesis.

The Flood Frequency, Flow Duration, and Trends analysis documents variations in precipitation and runoff over the past 70 years, but it does not document a positive trend over the past 40 years, when the majority of property erosion has occurred. These multi-decadal variations in flood frequency have been observed in other studies such as Webb and Betancourt (1992). This pattern generally displays episodes of frequent large floods followed by episodes of few large floods. These episodes can be irregular and may differ by geographic area, lasting several decades to more than 50 years. It appears that the Gila River has experienced a period of few large floods from the 1930's through the early 1970's bracketed by eras of more frequent large floods, one at the turn of the 20th century and one from the late 1970's through at least the early 1990's. The results of this analysis appear to invalidate the hypothesis that detectable trends runoff resulted in geomorphic change. Over the past several decades, an episode of frequent large floods, there is no clear trend in runoff.

A qualitative assessment of the upper box (Levish, 2002) in New Mexico shows that there is a clear record of stability of the geomorphic surfaces that bound the Gila River in the upper box, predating 19th and 20th century land use changes. This record of stability places doubt on the hypothesis that changes in the upstream watershed are a major cause of geomorphic change from the Arizona state line to the San Carlos Reservation.

In Safford and Duncan valleys, the geomorphic record fails to show that major changes in the upper basin have propagated to the downstream valleys. Impacts on the Gila River from land use change in the form of deforestation through logging or agriculture would destabilize hill slopes and result in an increased sediment influx from the upper watershed. Stratigraphy in downstream reaches should show recent system-wide deposition of sediment on developing soils. Instead, observations suggest that the Gila River is not currently undergoing widespread aggradation in Safford and Duncan Valleys. This is based on the absence of young sediments overlying older soils associated with the Pima Soil Boundary and Geomorphic Limit. Multiple buried soils in units such as the Gila alluvium are part of natural floodplain formation, where the vertical accretion of sediment occurs as floods access their floodplains and deposit sediment. If substantial degradation had occurred, the river would not be able to access its floodplain. This is not the case in both areas where there is substantial modification and in areas where there are few human modifications to the river and its floodplain. For instance, in northern Duncan Valley, where there are few structures, thick young deposits of vertically accreted alluvium are present and are still inundated during large floods (Figure 30).

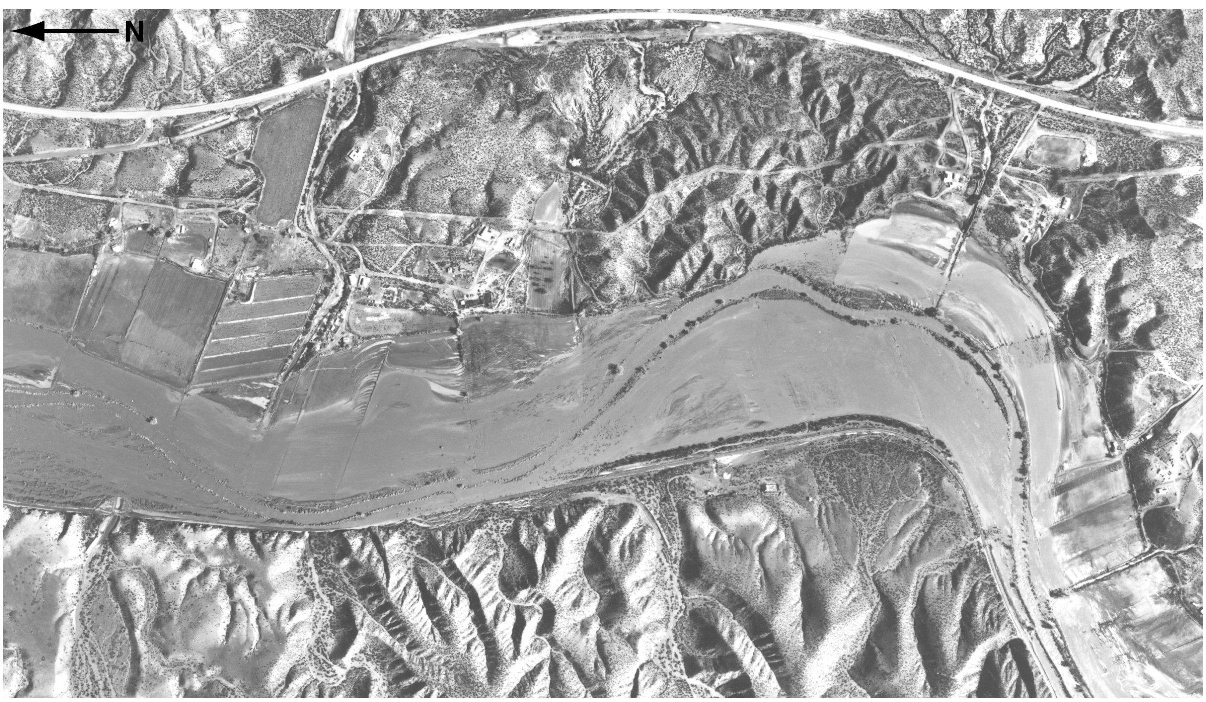

Figure 30. Flood waters inundating young alluvium near Sheldon, AZ. Photography dated Dec. 21, 1978. Flow is from right to left.

Floods are the primary cause of geomorphic change, while the local factors are the catalysts of change at specific locations during large floods. During recent decades, large floods paralleling the magnitude of floods in the late 19th-early 20th century brought about geomorphic change, impacting property owners in a significant way by eroding agricultural land. These floods had two major effects on the Gila River channel. First, floods widened the channel to approximately its former width in 1935. The Catalog of Historical Changes documents this trend in Figure 2. Second, local factors initiated changes in channel morphology that were unusual for the Gila River. Unusual channel characteristics include exaggerated meander bends and increased sinuosity, discussed in previous sections and in the Geomorphic Analysis report (Klawon, 2003).

In Duncan Valley, the most important factors appear to be levee construction and subsequent failure. Given that most alluvial banks are composed of unconsolidated, vertically accreted sand and silt, levee failure results in extensive and rapid property loss. Alluvial fans are also important controls on channel morphology and property loss. Railroad Wash is one such example, where the combination of high consolidated banks and the Railroad Wash alluvial fan directed flood waters toward the opposite levied bank. Where multiple alluvial fans impinge on the Gila River, they can form constrictions and force erosion either upstream or downstream of these constrictions during large floods.

In Safford Valley, diversion dams, levee construction and subsequent failure, and vegetation are the most important factors in historical geomorphic change. Diversion dams exert influence on channel morphology both upstream and downstream of the structure itself. Downstream, the orientation of the diversion dam may act in concert with extreme floods by directing flow toward river banks located opposite of the structure. Upstream, sediment storage to the height of the diversion and extending upstream to a similar elevation creates local changes in base level and slope that lead to aggradation and lateral instability of the river channel directly upstream. The majority of geomorphic change in the form of lateral instability is associated with three diversions: San Jose, Graham, and Smithville. Levees are prevalent throughout Safford Valley. Most levees constructed in the Safford Valley are not engineered, but rather unconsolidated berms build along the edges of farm fields or in the channel. Although the majority of levees are simply eroded during large floods, in some cases their failure leads to catastrophic property loss and the propagation of erosion downstream. Vegetation plays an important role downstream of Pima, Arizona where thick tamarisk encroached on the floodplain beginning in the 1920's. Much of this vegetation establishment coincided with a period of few large floods from the 1930s' into the 1960's.

CONCLUSIONS

In Safford and Duncan Valleys, the most substantial geomorphic changes in the Gila River in recent decades is due to changes in the magnitude and frequency of annual peak floods, as well channel straightening and flood interaction with levees and diversion dams. Using soil/stratigraphic information and lab analyses, geomorphic mapping in these valleys indicates that the Gila River has migrated within the Pima Soil boundary for the last several hundred years and within the Geomorphic Limit for at least the last 1,000 years. Areas of lateral change are indicated where historical floods eroded banks that are mapped as part of the Geomorphic Limit or Pima Soil Boundary.

The majority of property loss has occurred in areas of young alluvium, which is part of the active channel migration zone. Within this zone, lateral migration is common and it is not unexpected for areas to be eroded during large floods. Several areas with unusual channel geometries and erosion of banks older than several hundred years are clues that other factors are important in creating the current (year 2000) channel morphology. The Catalog of Historical Changes and the Geomorphic Map reveal the close correlation between the construction of man-made features and subsequent land resources loss during large floods along the Gila River in Arizona. Human factors that cause lateral instability include levee encroachment into the flood or active channel, diversion dams, and channel straightening. Vegetation and alluvial fan development may also act as controls on channel position in these reaches. The Catalog of Historical Changes, among other studies, shows that the majority of erosion occurs during high flow events such as the flood of October 2-3, 1983, and that channel widening is a geomorphic response to large floods. The local factors mentioned above appear to cause minimal geomorphic change during low to moderate flows but are the catalysts of substantial geomorphic change during the large floods of recent decades.

STABLE CHANNEL ANALYSIS

This report presents an analysis of the stability of the Gila River between the San Carlos Reservation and the Arizona-New Mexico state line, excluding the Gila Box. Alluvial channel stability, according to Mackin (1948), "occurs when, over a period of time, the slope is adjusted to provide, with available discharge and the prevailing channel characteristics, the velocity required to transport sediment supplied from the drainage basin." Lane (1953) defines alluvial stability as "an unlined earth channel which carries water, the banks and bed of which are not scoured objectionably by the moving water, and in which objectionable deposits of sediment do not occur." Chien (1955) contends that "…the equilibrium state of an alluvial channel is attained by adjusting the dimensions of the cross section and the slope of the channel to the natural conditions imposed on the channel by the drainage basin."

This analysis utilizes an analytical tool named SAM, developed by the US Army Corps of Engineers, to analyze the channel roughness, sediment transport, and discharge in four reaches of the Gila River in the study area. Input into SAM includes hydraulics produced by the HEC-RAS backwater model, bed material gradation data gathered during the Field Data Collection portion of the Upper Gila Fluvial Geomorphology study, and hydrology analyzed for this report based upon US Geological Survey stream gaging data collected at several gaging stations in the study area. The analysis uses hydrological data from water years 1965-2000.

This analysis indicates that the results of the stable channel modeling are consistent with the geometry of the Gila River in the study area. The modeling indicates that the river is moderately unstable at the effective discharge in many sub-reaches, mostly in the area downstream of Safford and upstream of Sheldon. The modeling shows that the river is stable in a few sub-reaches, mostly between York and Sheldon, possibly due to bed-rock controls in the area. The instability is greatest with respect to the width and sinuosity of the stream. In general the channel has widened in response to an increase in the magnitude and frequency of floods since 1965. Without large floods in the future the channel will narrow and may locally aggrade, similar to the 1935-1965 period.

STUDY AREA & REACHES

The downstream limit of the study area is the San Carlos Reservation. The upstream boundary of the study is the Arizona-New Mexico State line. Figure 1 shows the study area and several tributaries, towns, and highways. The analysis excludes the Gila Box area.

The length of river channel in the study area is roughly 102 miles. There are two reaches in the study area under analysis, an upper and lower reach. The upper reach includes the study area between York and the New Mexico State line. There are four sub-divided reaches in the lower reach of the study area between the San Carlos Reservation and the head of the Safford valley. The upper reach of the study area uses hydrologic data from the USGS stream gage near Virden, New Mexico. The lower reaches of the study area use hydrologic data from the USGS stream gage at Calva, Arizona, and the USGS stream gage at the head of the Safford Valley.

REACH DELINEATION

Figure 32 shows the four sub-reaches in the lower reach, all located in the Safford Valley. Beginning at the downstream boundary, the San Carlos Reservation, Lower Reach 1 continues upstream roughly 5.28 river miles or 8.5 km. Lower Reach 2 begins at the Fort Thomas road crossing of the Gila River and continues upstream roughly 5.11 river miles or 8.2 km. Lower Reach 3 begins east of Ashurst and continues upstream roughly 11.75 river miles or 18.9 km. Lower Reach 4 begins just upstream of the Graham canal diversion, northeast of Safford, and continues upstream roughly 10.83 river miles or 17.4 km, with the upstream boundary just below the San Jose canal diversion dam.

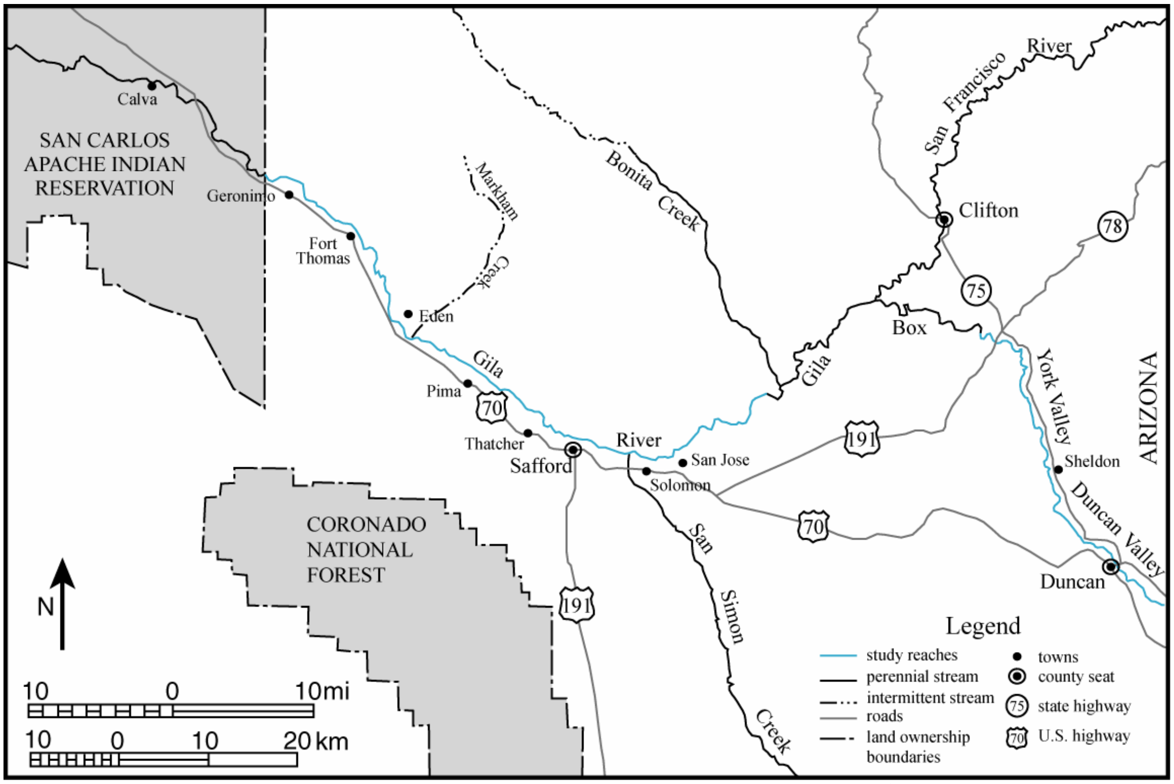

Figure 31. Study area between the San Carlos Reservation and the State of New Mexico.

Figure 32. Lower Reaches 1 through 4, delineated by red squares. Note USGS gages at Calva and Head of Safford Valley.

Sub-reaches were selected based upon observed geomorphic changes in those areas, as well as differences in geology, indicted by the relative width of the geomorphic limit. The selections were subjective based upon the expertise of the study Principal Investigators.

Figure 33 shows the upper reach, located in the York-Sheldon-Duncan-Virden valley. The downstream boundary of the Upper Reach is between Bitter Creek and Sanders wash, downstream of Sheldon. The Upper Reach continues upstream roughly 17.14 river miles, or 27.6 km. The upstream boundary is the Arizona-New Mexico State line.

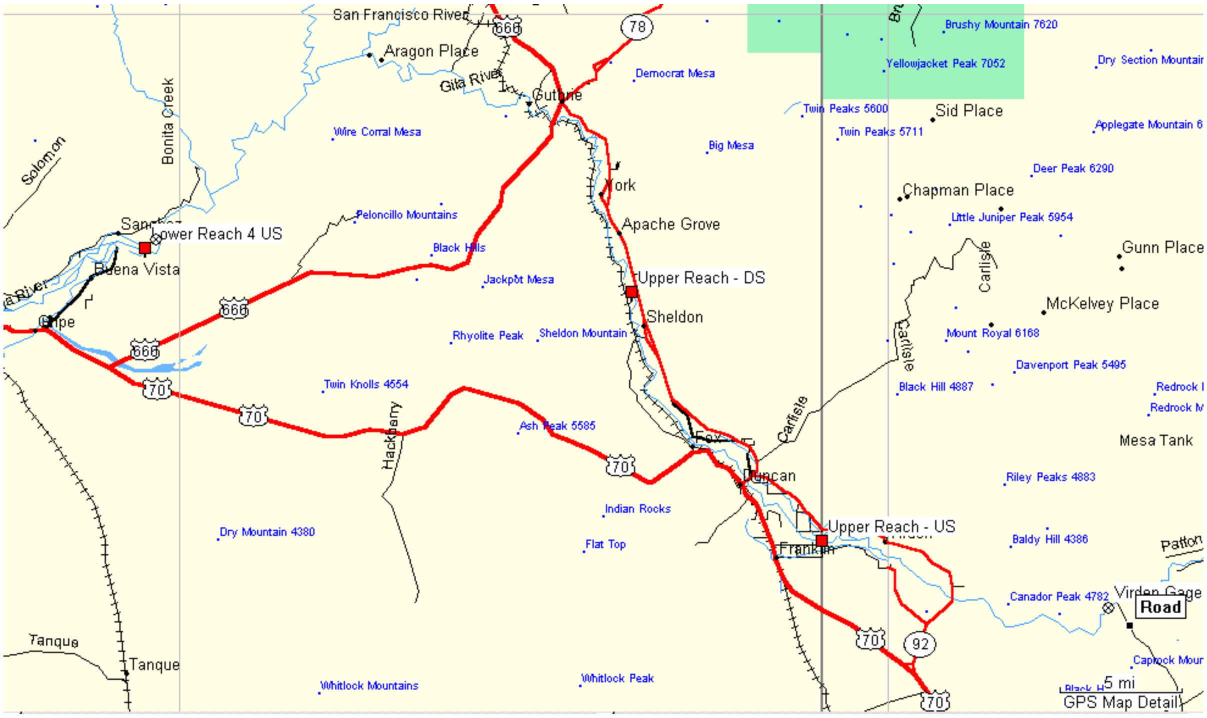

Figure 33. Upper Reach, delineated by red squares. Note USGS gage near Virden, New Mexico.

STABLE CHANNEL CONCEPTS

BACKGROUND DEFINITIONS AND CONCEPTS

A river channel is stable if the river bed is neither aggrading nor degrading. It is normal for banks to build, destabilize, collapse, and then rebuild. Abnormal rates of bank building or erosion is usually associated with instability in the bed or anthropogenic changes in the river alignment. A balanced sediment budget indicates that on average, through time, sediment is not stored in a channel reach. The channel is neither aggrading nor degrading. Sediment transported into the reach is transported out of the reach.

Water discharge in the river is a function of the hydrology of the watershed. Sediment supply from the watershed uplands is a function of the soil conditions and hydrology in the watershed. Sediment supply from river banks is a function of the relative stability of the river banks. Water discharge in the river channel governs the transport of sediments and the relative stability of the banks.

Velocity of water discharge in the river is a function of discharge, channel shape, valley slope, sinuosity of the plan form of the channel, and the roughness of the river channel boundary, including the bed and banks. An alluvial river channel is formed in alluvium, that is, material that is deposited along the banks and bed of a river as a result of erosion. Alluvium consists of different components -- sand, gravel, and topsoil. In the case of the Nile and Mississippi Rivers, rich topsoil from upstream farmland has been deposited as alluvium and created a rich area of agricultural land that is sufficient for growing crops.

Stability, according to Mackin (1948), "occurs when, over a period of time, the (river) slope is adjusted to provide, with available discharge and the prevailing channel characteristics, the velocity required to transport sediment supplied from the drainage basin." Lane (1953) defines stability as "an unlined earth channel which carries water, the banks and bed of which are not scoured objectionably by the moving water, and in which objectionable deposits of sediment do not occur." Chien (1955) contends that "…the equilibrium state of an alluvial channel is attained by adjusting the dimensions of the cross section and the slope of the channel to the natural conditions imposed on the channel by the drainage basin."

Stability of a river reach is dependent upon the following factors:

1) Valley, channel, and water surface slope (sinuosity of the plan form of the river)
2) Channel cross sectional dimensions (width and depth)
3) Roughness of the channel bed, banks, and over banks
4) Sediment supplied to the reach; transported through the reach; transported out of the reach
5) Discharge into the reach; through the reach; out of the reach
6) Channel hydraulic controls, natural or man-made

CHARACTERIZING THE CHANNEL WITH A SINGLE DISCHARGE

Rivers have seasonal, annual, and episodic variations in discharge. It is useful, for the purpose of analysis, to derive a single discharge that represents the variation. Hydraulic Engineers and Fluvial Geomorphologists call this single discharge the channel forming or dominant discharge. Researchers have formulated multiple methods for determining the channel forming discharge. Some of those methods are:

1) Average discharge
2) Bank Full discharge
3) Effective discharge

Averaging discharge over a period is the simplest method. This method is the also the least relevant. Average discharge considers only hydrologic response of the watershed reflected in the discharge in the channel. It ignores the channel itself.

According to Copeland (Copeland, 2000), "Bank-full discharge is the maximum discharge that the channel can convey without overflowing onto the floodplain. This discharge is considered to have morphological significance because it represents the breakpoint between the processes of channel formation and floodplain formation."

Andrews (Andrews, 1980) defines effective discharge as the mean of the discharge increment that transports the largest fraction of the annual sediment load over a period of years. The effective discharge incorporates the principle prescribed by Wolman and Miller (Wolman, 1960) that the channel-forming discharge is a function of both the magnitude of the event and its frequency of occurrence. It is calculated by convoluting the flow-duration curve and a bed-material-sediment rating curve.

Figure 34 is an illustration of the temporal distribution of suspended sediment transport over the course of several years at the Head of Safford Valley (USGS Gage 09448500). The illustration is part of a USGS (USGS, 2001) study of sediment transport in the years between 1966 and 1974.

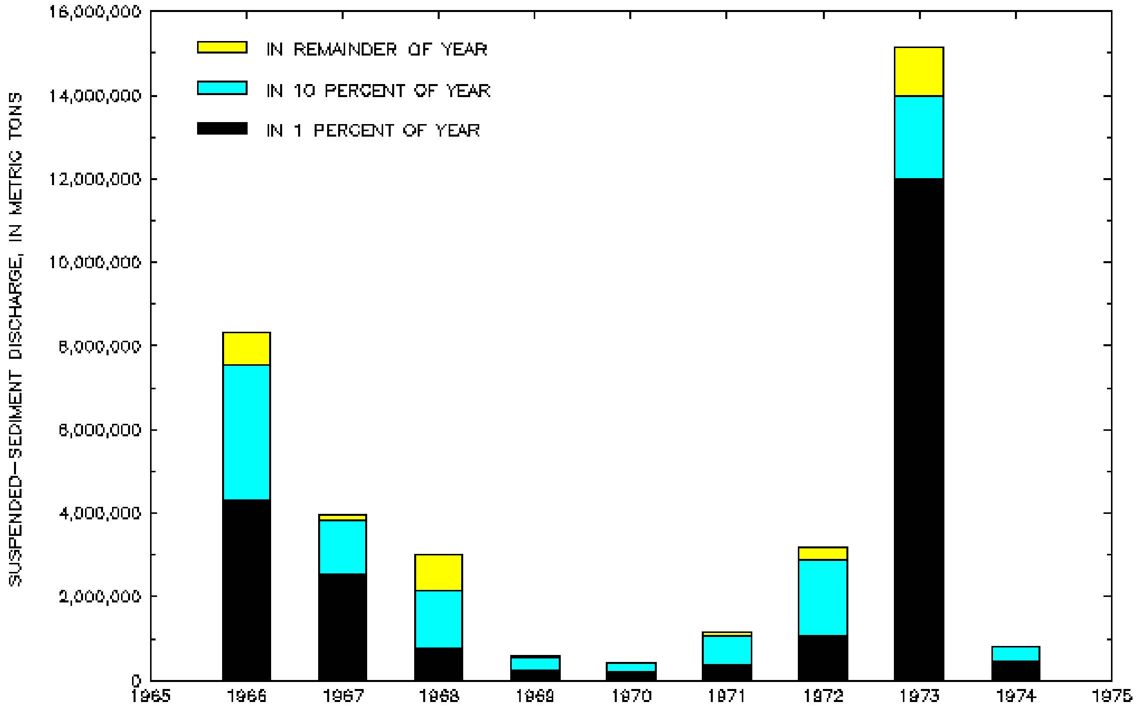

Figure 34. Gila River at Head of Safford Valley suspended sediment discharge (USGS, 2001).

In many years, a single storm may be responsible for transporting the majority of sediment transported during the entire year. The effective discharge accounts for this temporal variation in sediment transport as well as hydrological variation of the discharge. This analysis calculates the effective discharge at three points, representing the five study sub-reaches. They include, at Calva, representing Lower Reaches 1 & 2, at the Head of Safford Valley, Near Solomon, representing Lower Reaches 3 & 4, and Below Blue Creek, Near Virden, NM, representing the Upper Reach. Figure 35, Figure 36, and Figure 37 show the discharges during their periods of records for the Gila River at Calva, AZ, the Gila River at the Head of the Safford Valley, Near Solomon, AZ, and the Gila River Below Blue Creek, Near Virden, NM. The three records all show an obvious change in the magnitude of the annual peaks following the mid 1960's.

Figure 38 shows Klawon's (Klawon, 2001) analysis of the width changes in the Safford Valley since the 1930's. Klawon reported general widening of the channel beginning in the mid-1960's.

Figure 39 shows the cumulative sediment transport over the entire record (1929-2000) for the Gila River at Calva, AZ (USGS Gage 09466500). The discharges corresponding to the 75th and 25th percentile of total sediment transport are 2,189 m^3/s (77,300 ft^3/s) and 116 m^3/s (4,100 ft^3/s). The mean of these discharges is 1,152 m^3/s (40,700 ft^3/s). The discharge at the 50th percentile is 815 m^3/s (28,800 ft^3/s), a difference of roughly 41%. The range of discharges between the 75th and 25th percentiles and the difference between the mean and the 50th percentile discharge indicates that the entire record does not represent the last 35 years of the record. Using the discharges between 1965 and 2000, the difference is roughly 16%. Based upon these observations, this analysis uses the period of record beginning with water year 1965 for the effective discharge calculations.

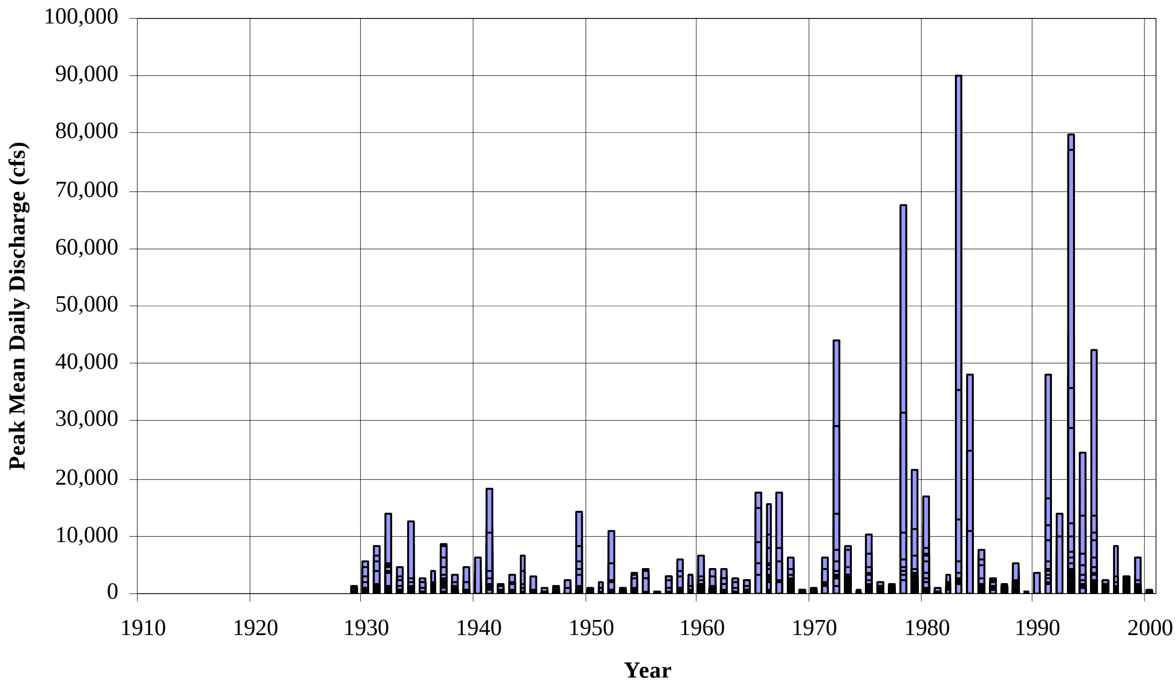

Figure 35. Peak discharges from 1929-2000 for Gila River at Calva, AZ.

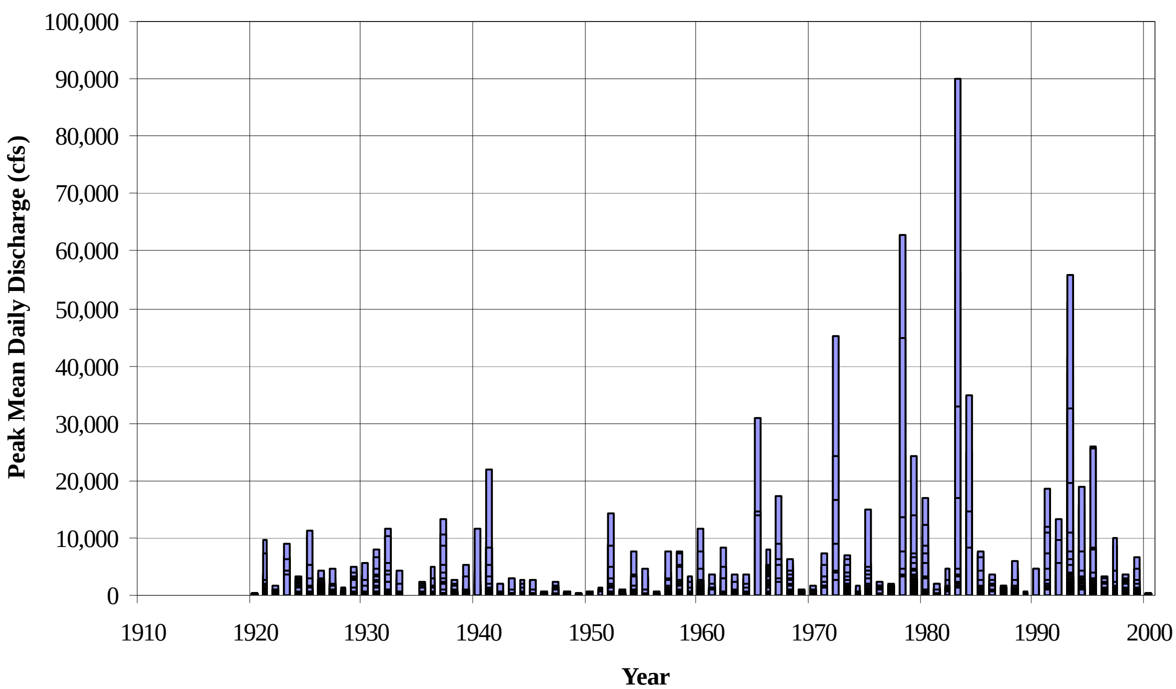

Figure 36. Peak discharges from 1914 to 2000 for Gila River at Head of Safford Valley.

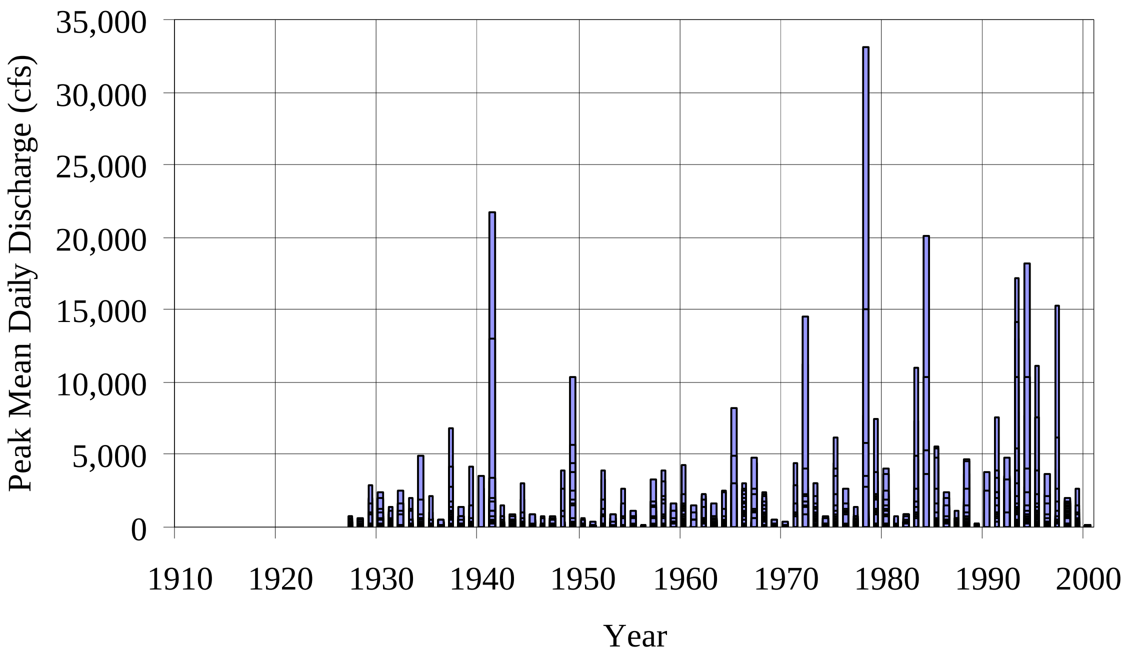

Figure 37. Peak discharges from 1927-2000 for Gila River Below Blue Creek, Near Virden, NM.

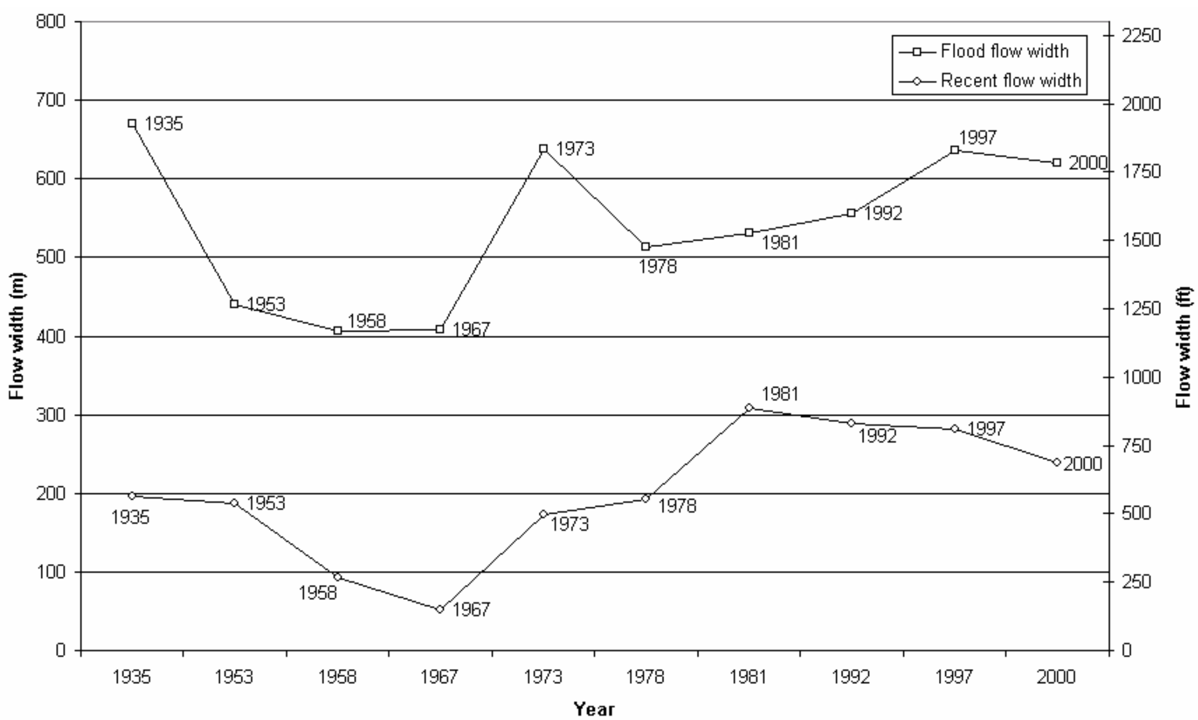

Figure 38. Channel widths in the Safford Valley. (Klawon, 2001)

In Figure 38 Klawon's reference to 'Recent flow width' is synonymous with 'active channel width', and the 'Flood flow width' is synonymous with 'Flood Channel Width'.

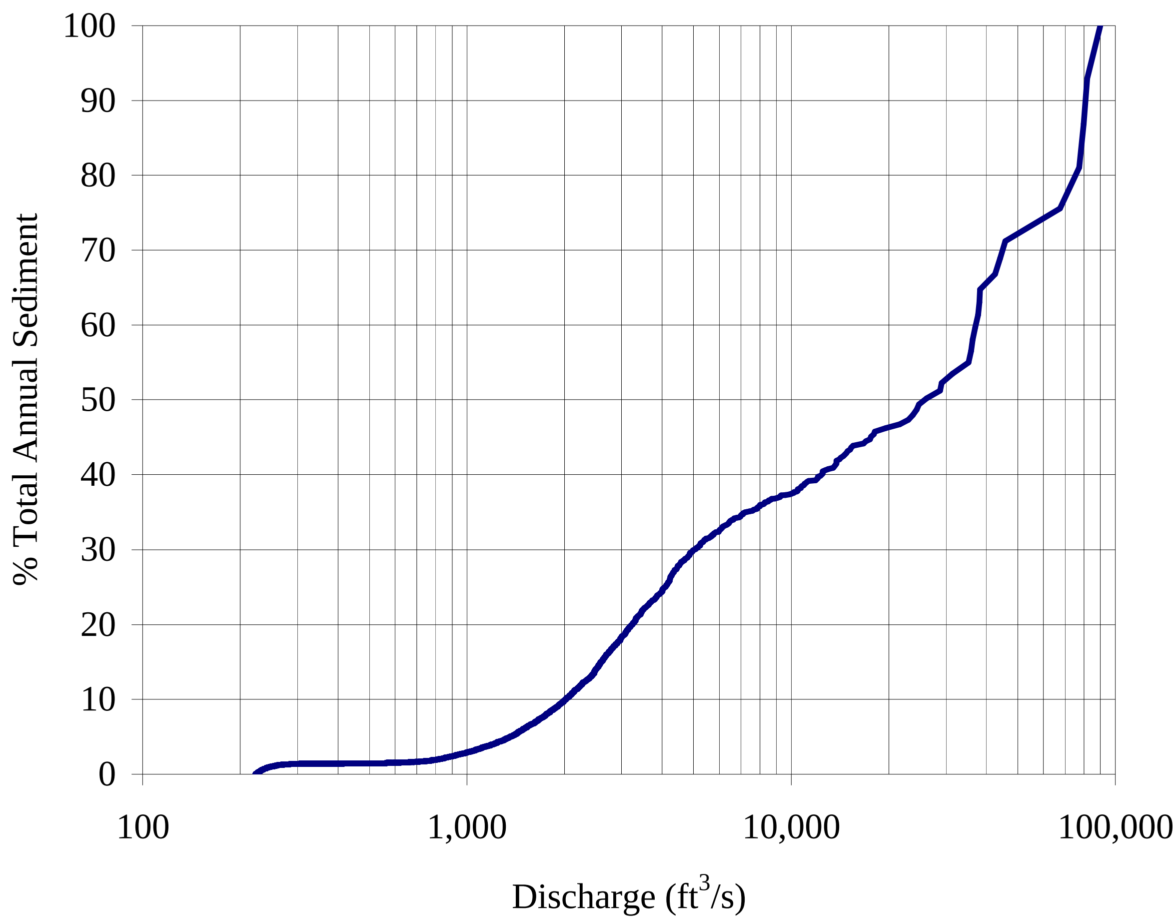

Figure 39. Cumulative sediment transport at Calva from 1929 to 2000.

SAM & RISAD

The SAM model is an integrated system of programs developed through the US Army Corps of Engineers Flood Damage Reduction and Stream Restoration Research Program to aid engineers in analyses associated with designing, operating, and maintaining flood control channels and stream restoration projects. SAM is designed to run on PC computers and is primarily for the design of stable channels. The package satisfies the need for qualitative, easy-to-use methodology, especially for use in preliminary screening of alternatives where funds for more extensive investigations are not available. The Stable Channel Design Method for Gravel Bed Streams, named RISAD, is a Windows version of the SAM - Copeland Stable Channel Design option.

RISAD has additional equations for use in the design of gravel bed streams, utilizing the Meyer-Peter Mueller gravel transport equation. Its design determines the stable width, depth, and slope of a stream given a few characteristics of the study reach. The gravel bed stream equations are not available in the SAM.hyd version of this option.

The graphical user interface (GUI) for this module consists of two windows – the Stable Channel Design Input window and the Stable Channel Design Output window. RISAD, using the effective discharge, HEC-RAS results, and bed material information described in the next section, is the primary tool of this stable channel analysis.

GRADATION OF THE RIVER BED MATERIAL

BACKGROUND

Wittler and Levish (Wittler, 2001) describe the methods, purposes, and intentions of the bed material sampling plan for the Upper Gila Fluvial Geomorphology study. Wittler and Baca, of the US Bureau of Reclamation Technical Service Center Water Resources Research Laboratory, collected the samples according to the procedures specified in the Field Data Collection Plan (Wittler, 2001). Appendix B tabulates all of the sediment samples collected by Wittler and Baca by sample number, date, name, description, latitude, longitude, UTM northing, UTM easting, location in the stream, sample depth, and type, either grab or photographic. Photographic samples were collected in places where the largest particle sizes would not fit into the sample bag. In the numbering system, sample numbers alone generally indicate a grab sample, while a numeric sample number followed by an alphabetic modifier, e.g. 5A, indicates a photographic sample.

Photographic samples were collected first. Then, after removing the large surface particle, a volume of one to three times of the largest particle of finer particles beneath the large particle was collected into a plastic sample bag, using a hand trowel. Care was exercised to collect material immediately below the surface by keeping the walls of the excavation vertical. Photographs of the river in the upstream and downstream directions were also taken from the sample location. Samples were logged and transported to the laboratory for analysis. Figure 40 shows Photographic Sample 44A, near Holyoke, Arizona.

The US Bureau of Reclamation Phoenix Area Office Materials Laboratory, and Gary Stevens, analyzed the grab samples following established Reclamation procedures. Wittler analyzed the photographic samples using the GoldSize program produced by Golder Associates of Seattle, Washington.

Figure 40. Photographic sample 44A near Holyoke, Arizona.

LOCATION MAPS OF BED MATERIAL SAMPLING

The following maps show the locations of the individual samples, indicated by the flag symbol. In some cases the symbols overlap due to the close proximity of the sample locations. The general scheme specified locations upstream and downstream of bridges and diversions, as well as selected locations in long reaches between those types of structures.

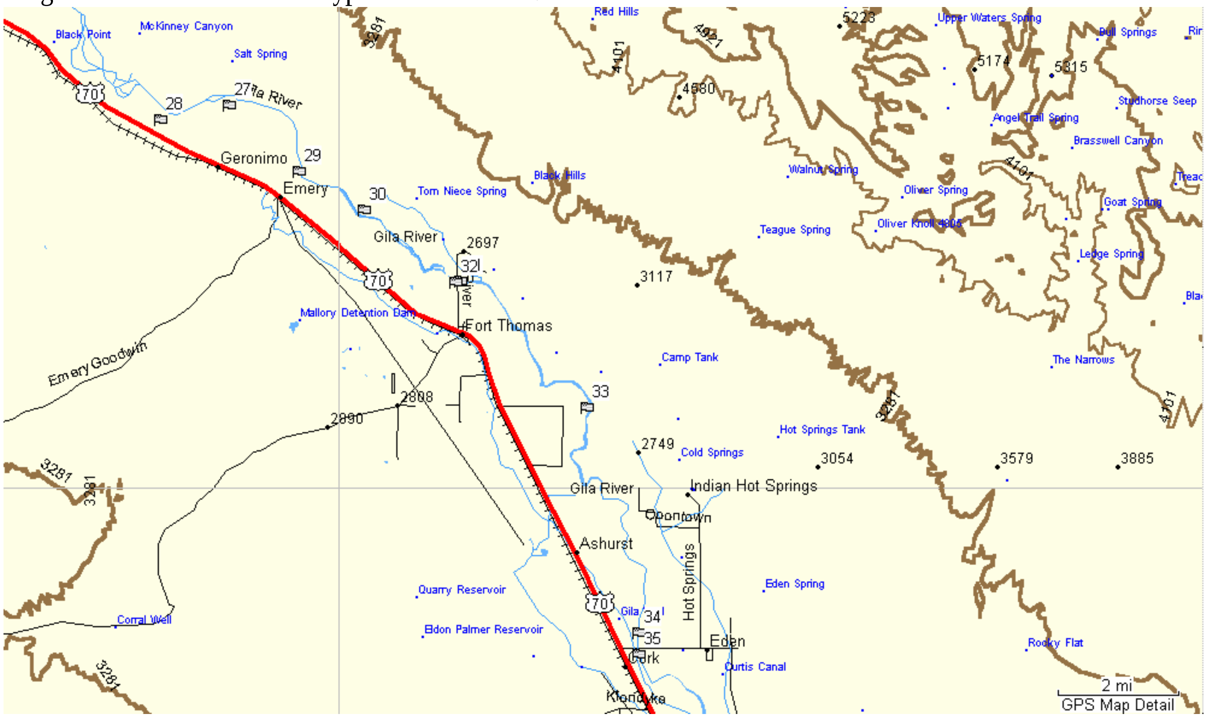

Figure 41. Study reach between San Carlos Reservation and the Eden area.

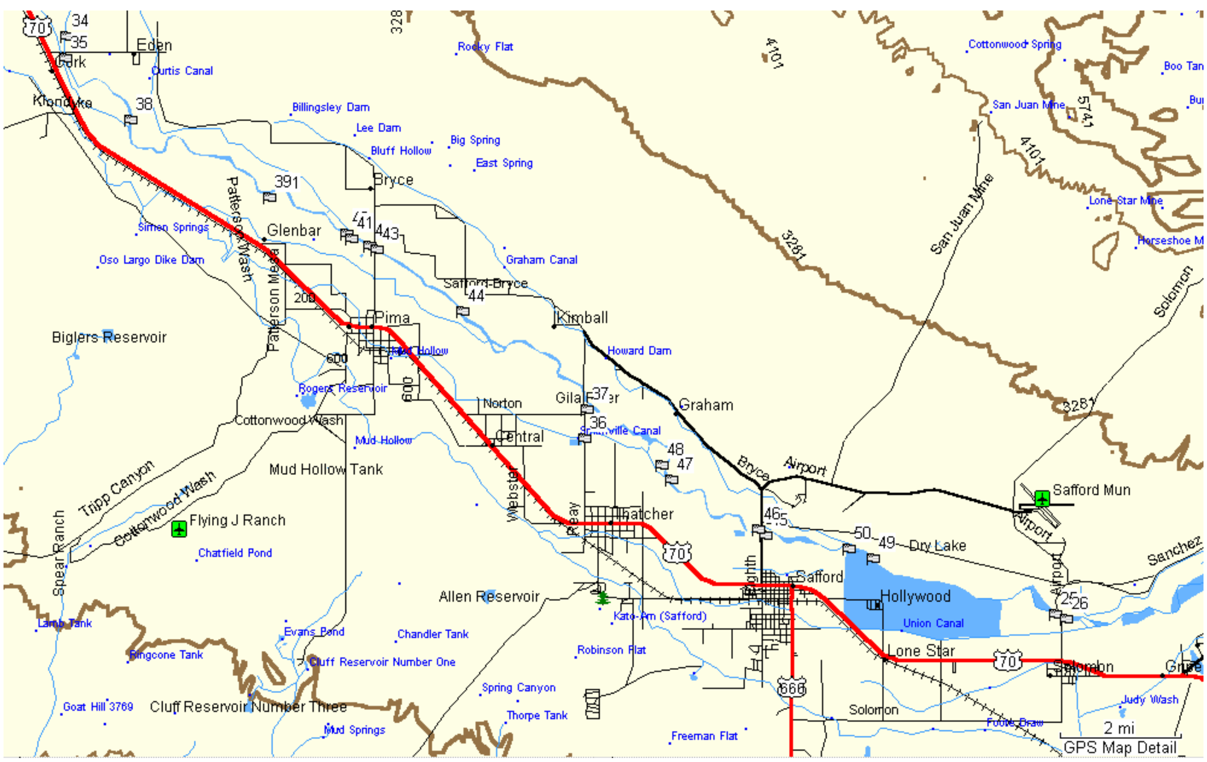

Figure 42. Study reach between the Eden and Solomon areas.

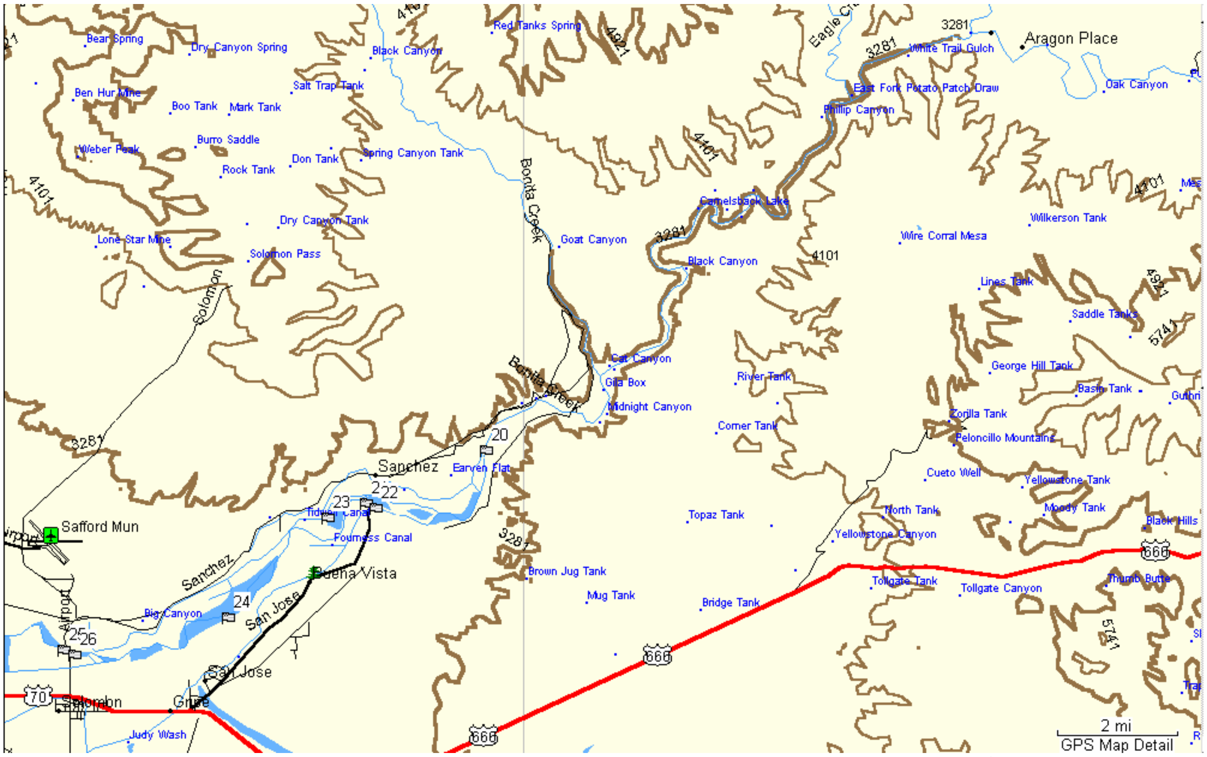

Figure 43. Study reach between Solomon and the 'Box.' Note the San Francisco River entering from the north.

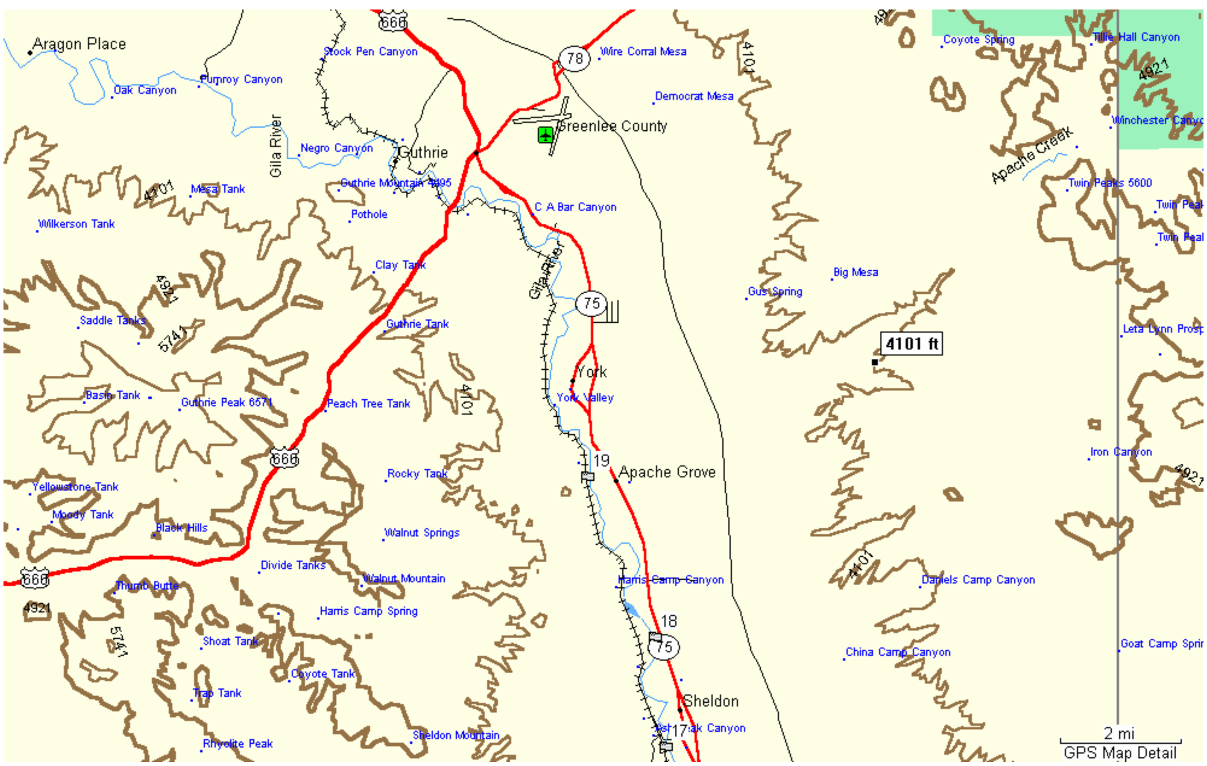

Figure 44. Study reach between the 'Box' and the York Valley, including Sheldon.

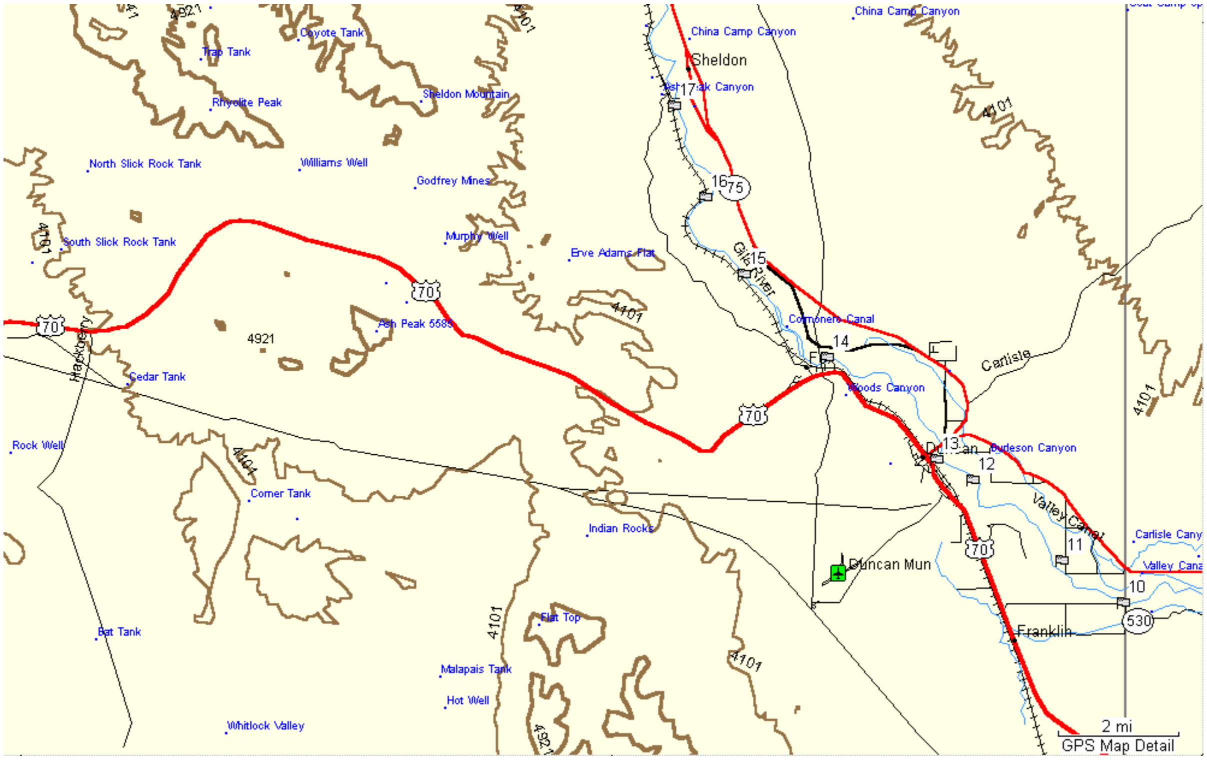

Figure 45. Study reach between Sheldon and the New Mexico state line.

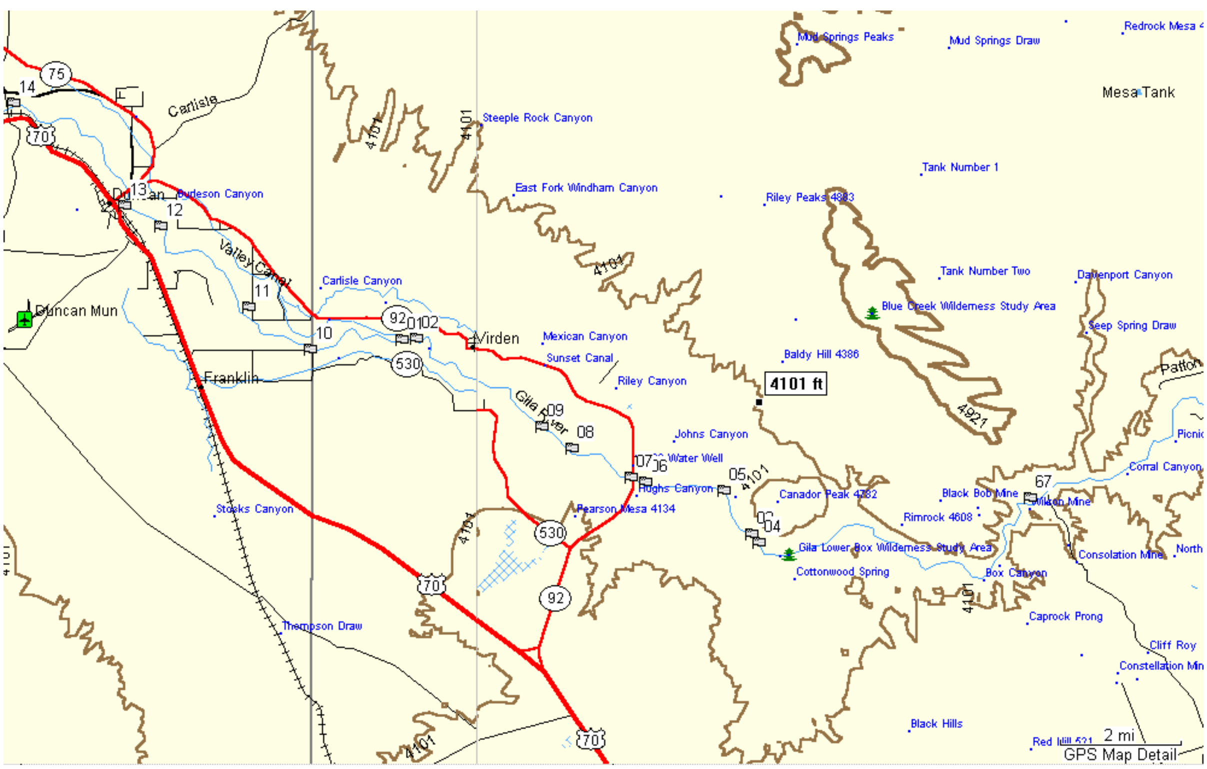

Figure 46. Area outside of study reach between Duncan, the state line (near Carlisle Canyon), and the 'Gila Lower Box' in New Mexico, including the Gila River below Blue Creek, Near Virden, New Mexico gaging station.

Table 12 and Table 13 list the specific locations (Lat/Long - UTM) of all project samples.

Table 12. Sediment sample information (Samples 1-41).

	A	B	C	D	E	F	G	H	I	J	K	L
1	Sample	Date	UTC	Description	Latitude	Longitude	Northing (m)	Easting (m)	State	Type	Depth	Location
2	1	12/13/2000	2131	DS Valley Canal Diversion	N 32°41.339'	W 109°01.333'	3,618,347	685,421	NM	Grab	S - 6 in	REW
3	1A	12/13/2000	2134	DS Valley Canal Diversion	do	do	do	do	NM	Grab	S - 3 in	Bar
4	2	12/13/2000	2217	US Valley Canal Diversion	N 32°41.389'	W 109°00.216'	3,618,472	687,165	NM	Grab	S - 4 in	Bar
5	3	12/13/2000	2321	DS Sunset Ditch Diversion	N 32°38.554'	W 108°55.348'	3,613,379	694,875	NM	Grab	S - 4 in	Bar
6	3A	12/13/2000	2328	DS Sunset Ditch Diversion	do	do	do	do	NM	Grab	S - 4 in	REW
7	4	12/13/2000	2350	US Sunset Ditch Diversion	N 32°38.430'	W 108°55.234'	3,613,154	695,058	NM	Grab	S - 5 in	
8	5	12/13/2000	0026	DS Sunset Ditch Diversion	N 32°39.171'	W 108°55.826'	3,614,505	694,106	NM	Grab	S - 6 in	Bar
9	5A	12/13/2000	0030	Right Bank Tributary Delta opposite Sample 5	do	do	do	do	NM	Photo		REW
10	6	12/14/2000	1545	US Virden Bridge	N 32°39.292'	W 108°57.173'	3,614,688	691,996	NM	Grab	S - 6 in	Midbar
11	6A	12/14/2000	1545	Left Bank Tributary Delta US of Virden Bridge	N 32°39.273'	W 108°57.294'	3,614,649	691,807	NM	Photo	S - 6 in	
12	6B	12/14/2000	1545	do	do	do	do	do	NM	Photo	S - 6 in	
13	7	12/14/2000	1558	DS Virden Bridge	N 32°39.364'	W 108°57.427'	3,614,813	691,596	NM	Grab	S - 6 in	Midbar
14	7A	12/14/2000	1558	DS Virden Bridge	do	do	do	do	NM	Photo		Midbar
15	8	12/14/2000	1630	US Model Canal Diversion	N 32°39.777'	W 108°58.437'	3,615,546	690,002	NM	Grab	S - 6 in	Midbar
16	8A	12/14/2000	1625	Right Bank Tributary Delta US Model Canal Diversion	N 32°39.803'	W 108°58.459'	3,615,593	689,967	NM	Photo		REW
17	9	12/14/2000	1700	DS Model Canal Diversion	N 32°40.088'	W 108°58.945'	3,616,106	689,197	NM	Grab	S - 6 in	REW Midbar
18	9A	12/14/2000	1700	do	do	do	do	do	NM	Photo		do
19	9B	12/14/2000	1706	do	N 32°40.095'	W 108°58.960'	3,616,118	689,174	NM	Photo		do
20	9C	12/14/2000	1706	do	do	do	do	do	NM	Photo		do
21	10	12/14/2000	1755	State Line	N 32°41.203'	W 109°02.898'	3,618,051	682,980	AZ	Grab	S - 6 in	LEW
22	10A	12/14/2000	1751	do	N 32°41.214'	W 109°02.909'	3,618,071	682,963	AZ	Photo		REW
23	11	12/14/2000	1819	Lunt Farm	N 32°41.816'	W 109°03.946'	3,619,153	681,322	AZ	Grab	S - 4 in	Midbar
24	12	12/14/2000	1840	Deadmans Corner	N 32°42.966'	W 109°05.460'	3,621,236	678,918	AZ	Grab	S - 6 in	Midbar
25	13	12/14/2000	1909	US Duncan Bridge	N 32°43.270'	W 109°06.082'	3,621,780	677,936	AZ	Grab	S - 6 in	REW
26	13A	12/14/2000	1912	do	N 32°43.270'	W 109°06.082'	3,621,780	677,936	AZ	Grab	6 - 10 in	do
27	14	12/14/2000	2040	Utilities Crossing	N 32°44.732'	W 109°07.967'	3,624,429	674,943	AZ	Grab	S - 7 in	LEW
28	15	12/14/2000	2118	Little Sand Wash	N 32°45.944'	W 109°09.386'	3,626,630	672,688	AZ	Grab	S - 6 in	Midbar
29	15A	12/14/2000	2122	do	N 32°45.961'	W 109°09.409'	3,626,661	672,652	AZ	Photo		do
30	16	12/14/2000	2153	Sandia Wash Levee	N 32°47.049'	W 109°10.048'	3,628,654	671,619	AZ	Grab	S - 4 in	REW
31	17	12/14/2000	2221	Sheldon	N 32°48.369'	W 109°10.576'	3,631,079	670,753	AZ	Grab	S - 6 in	Midbar
32	18	12/14/2000	2239	Bridge DS of Sheldon	N 32°49.947'	W 109°10.759'	3,633,990	670,417	AZ	Grab	S - 6 in	REW
33	19	12/14/2000	2300	Apache Grove	N 32°52.247'	W 109°11.908'	3,638,210	668,552	AZ	Grab	S - 6 in	LEW
34	20A	12/15/2000	1533	Head of Safford Valley	N 32°52.524'	W 109°30.679'	3,638,265	639,271	AZ	Photo		REW
35	20B	12/15/2000	1533	do	do	do	do	do	AZ	Photo		REW
36	21	12/15/2000	1608	DS San Jose Diversion	N 32°51.764'	W 109°32.758'	3,636,816	636,049	AZ	Grab	S - 6 in	Midbar
37	22	12/15/2000	1626	US San Jose Diversion	N 32°51.690'	W 109°32.576'	3,636,683	636,334	AZ	Grab	S - 6 in	Midbar
38	23	12/15/2000	1701	Brandau Farm	N 32°51.553'	W 109°33.403'	3,636,412	635,048	AZ	Grab	S - 6 in	Midbar
39	24	12/15/2000	1737	Runway	N 32°50.114'	W 109°35.122'	3,633,717	632,403	AZ	Grab	S - 6 in	REW
40	24A	12/15/2000	1735	do	N 32°50.139'	W 109°35.186'	3,633,762	632,302	AZ	Photo		REW
41	24B	12/15/2000	1735	do	do	do	do	do	AZ	Photo		REW
42	24C	12/15/2000	1737	do	N 32°50.114'	W 109°35.122'	3,633,717	632,403	AZ	Photo		REW
43	25	12/15/2000	1812	DS Solomon Bridge	N 32°49.658'	W 109°37.958'	3,632,816	627,989	AZ	Grab	S - 2 in	REW
44	25A	12/15/2000	1812	do	do	do	do	do	AZ	Photo		REW
45	25B	12/15/2000	1812	do	do	do	do	do	AZ	Photo		REW
46	26	12/15/2000	1827	US Solomon Bridge	N 32°49.586'	W 109°37.767'	3,632,687	628,289	AZ	Grab	S - 3 in	REW
47	26A	12/15/2000	1827	do	do	do	do	do	AZ	Photo		REW
48	27	12/15/2000	2000	Geronimo Gage	N 33°05.525'	W 110°01.923'	3,661,721	590,332	AZ	Grab	S - 5 in	REW
49	28	12/15/2000	2028	San Carlos Reservation	N 33°05.312'	W 110°03.094'	3,661,310	588,514	AZ	Grab	S - 6 in	Midbar
50	29	12/15/2000	2100	Black Lane	N 33°04.568'	W 110°00.726'	3,659,970	592,210	AZ	Observation		
51	30	12/15/2000	2131	Emery	N 33°04.018'	W 109°59.606'	3,658,970	593,962	AZ	Grab	S - 5 in	LEW
52	30A	12/15/2000	2131	do	do	do	do	do	AZ	Photo		LEW
53	31	12/15/2000	2215	US Ft. Thomas River Road (Low Water Crossing)	N 33°02.991'	W 109°57.953'	3,657,097	596,553	AZ	Grab	S - 5 in	LEW
54	32	12/15/2000	2223	DS Ft. Thomas River Road (Low Water Crossing)	N 33°02.969'	W 109°58.024'	3,657,056	596,443	AZ	Grab	S - 5 in	LEW
55	32A	12/15/2000	2223	do	do	do	do	do	AZ	Photo		LEW
56	32B	12/15/2000	2223	do	do	do	do	do	AZ	Photo		LEW
57	33	12/15/2000	2250	Forty Lane	N 33°01.178'	W 109°55.769'	3,653,781	599,986	AZ	Grab	S - 5 in	LEW
58	34	12/15/2000	2331	DS Eden Bridge	N 32°57.923'	W 109°54.876'	3,647,781	601,438	AZ	Grab	S - 3 in	REW
59	35	12/15/2000	2347	US Eden Bridge	N 32°57.608'	W 109°54.888'	3,647,199	601,425	AZ	Grab	S - 3 in	Midbar
60	36	12/16/2000	1416	DS Thatcher Bridge	N 32°52.169'	W 109°46.016'	3,637,301	615,363	AZ	Grab	S - 4 in	REW
61	36A	12/16/2000	1416	do	do	do	do	do	AZ	Photo		REW
62	36B	12/16/2000	1416	do	do	do	do	do	AZ	Photo		REW
63	37	12/16/2000	1420	US Thatcher Bridge	N 32°52.584'	W 109°45.962'	3,638,069	615,439	AZ	Grab	S - 5 in	Midbar
64	38	12/16/2000	1515	DS Ft. Thomas Canal Diversion	N 32°56.728'	W 109°53.789'	3,645,591	603,154	AZ	Grab	S - 4 in	Midbar
65	38A	12/16/2000	1515	do	N 32°56.728'	W 109°53.788'	3,645,591	603,156	AZ	Photo		Midbar
66	38B	12/16/2000	1515	do	do	do	do	do	AZ	Photo		Midbar
67	39	12/16/2000	1602	Glenbar	N 32°55.624'	W 109°51.399'	3,643,591	606,900	AZ	Grab	S - 4 in	Midbar
68	40	12/16/2000	1641	DS Curtis Canal Diversion	N 32°55.092'	W 109°50.087'	3,642,630	608,956	AZ	Grab	S - 6 in	LEW of Island
69	40A	12/16/2000	1641	do	do	do	do	do	AZ	Photo		do
70	40B	12/16/2000	1641	do	do	do	do	do	AZ	Photo		do
71	41	12/16/2000	1657	US Curtis Canal Diversion	N 32°55.034'	W 109°55.008'	3,642,441	601,287	AZ	Grab	S - 3 in	LEW

Table 13. Sediment sample information (Samples 41-72).

	A	B	C	D	E	F	G	H	I	J	K	L
72	42	12/16/2000	1730	DS Pima Bridge	N 32°54.924'	W 109°49.686'	3,642,326	609,584	AZ	Grab	S - 5 in	REW of Midbar
73	42A	12/16/2000	1730	do	do	do	do	do	AZ	Photo		do
74	42B	12/16/2000	1730	do	do	do	do	do	AZ	Photo		do
75	43	12/16/2000	1742	US Pima Bridge	N 32°54.868'	W 109°49.574'	3,642,225	609,760	AZ	Grab	S - 6 in	REW
76	43A	12/16/2000	1742	do	do	do	do	do	AZ	Photo		REW
77	44	12/16/2000	1826	Holyoke	N 32°53.982'	W 109°48.105'	3,640,614	612,068	AZ	Grab	S - 4 in	REW-ROB
78	44A	12/16/2000	1826	do	N 32°53.979'	W 109°48.110'	3,640,608	612,060	AZ	Photo		do
79	44B	12/16/2000	1826	do	do	do	do	do	AZ	Photo		do
80	45	12/16/2000	1945	US Safford Bridge	N 32°50.781'	W 109°42.917'	3,634,794	620,227	AZ	Grab	S - 5 in	LEW
81	45A	12/16/2000	1945	do	do	do	do	do	AZ	Photo		LEW
82	45B	12/16/2000	1945	do	do	do	do	do	AZ	Photo		LEW
83	46	12/16/2000	1955	DS Safford Bridge	N 32°50.857'	W 109°43.046'	3,634,932	620,024	AZ	Grab	S - 3 in	LEW
84	47	12/16/2000	2118	US Smithville Canal Diversion	N 32°51.574'	W 109°34.521'	3,636,427	633,304	AZ	Grab		Bed
85	48BB	12/16/2000	2143	DS Smithville Canal Diversion	N 32°51.777'	W 109°44.686'	3,636,601	617,446	AZ	Grab	S - 4 in	LEW
86	48RJW	12/16/2000	2143	do	do	do	do	do	AZ	Grab	S - 4 in	LEW
87	48A	12/16/2000	2143	do	do	do	do	do	AZ	Photo		LEW
88	48B	12/16/2000	2143	do	do	do	do	do	AZ	Photo		LEW
89	49	12/16/2000	2308	US Graham Diversion Canal	N 32°50.446'	W 109°41.079'	3,634,210	623,102	AZ	Grab	S - 6 in	Midbar
90	49A	12/16/2000	2308	do	do	do	do	do	AZ	Photo		
91	49B	12/16/2000	2308	do	do	do	do	do	AZ	Photo		
92	49C	12/16/2000	2308	do	do	do	do	do	AZ	Photo		
93	49D	12/16/2000	2308	do	do	do	do	do	AZ	Photo		
94	49E	12/16/2000	2308	do	do	do	do	do	AZ	Photo		
95	50	12/16/2000	0000	DS Graham Diversion Canal	N 32°50.582'	W 109°41.491'	3,634,454	622,456	AZ	Grab		REW
96	50A	12/16/2000	0000	do	do	do	do	do	AZ	Photo		REW
97	50B	12/16/2000	0000	do	do	do	do	do	AZ	Photo		REW
98	50C	12/16/2000	0000	do	do	do	do	do	AZ	Photo		REW
99	51	12/18/2000	1645	DS Hooker Dam Site @ USGS Gage	N 33°03.671'	W 108°32.276'	3,660,574	729,871	NM	Grab	S - 4 in	REW
100	51A	12/18/2000	1645	do	do	do	do	do	NM	Photo		REW
101	51B	12/18/2000	1645	do	do	do	do	do	NM	Photo		REW
102	51C	12/18/2000	1645	do	do	do	do	do	NM	Photo		Bed
103	52	12/18/2000	1709	1/4 mi. DS Hooker Dam Site & USGS Gage	N 33°03.379'	W 108°32.447'	3,660,028	729,618	NM	Grab	S - 4 in	Midbar
104	53	12/18/2000	1817	DS Shelley Ditch Diversion	N 33°01.411'	W 108°32.267'	3,656,397	729,983	NM	Grab	S - 2 in	REW
105	53A	12/18/2000	1817	do	do	do	do	do	NM	Photo		
106	53B	12/18/2000	1817	do	do	do	do	do	NM	Photo		
107	54	12/18/2000	1833	US Shelley Ditch Diversion	N 33°01.674'	W 108°32.196'	3,656,886	730,082	NM	Grab	S - 5 in	Midbar
108	55	12/18/2000	1948	DS Seeds of Change	N 33°00.835'	W 108°33.008'	3,655,305	728,854	NM	Grab	S - 4 in	
109	55A	12/18/2000	1948	do	do	do	do	do	NM	Photo		
110	55B	12/18/2000	1948	do	do	do	do	do	NM	Photo		
111	55C	12/18/2000	1948	do	do	do	do	do	NM	Photo		
112	56	12/18/2000	2015	US 211 Bridge	N 32°58.175'	W 108°35.219'	3,650,309	725,524	NM	Grab	S - 5 in	REW
113	57	12/18/2000	2023	DS 211 Bridge	N 32°58.140'	W 108°35.269'	3,650,243	725,447	NM	Grab	S - 5 in	Midbar
114	58	12/18/2000	2056	Riverside	N 32°55.674'	W 108°35.776'	3,645,667	724,761	NM	Grab	S - 6 in	LEW
115	58A	12/18/2000	2056	do	do	do	do	do	NM	Photo		LEW
116	58B	12/18/2000	2056	do	do	do	do	do	NM	Photo		LEW
117	58C	12/18/2000	2056	do	do	do	do	do	NM	Photo		LEW
118	59	12/18/2000	2110	Bill Evans DS Greenwood	N 32°54.596'	W 108°35.679'	3,643,678	724,958	NM	Grab	S - 3 in	LEW
119	60	12/18/2000	2122	US Bill Evans	N 32°53.795'	W 108°35.842'	3,642,192	724,738	NM	Grab	S - 6 in	
120	61	12/18/2000	2200	River Vista	N 32°49.949'	W 108°36.697'	3,635,053	723,565	NM	Grab	S - 5 in	Midbar
121	62	12/18/2000	2227	Mouth of Ira Canyon	N 32°48.806'	W 108°36.169'	3,632,959	724,437	NM	Grab	S - 6 in	
122	62A	12/18/2000	2227	do	do	do	do	do	NM	Photo		
123	62B	12/18/2000	2227	do	do	do	do	do	NM	Photo		
124	63	12/18/2000	2300	Cherokee Canyon	N 32°51.304'	W 108°35.394'	3,637,604	725,541	NM	Grab	S - 6 in	Midbar
125	64	12/18/2000	2325	DS Iron Bridge	N 32°56.240'	W 108°36.254'	3,646,696	723,992	NM	Grab	S - 6 in	Point Bar
126	65	12/18/2000	2348	US Iron Bridge/DS 180 Bridge	N 32°56.563'	W 108°36.555'	3,647,282	723,510	NM	Grab	S - 6 in	LEW
127	65A	12/18/2000	2348	do	do	do	do	do	NM	Photo		
128	65B	12/18/2000	2348	do	do	do	do	do	NM	Photo		
129	66	12/18/2000	0005	US 180 Bridge	N 32°56.824'	W 108°36.420'	3,647,769	723,709	NM	Grab	S - 6 in	LEW
130	66A	12/18/2000	0005	do	do	do	do	do	NM	Photo		LEW
131	67	12/19/2000	1542	Nichols Canyon	N 32°39.073'	W 108°50.588'	3,614,487	702,299	NM	Grab	S - 3 in	LEW
132	67A	12/19/2000	1542	do	do	do	do	do	NM	Photo		LEW
133	67B	12/19/2000	1542	do	do	do	do	do	NM	Photo		LEW
134	67C	12/19/2000	1542	do	do	do	do	do	NM	Photo		LEW
135	68	12/19/2000	1643	US Redrock Bridge	N 32°41.713'	W 108°44.014'	3,619,580	712,474	NM	Grab	S - 5 in	REW Point Bar
136	69	12/19/2000	1656	DS Redrock Bridge	N 32°41.597'	W 108°43.979'	3,619,367	712,533	NM	Grab	S - 5 in	REW
137	69A	12/19/2000	1656	do	do	do	do	do	NM	Photo		REW
138	69B	12/19/2000	1656	do	do	do	do	do	NM	Photo		REW
139	70	12/19/2000	1808	Conner Ranch	N 32°43.636'	W 108°41.670'	3,623,213	716,059	NM	Grab	S - 4 in	LEW
140	70A	12/19/2000	1808	Conner Ranch	N 32°43.636'	W 108°41.670'	3,623,213	716,059	NM	Photo		REW
141	70B	12/19/2000	1808	Conner Ranch	N 32°43.636'	W 108°41.670'	3,623,213	716,059	NM	Photo		REW
142	71	12/19/2000	1900	Gila@Redrock USGS gage	N 32°43.592'	W 108°40.706'	3,623,165	717,567	NM	Grab	S - 5 in	LEW

SELECTED BED MATERIAL SAMPLES

The stable channel analysis and RISAD require a gradation of the bed material as well as a maximum size, D_{100}, and median size, D_{50}. After review of the sample locations and types in each of the four lower sub-reaches and the Upper Reach, the following representative samples were selected for the analysis.

Lower Reach 1

Grab samples 27 and 28 represent the gradation of the bed material in Lower Reach 1. Sample 27 was collected near the Geronimo USGS gaging station. Sample 28 was collected at the San Carlos Reservation boundary. Figure 47 show the gradations.

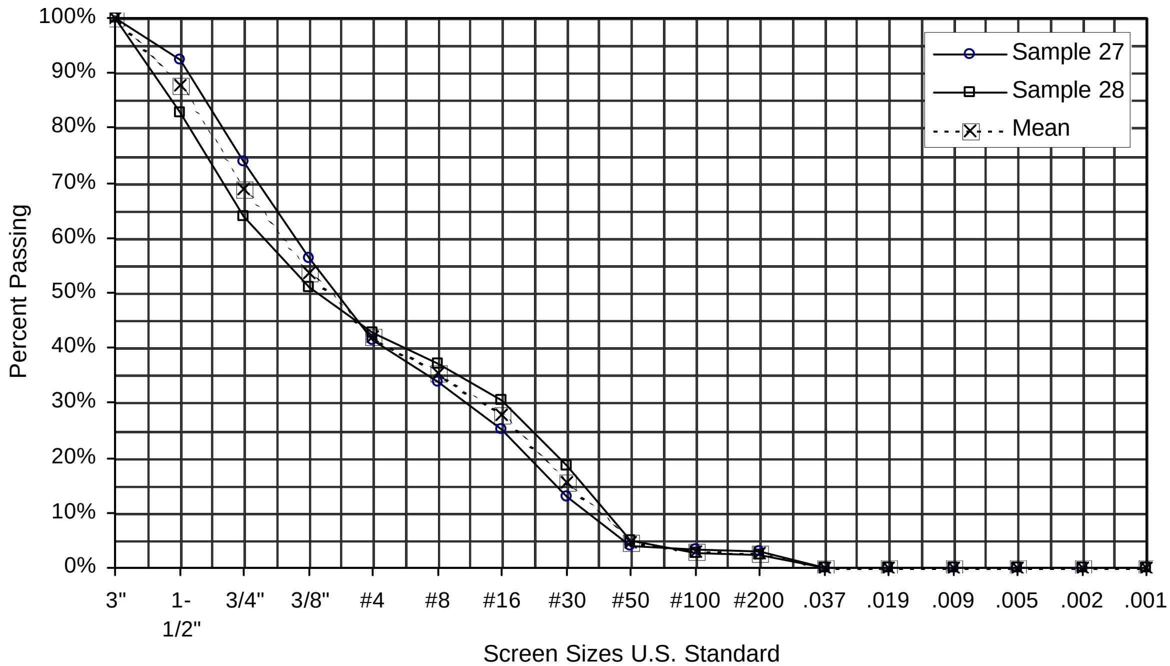

Figure 47. Gradations of grab samples 27 and 28, and their mean. Particle sizes in inches, standard sieve size, or millimeters. Lower Reach 1.

Lower Reach 2

Grab samples 31 and 33 represent the gradation of the bed material in Lower Reach 2. Sample 31 was collected near upstream of the Fort Thomas River Road. Sample 33 was collected at Forty Lane. Figure 48 shows the gradations.

Lower Reach 3

Grab samples 34, 39, and 44, and photographic samples 44A and 44B, and their combinations, represent Lower Reach 3. Figure 49 shows the gradations. The bi-modal nature of the bed material was especially pronounced in Lower Reach 3. There was a large difference, up to four orders of magnitude, between the maximum and minimum sizes of sediment in all of the reaches. The bi-modal nature of the bed material, split between a fine sub-surface layer and a coarse surface layer, made combining grab and photographic samples necessary to characterize the bed material.

Grab samples 34 and 44 are similar. Photographic samples 44A and 44B are similar. Grab sample 39 fell in between the two. The combination gradation consists of a 33.3% portion of grab samples 34 and 44, and a 66.7% portion of photographic samples 44A and 44B. Both the combination gradation and grab sample 39 were applied in the RISAD analysis, with no appreciable difference. The combination gradation was chosen for the final analysis.

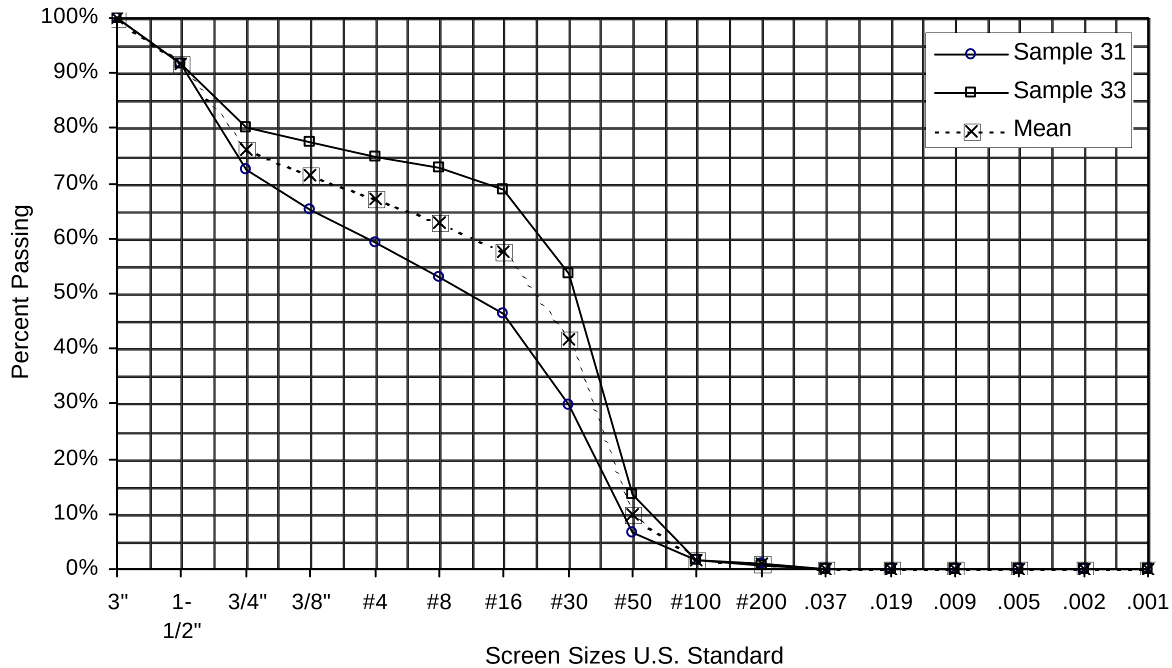

Figure 48. Gradations of grab samples 31 and 33 and their mean. Lower Reach 2. Particle sizes in inches, standard sieve size, or millimeters.

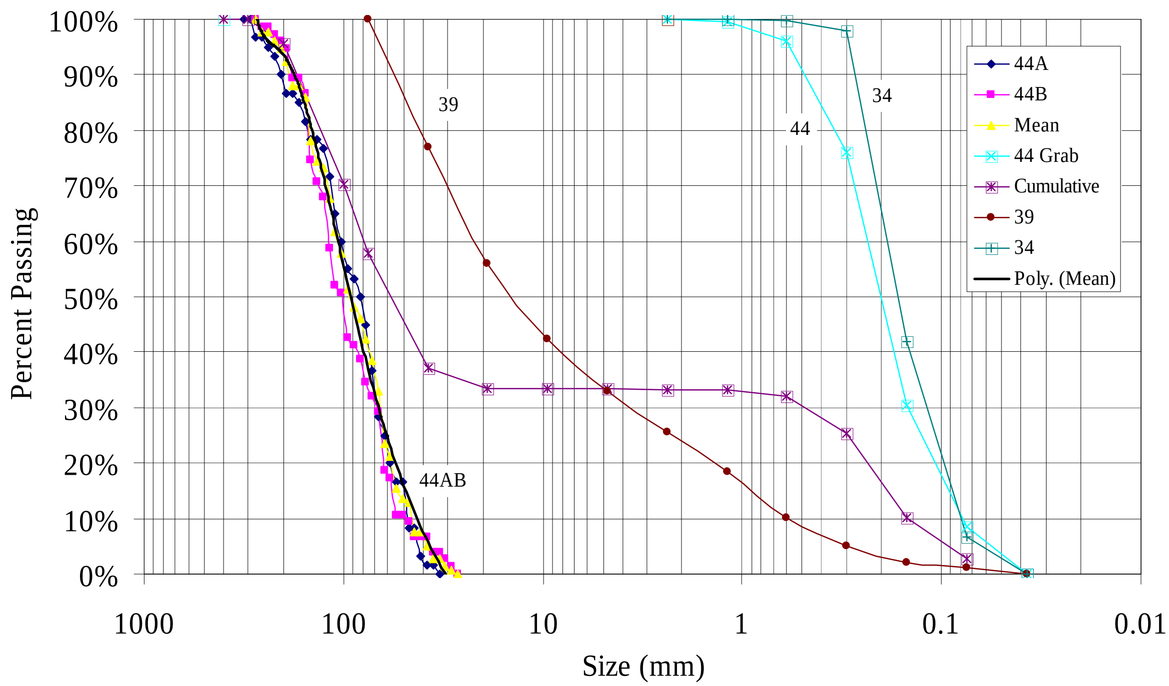

Figure 49. Gradations of grab samples 34, 39, and 44, and photographic samples 44A and 44B, and their combinations. Lower Reach 3.

Lower Reach 4

Grab samples 23 and 24 represent the gradation of the bed material in Lower Reach 4. Sample 23 was collected near the Brandau farm below the San Jose diversion. Sample 24 was collected near the ‘runway’ below Brandau’s farm. Sample 24 was one of the few attempts to collect both the surface and sub-surface material. A single particle greater than 3” (76 mm) in diameter was collected in the grab sample. That is why the sample is designated 24/w, indicating that the sample was analyzed ‘with’ the large particle. The laboratory also analyzed the sample without the large particle. The USGS (USGS, 2001) sampled bed material near the gage at the head of the Safford Valley. That material, collected upstream of the San Jose diversion, is much finer than the bed material collected in samples 23 and 24 below the diversion.

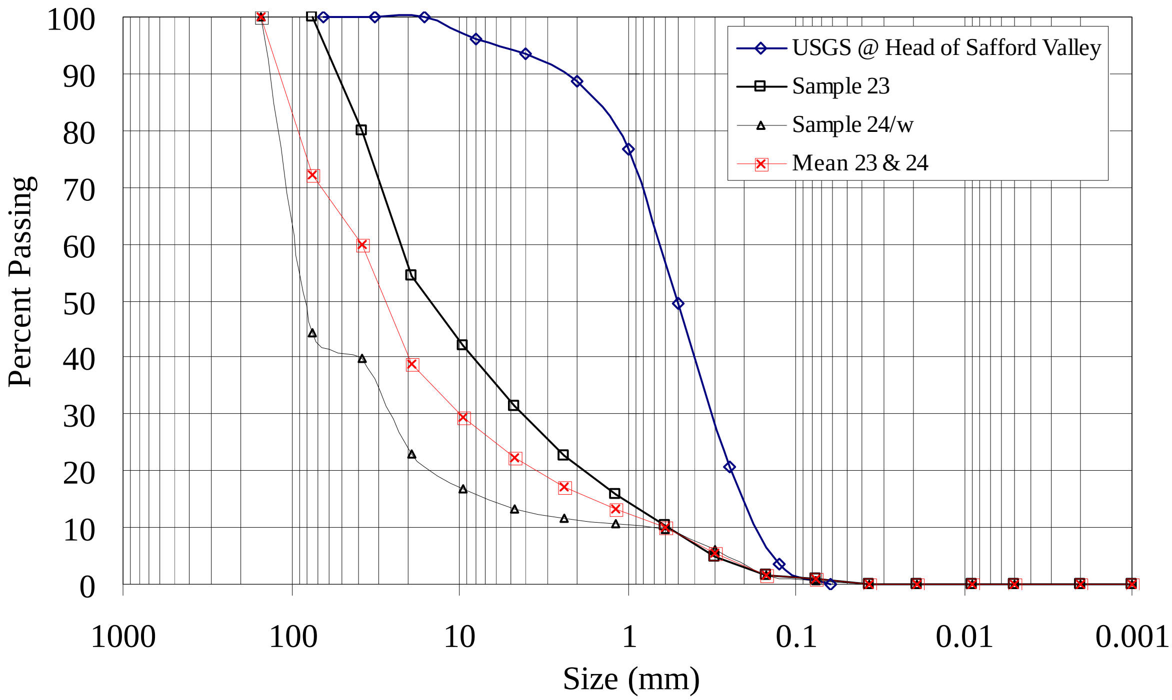

Figure 50. Gradations of grab samples 23 and 24/w, their mean, and the mean USGS gradation from near the gaging station at the head of the Safford Valley. Lower Reach 4.

<u>Upper Reach</u>

Grab samples 11, 12, 16, 17, and 18 represent the gradation of the bed material in the Upper Reach. Sample 11 was collected near the Lunt farm, upstream from Duncan, Arizona. Sample 12 was collected near Deadman’s Corner, downstream from the Lunt farm. Sample 16 was collected near the Sandia wash levee. Sample 17 was collected near Sheldon, Arizona, and Sample 18 was collected near the flatcar bridge downstream of Sheldon.

The mean of these five gradations appears to represent the range of bed material sizes in the individual samples, being similar to samples 11, 17, and 18, and splitting the difference between the extremes of samples 12 and 16.

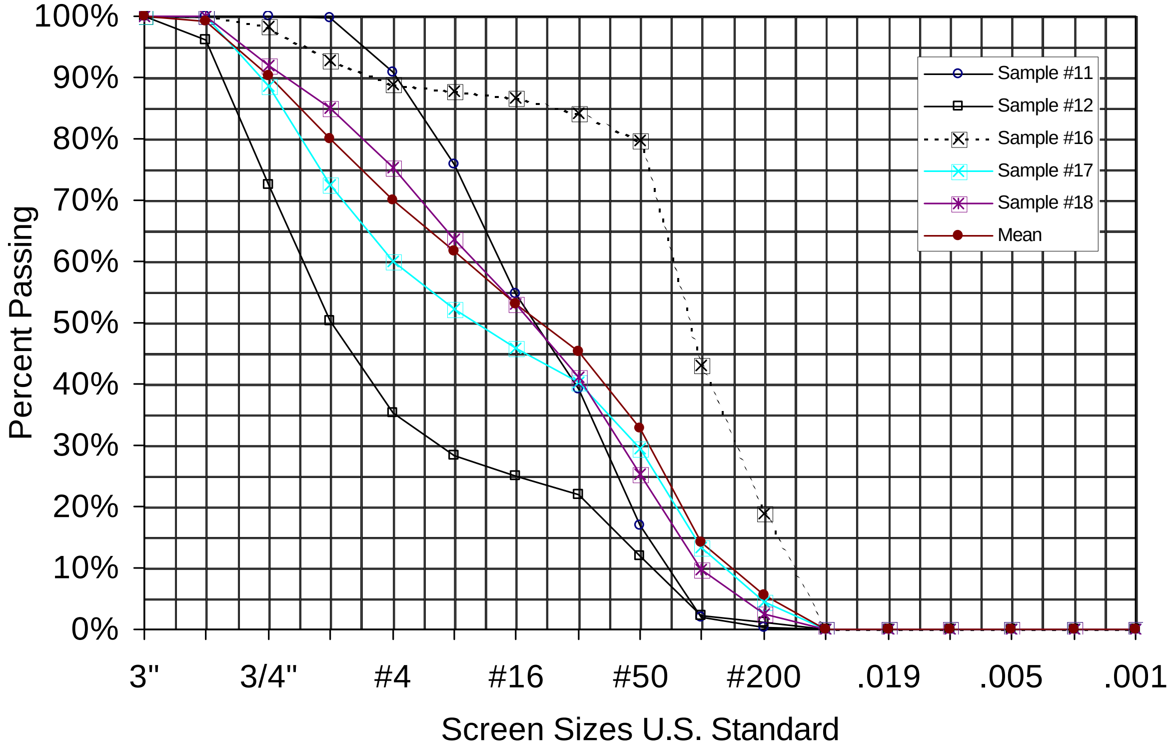

Figure 51. Gradations of grab samples 23 and 24/w, their mean. Particle sizes in inches, standard sieve size, or millimeters. Upper Reach.

BACKWATER ANALYSIS USING HEC-RAS 3.01

HEC-RAS, River Analysis System, Version 3.01, calculates water surface profiles for both steady and unsteady gradually varied flow. The system can handle a full network of channels, a dendritic system, or a single river reach. Cross sections were developed from the Digital Terrain Models (DTM's) produced under Tasks 5 and 6, Orthophotography and Topography, of the Upper Gila River Fluvial Geomorphology Study. The cross sections were checked against aerial photographs and orthophotographs to insure accuracy of the ground terrain. The Manning roughness, *n*, for the main channel was designated to be 0.035, and 0.080 for the left and right over banks. HEC-RAS uses a local coordinate system for measuring the channel distance and thus the cross sectional stationing (meters). In each modeling reach HEC-RAS begins at Cross Section 1, and begins measuring upstream, in meters, along the centerline of the channel. The stationing accumulates from '0' and is labeled in each of the cross-section figures. The stationing in HEC-RAS does not relate to other stationing systems. The stationing begins at zero in each of the four separate reaches analyzed in this study. All lengths are in meters.

Lower Reach 1

Figure 52 illustrates in plan view the cross sections and thalweg of Lower Reach 1. The arrow indicates the flow direction. The thalweg is the lowest point in the cross section. The blue line indicates the location of the low-flow channel thalweg. The reach length is roughly 8.5 km. The green lines indicate the locations of the cross sections. The first downstream section is at station 156.1907 meters (512 ft). The upstream section is at station 8502.539. The pair of red dots on each green cross section indicates the location of the left and right banks of the active channel.

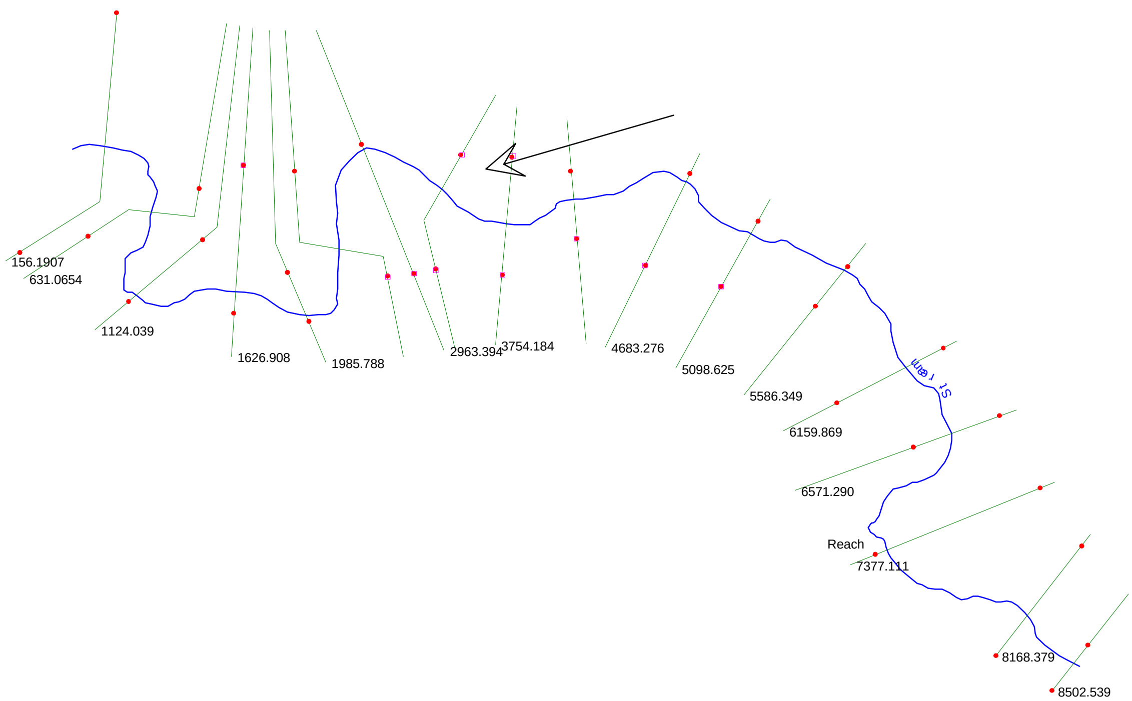

Figure 52. Plan view of HEC-RAS sections and thalweg in Lower Reach 1. (meters)

Figure 53 plots the stream bed profile and water surface profiles (PF) corresponding to discharges of 2,329 m^3/s (82,252 ft^3/s) (PF 1), 422 m^3/s (14, 907 ft^3/s) (PF 3), and 0.002 m^3/s (0.08 ft^3/s) (PF 19).

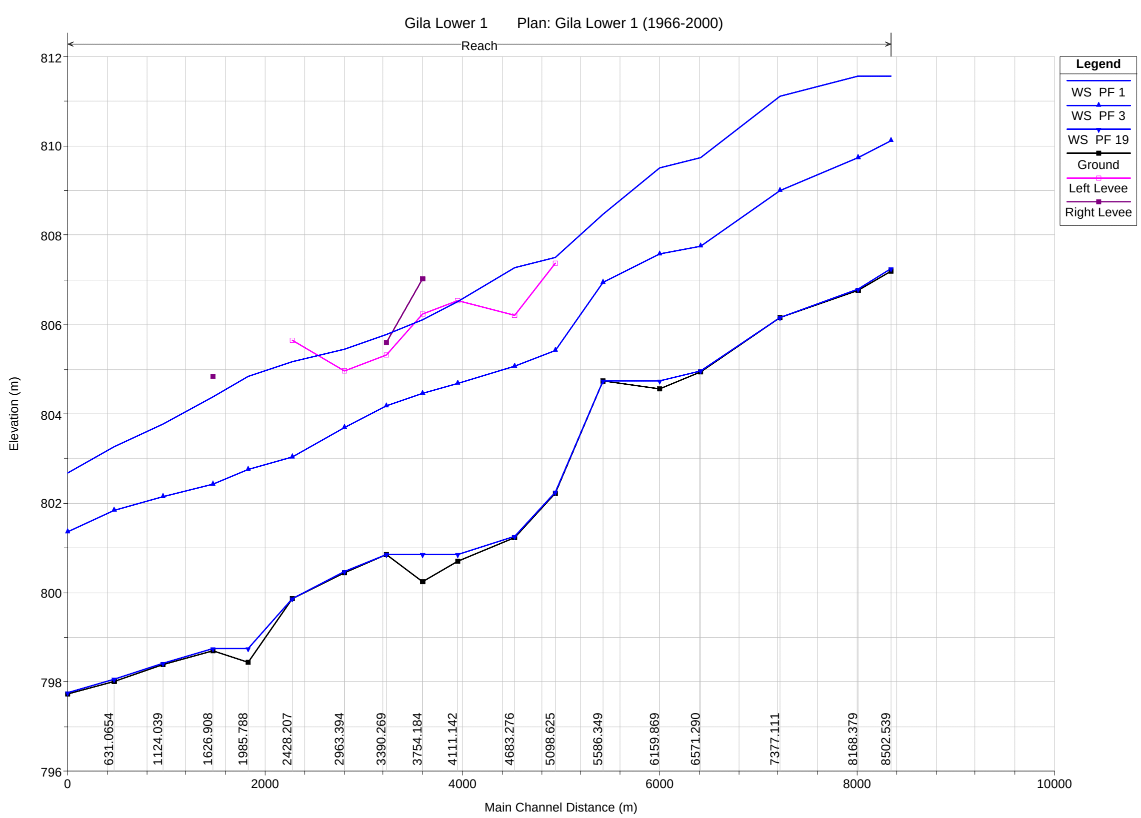

Figure 53. Profile of Lower Reach 1, showing water surface profiles at 2,329 m^3/s (82,252.68 ft^3/s) (PF1), 422 m^3/s (14,907.88 ft^3/s) (PF 3), and 0.002 m^3/s (0.08 ft^3/s) (PF 19).

Lower Reach 2

Figure 54 illustrates in plan view the cross sections and thalweg of Lower Reach 2. The thalweg is the lowest point in the cross section. The solid blue line indicates the location of the low-flow channel thalweg. The reach length is roughly 8.2 km. The green lines indicate the location of the cross sections. The downstream section is at station 0, the first upstream section is at station 29.5708. The upstream section is at station 8221.621. The pair of red dots on each cross section indicates the location of the left and right banks of the active channel.

Figure 55 plots the stream bed profile and water surface profiles (PF) at discharges of 2,329 m^3/s (82,252.68 ft^3/s) (PF1), 422 m^3/s (14,907.88 ft^3/s) (PF 3), and 0.002 m^3/s (0.08 ft^3/s) (PF 19).

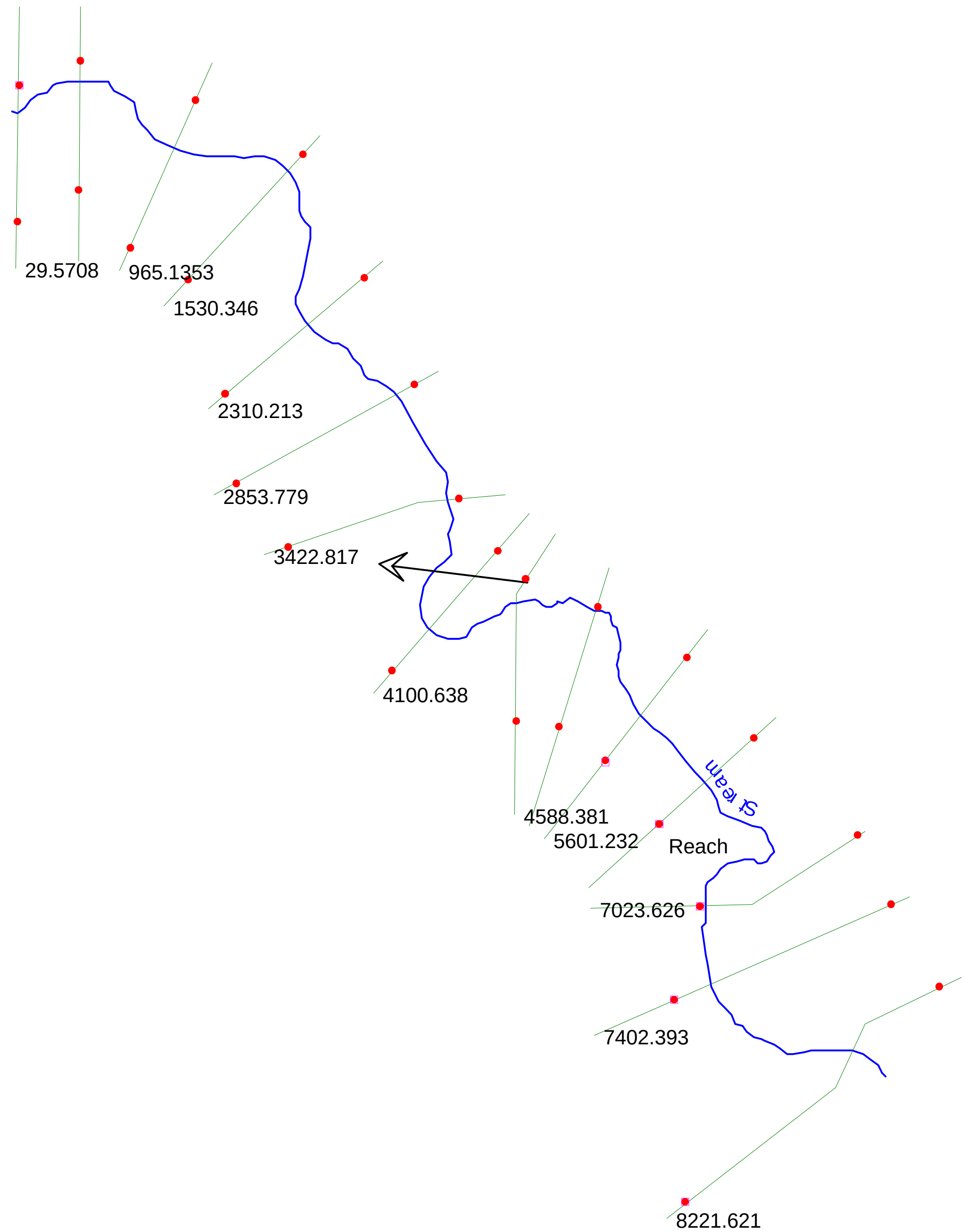

Figure 54. Plan view of HEC-RAS sections and channel in Lower Reach 2. (meters)

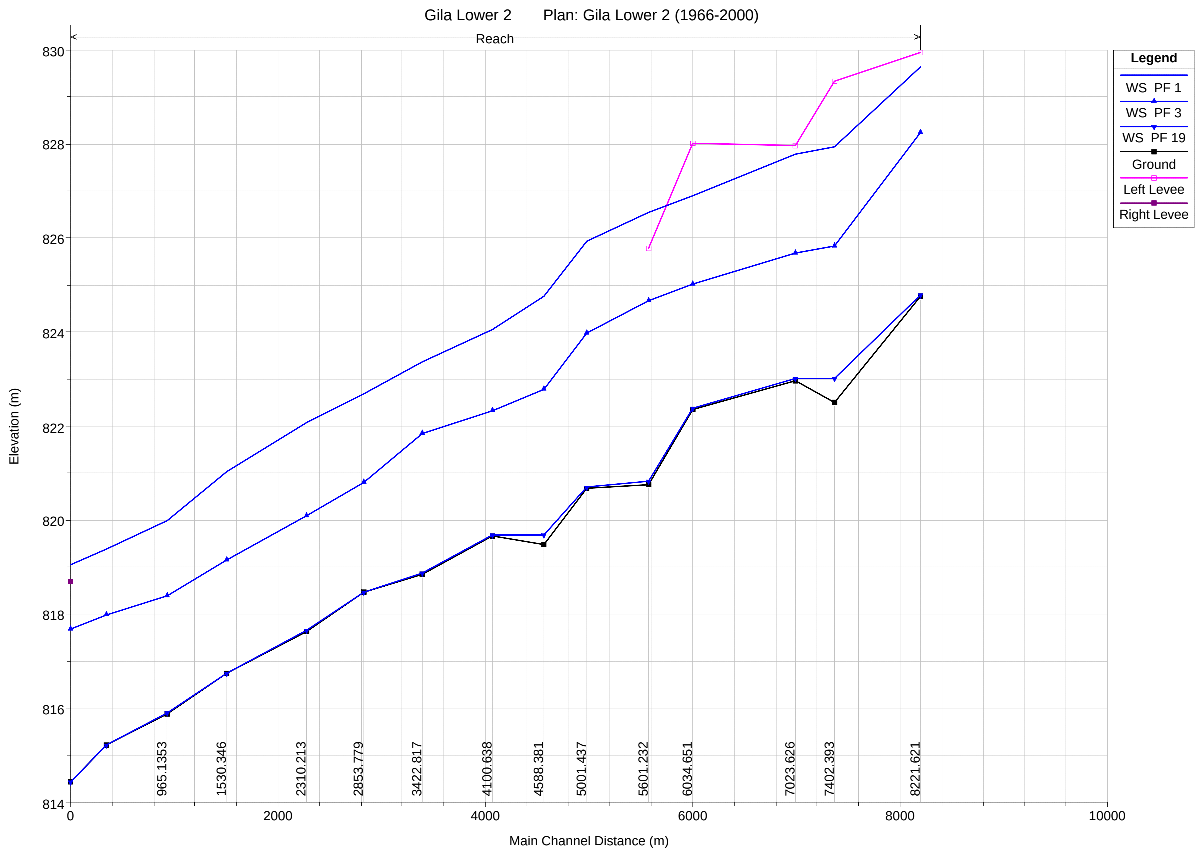

Figure 55. Profile of Lower Reach 2, showing water surface profiles at 2,329 m^3/s (82,252.68 ft^3/s) (PF1), 422 m^3/s (14,907.88 ft^3/s) (PF 3), and 0.002 m^3/s (0.08 ft^3/s) (PF 19).

Lower Reach 3

Figure 56 illustrates in plan view the cross sections and thalweg of Lower Reach 3. The thalweg is the lowest point in the cross section. The blue line indicates the location of the low-flow channel. The thalweg in this reach is roughly 18.9 km in length. The green lines indicate the location of the cross sections. The downstream section is at station 0, the first upstream section is at station 93.9761. The upstream section is at station 18193.84. The pair of red dots indicates the location of the left and right banks of the active channel.

Figure 57 plots the stream bed profile and water surface profiles (PF) corresponding to discharges of 1,924 m^3/s (67,932.73 ft^3/s) (PF 1), 1,197 m^3/s (42,286.92 ft^3/s) (PF 2), 426 m^3/s (15,045.98 ft^3/s) (PF 3), and 0.52 m^3/s (18.40 ft^3/s) (PF 19).

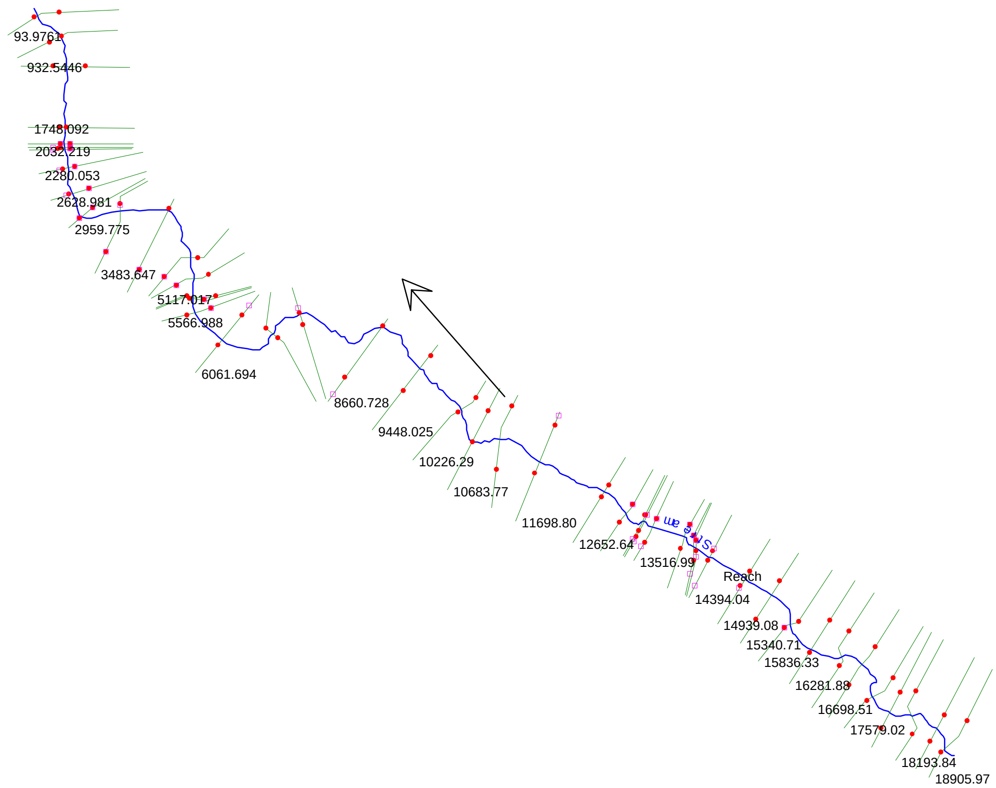

Figure 56. Plan view of HEC-RAS sections and channel in Lower Reach 3. (meters)

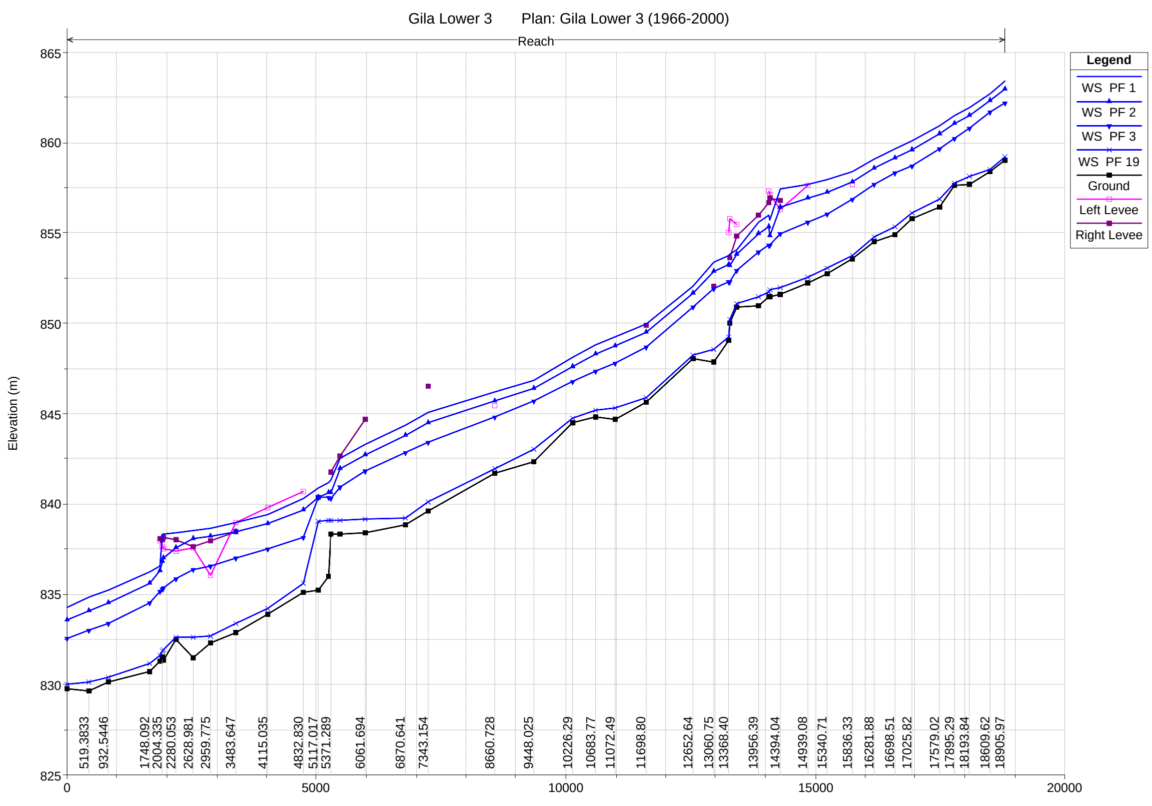

Figure 57. Profile of Lower Reach 3, showing water surface profiles at 1,924 m³/s (67,932.73 ft³/s) (PF 1), 1,197 m³/s (42,286.92 ft³/s) (PF 2), 426 m³/s (15,045.98 ft³/s) (PF 3), and 0.52 m³/s (18.40 ft³/s) (PF 19).

Lower Reach 4

Figure 58 illustrates in plan view the cross sections and thalweg of Lower Reach 4. The thalweg is the lowest point in the cross section. The thalweg in this reach is roughly 17.4 km long. The downstream section is at station 0, the first upstream section is at station 46.5883. The upstream section is at 17428.

Figure 59 plots the stream bed profile and water surface profiles (PF) corresponding to discharges of 1,924 m^3/s (67,932.73 ft^3/s) (PF 1), 1,197 m^3/s (42,286.92 ft^3/s) (PF 2), 426 m^3/s (15,045.98 ft^3/s) (PF 3), and 0.52 m^3/s (18.40 ft^3/s) (PF 19).

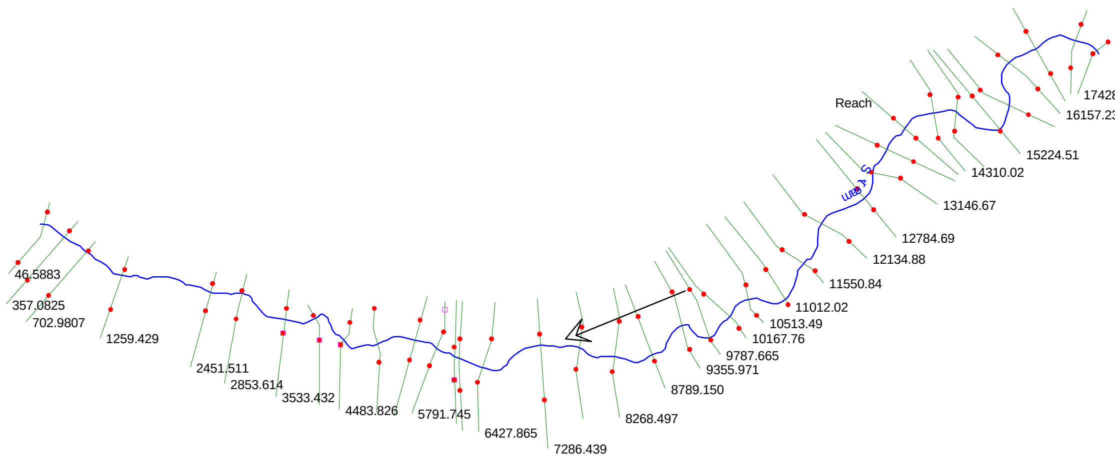

Figure 58. Plan view of HEC-RAS sections and channel in Lower Reach 4. (meters)

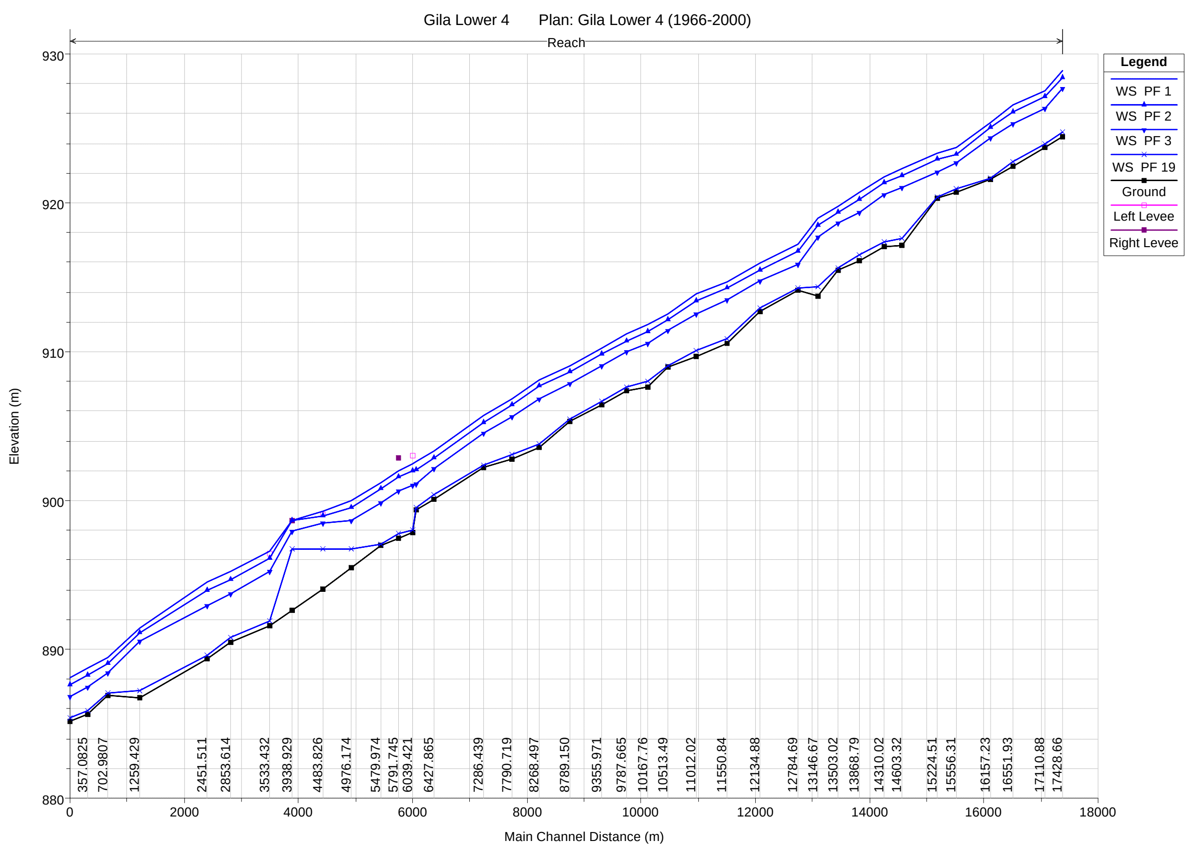

Figure 59. Profile of Lower Reach 4, showing water surface profiles at 1,924 m^3/s (67,932.73 ft^3/s) (PF 1), 1,197 m^3/s (42,286.92 ft^3/s) (PF 2), 426 m^3/s (15,045.98 ft^3/s) (PF 3), and 0.52 m^3/s (18.40 ft^3/s) (PF 19).

Upper Reach

Figure 60 illustrates in plan view the cross sections and thalweg of the Upper Reach. The thalweg is the lowest point in the cross section. The thalweg in this reach is roughly 27.6 km in length. The downstream section is at station 0, the first upstream section is at station 484.3019. The upstream section is at station 27581.31.

Figure 61 plots the stream bed profile and water surface profiles (PF) corresponding to discharges of 652.26 m^3/s (23,034.46 ft^3/s) (PF 1), 402.72 m^3/s (14,221.95 ft^3/s) (PF 2), 152.47 m^3/s (5,384.36 ft^3/s) (PF 3), and 0.033 m^3/s (1.17 ft^3/s) (PF 19).

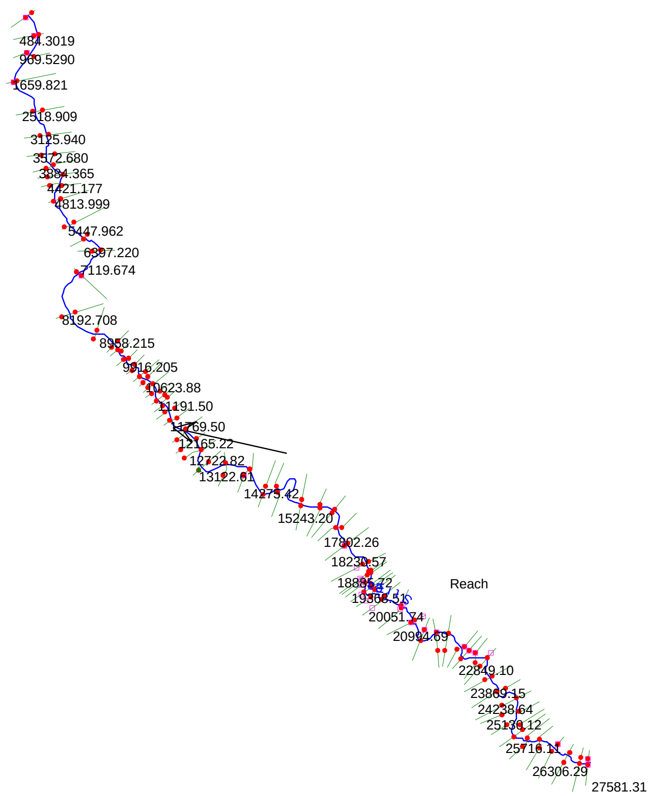

Figure 60. Plan view of HEC-RAS sections and channel in Upper Reach. (meters)

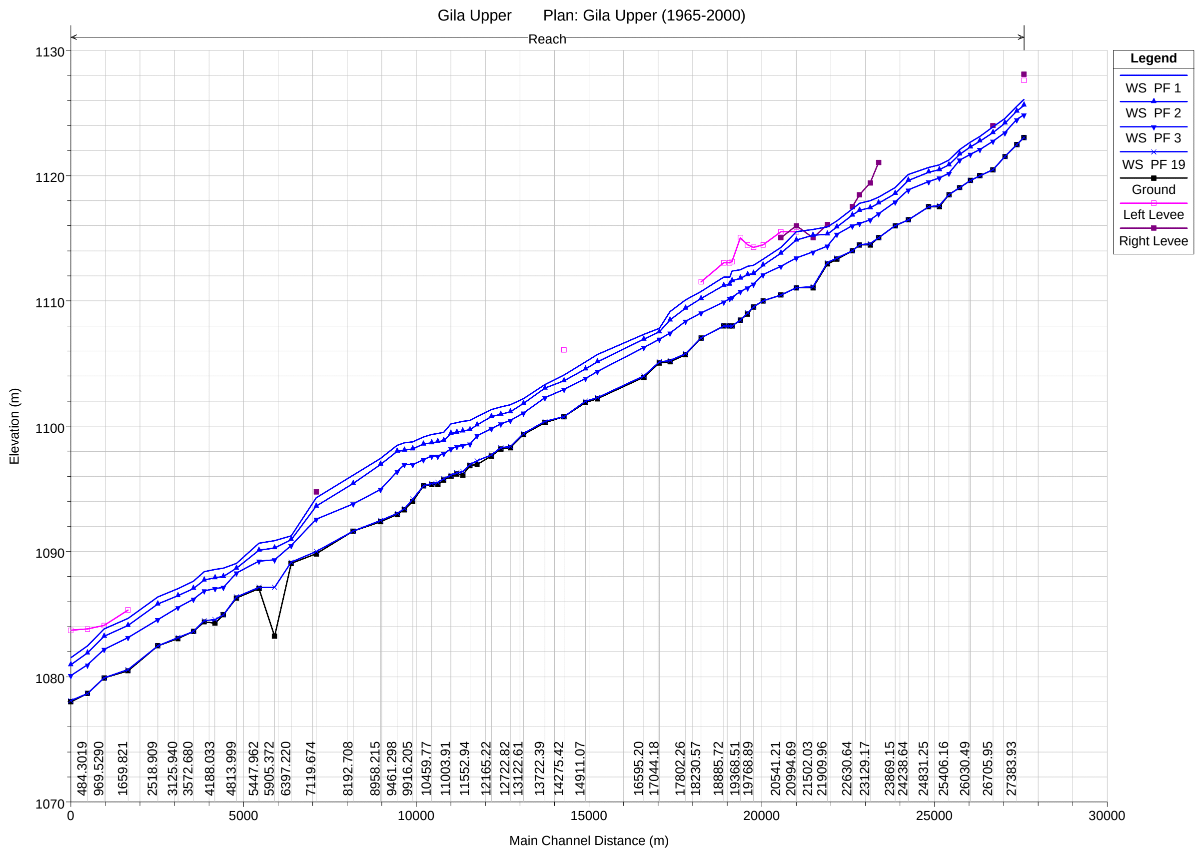

Figure 61. Profile of Upper Reach, showing water surface profiles at 652.26 m^3/s (23,034.46 ft^3/s) (PF 1), 402.72 m^3/s (14,221.95 ft^3/s) (PF 2), 152.47 m^3/s (5,384.36 ft^3/s) (PF 3), and 0.033 m^3/s (1.17 ft^3/s) (PF 19).

TRIBUTARY INVENTORY & HYDRAULIC CONTROLS

TRIBUTARY INVENTORY

Table 14 and Table 15 list major tributaries to the Gila River in the study reach. Major tributaries are tributaries that are readily visible from the aerial photographs, contribute significant quantities of sediment during and after rainfall events, and have been observed by the study team to be hydraulically or geomorphologically significant to the study. The table lists the tributaries by sub-reach, i.e. L-1, L-2, etc. for Lower Reach 1, 2, and so on. The inventory includes bridges and diversions. The table also includes the rough location (Lat/Long (WGS 84)) of each feature. The names of the features follow from the USGS Topographic maps of the area.

Table 14. Tributary inventory of lower reaches, with rough location (Lat/Long) of tributary confluence, diversion, or bridge.

Reach	Tributaries Entering Left Bank	Bridges/Diversions	Tributaries Entering Right Bank
L-1			Dry Mine Wash N33° 04.291′ W109° 59.960′
L-1	Fine Wash N33° 03.401′ W109° 58.820′		
L-2	Black Rock Wash N33° 02.287′ W109° 57.069′		Burton Wash N33° 03.207′ W109° 58.081′
		Fort Thomas Bridge (Box Culvert) N33° 02.970′ W109° 58.026′	
		Colvin Jones Diversion (Lift Pump) N33° 03.004′ W109° 57.585′	
			Clay Mine Wash N33° 02.949′ W109° 57.445′
			Teague Spring Canyon N33° 01.361′ W109° 55.768′
L-2			Oliver Spring Canyon N33° 00.692′ W109° 55.243′
L-3		Eden Bridge N32° 57.708′ W109° 54.900′	
		Fort Thomas Canal Diversion N32° 56.539′ W109° 53.815′	
	Tripp & Underwood Wash N32° 56.251′ W109° 53.244′		Markham Wash N32° 56.289′ W109° 53.263′
		Curtis Canal Diversion N32° 55.063′ W109° 49.998′	
			Peck Wash N32° 55.123′ W109° 50.082′
		Pima Bridge N32° 34.899′ W109° 49.611′	
L-3			Butler Wash N32° 53.556′ W109° 47.109′
			Watson Wash N32° 53.353′ W109° 46.523′
		Thatcher Bridge N32° 52.897′ W109° 46.040′	
			Talley Wash N32° 52.694′ W109° 45.938′
		Smithville Diversion N32° 51.590′ W109° 44.614′	
			Peterson Wash N32° 51.112′ W109° 43.620′
		Safford Bridge N32° 50.854′ W109° 42.982′	
			Wilson Wash N32° 50.754′ W109° 42.180′
			Lonestar Wash

Reach	Tributaries Entering Left Bank	Bridges / Diversions	Tributaries Entering Right Bank
			N32° 50.754′ W109° 42.180′
L-4	Graveyard Wash N32° 50.639′ W109° 41.963′ San Simon River N32° 49.846′ W109° 38.894	Graham Canal Diversion N32° 50.603′ W109° 41.399′	
			Tidwell Wash N32° 49.770′ W109° 38.070′
		Solomon Bridge N32° 49.656′ W109° 37.856′	
L-4	San Jose Wash N32° 49.682′ W109° 35.958	San Jose Diversion N32° 51.713′ W109° 32.636′	
		Brown Diversion N32° 52.617′ W109° 30.674′	

Table 15. Tributary inventory of upper reach, with rough location (Lat/Long) of tributary confluence, diversion, or bridge.

Reach	Tributaries Entering Left Bank	Bridges/Diversions	Tributaries Entering Right Bank
Gila Box			San Francisco River N32° 58.563′ W109° 22.299′
York Valley			Apache Creek N32° 52.110′ W109° 11.868′
			Stove Wash N32° 51.284′ W109° 11.197′
York Valley			Bitter Creek N32° 50.282′ W109° 11.037′
U-1			Sanders Wash N32° 49.525′ W109° 10.867′
			Harris Wash N32° 47.812′ W109° 10.408′
			Sandia Wash N32° 47.222′ W109° 09.892′
	Whitefield Creek N32° 44.266′ W109° 06.750′		Little Sand Wash N32° 45.745′ W109° 09.252′
			Waters Wash N32° 45.238′ W109° 08.741′
		Duncan Bridge N32° 43.490′ W109° 06.003′	
	Rainville Wash N32° 42.575′ W109° 05.359′		
U-1	Burro Wash N32° 41.757′ W109° 04.127′		Carlisle Canyon Wash N32° 41.302′ W109° 02.859′

HYDRAULIC CONTROLS

A Hydraulic Control is any feature that determines a unique depth-discharge relationship (Henderson, 1966). This inventory counts two types of hydraulic controls, man-made and geologic. Man-made hydraulic controls include diversion dams and bridges. Geologic hydraulic controls are geologic features intersecting the Gila River that display a resistance to erosion over long periods, and in particular, govern a non-alluvial reach of the river.

Each of the diversion structures listed in Table 14 acts as a hydraulic control, with the exception of the Colvin-Jones diversion. That diversion is a lift-pump, not a dam across the channel. During the pumping season there is a small diversion across the low-flow channel. This low-flow diversion dam probably washes out at flows significantly less than bank-full.

The degree of hydraulic control may decrease as the stage, or discharge in the main channel, increases. The increasing role of channel and vegetation roughness at higher flows ameliorates the effect of low diversion dams as controls. However, following observation of the diversion dams during the Field Data Collection Plan execution, we hypothesize that all of the diversions, with the exception of Colvin-Jones, in the Safford Valley, are significant hydraulic controls at even the highest discharges.

The bridges act as hydraulic controls beginning below the effective discharge and up to the highest discharges. Lower Reach 1 contains no bridges. The downstream boundary of Lower Reach 2 is the Fort Thomas bridge/box culvert. The culvert is not hydraulically significant to this analysis as it overtops at relatively low discharges. Lower Reach 2 contains the Eden and Pima bridges. The bridges were not modeled using the bridge routines in RAS. However, cross sections were cut upstream and downstream of the bridges to capture the contraction and expansion at higher flows. Lower Reach 4 contains the Solomon Bridge. This bridge was likewise modeled. The diversion dams were modeled as deformities in the bed profile. Cross sections were cut at the crest and the toe of each structure to capture the width, contraction, expansion, and hydraulics of the diversion. The weir function in RAS was not utilized.

GEOLOGIC CONTROLS

The following figures show the longitudinal profile of each of the five sub-reaches studied in this analysis. The longitudinal profile illustrates the thalweg of the channel, the thalweg being the lowest point in the channel. The thalweg profiles vividly shows abrupt changes in the bed of the channel, indicating probable hydraulic control points, either man-made or geologic. Geologic controls are prevalent in the reach very near the San Carlos Reservation, at the downstream end of the study reach, Lower Reach 1. We have no information on the makeup of the geologic controls in this area at this time. The Gila Box serves as a regional control for the York and Duncan valleys. There are significant sections of bedrock channel in the Apache Grove area (Upper Reach), indicating geologic controls.

Figure 62 . Longitudinal profile of thalweg in Lower Reach 1.

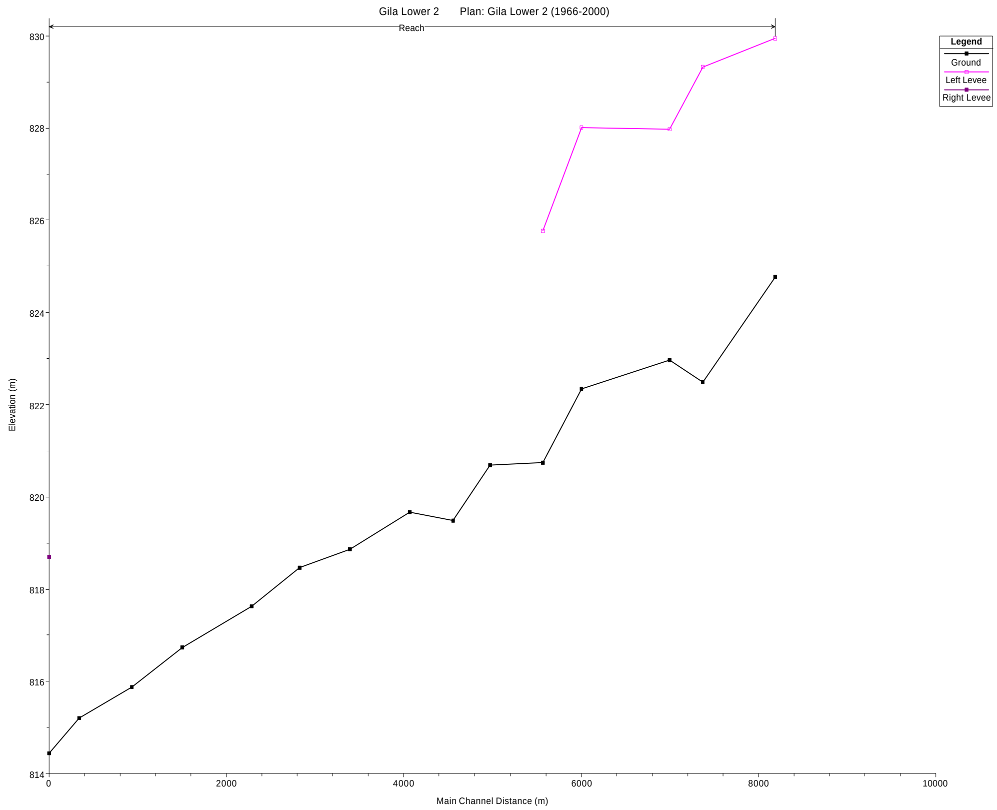

Figure 63. Longitudinal profile of thalweg in Lower Reach 2.

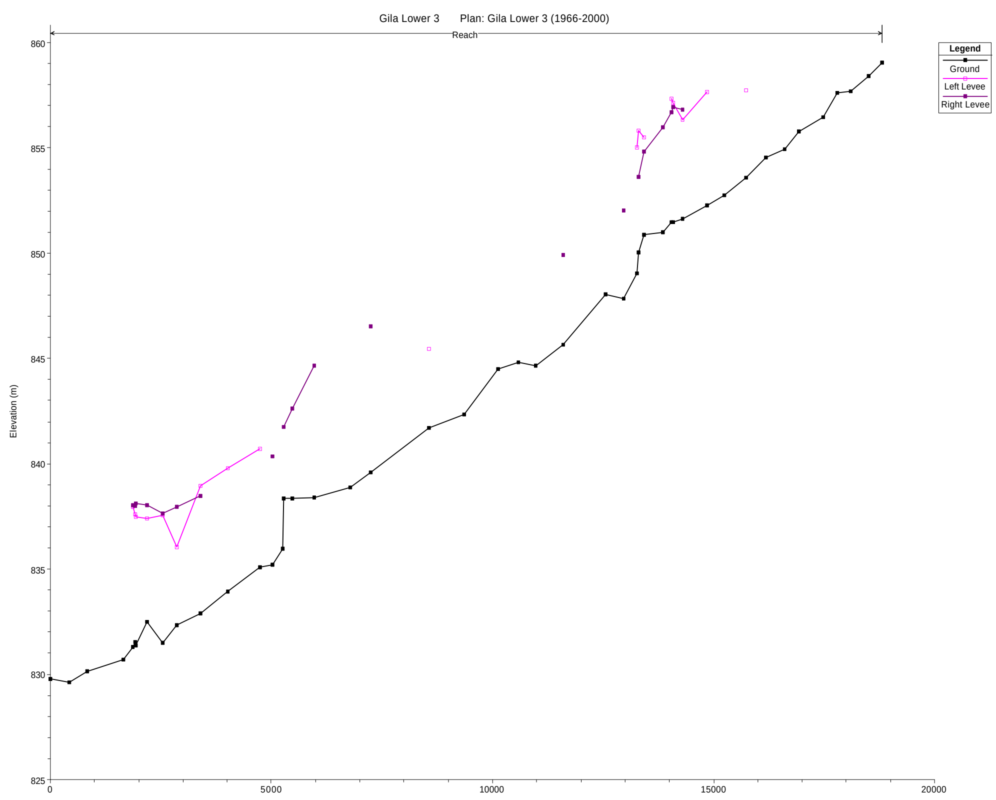

Figure 64. Longitudinal profile of thalweg in Lower Reach 3.

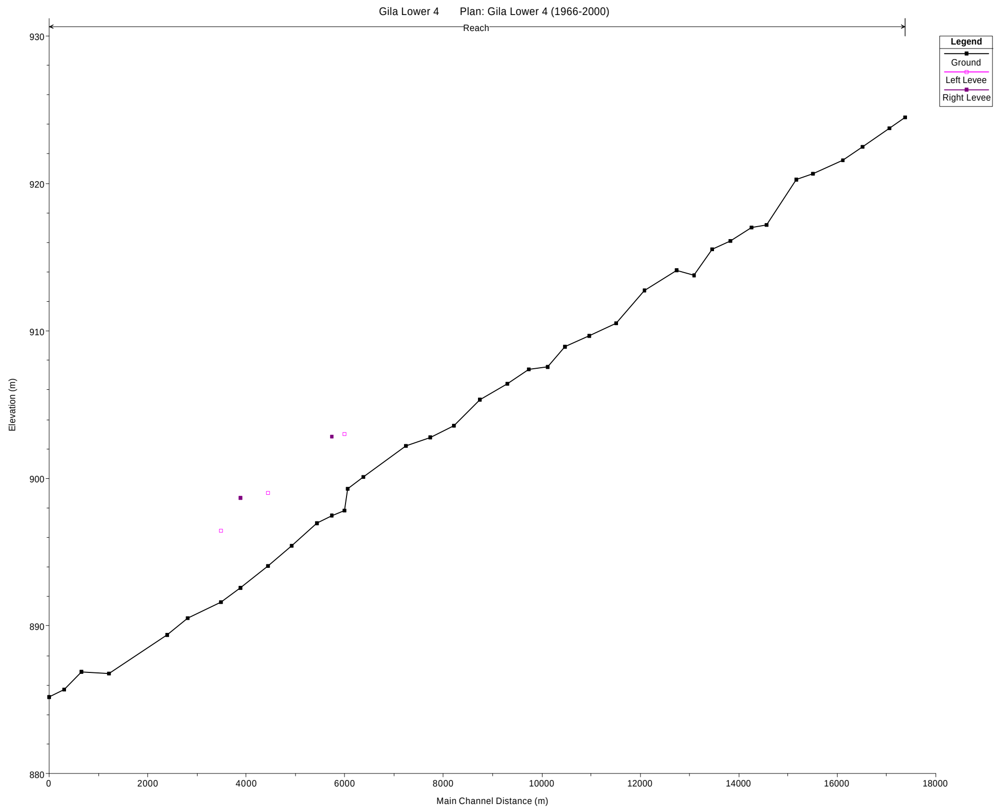

Figure 65. Longitudinal profile of thalweg in Lower Reach 1.

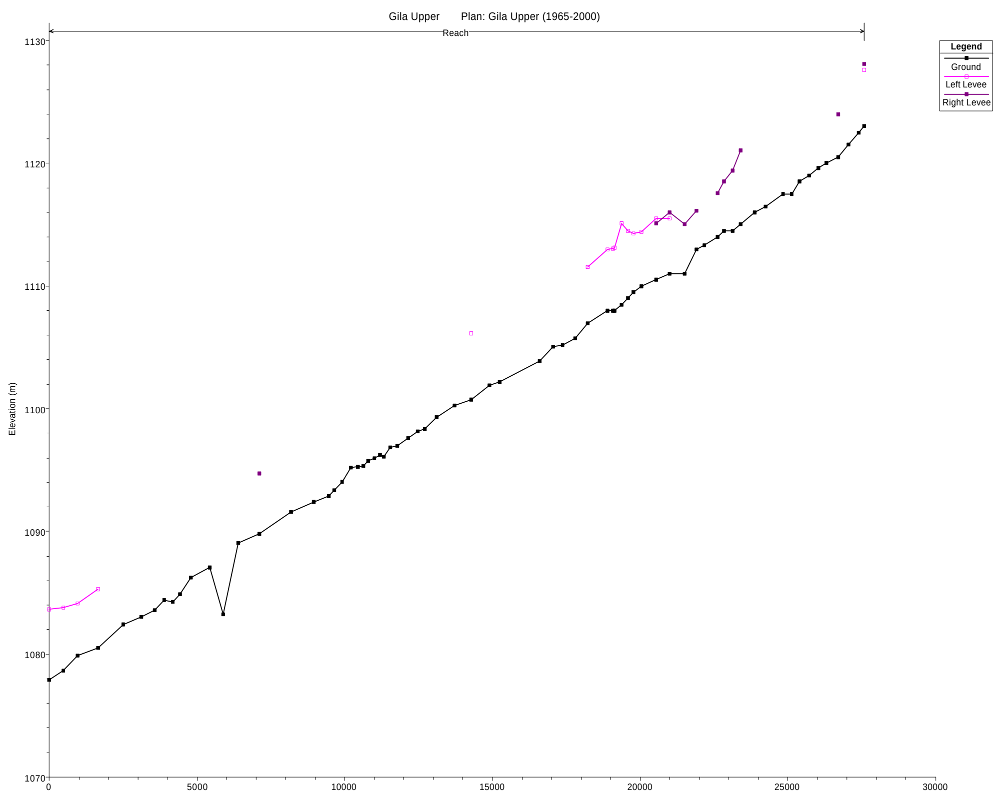

Figure 66. Longitudinal profile of thalweg in Upper Reach 1.

EFFECTIVE DISCHARGE

Andrews (Andrews, 1980) defines effective discharge as the mean of the discharge increment that transports the largest fraction of the annual sediment load over a period of years. The effective discharge incorporates the principle prescribed by Wolman and Miller (Wolman, 1960) that the channel-forming discharge is a function of both the magnitude of the event and its frequency of occurrence. It is calculated by convoluting the flow-duration curve and a bed-material-sediment load rating curve. Figure *67* (Watson, 1999) shows how the effective discharge derives from the flow frequency and sediment transport curves. Smaller discharges may happen more frequently, but they carry less sediment. Larger discharges may transport more sediment, but they occur less frequently.

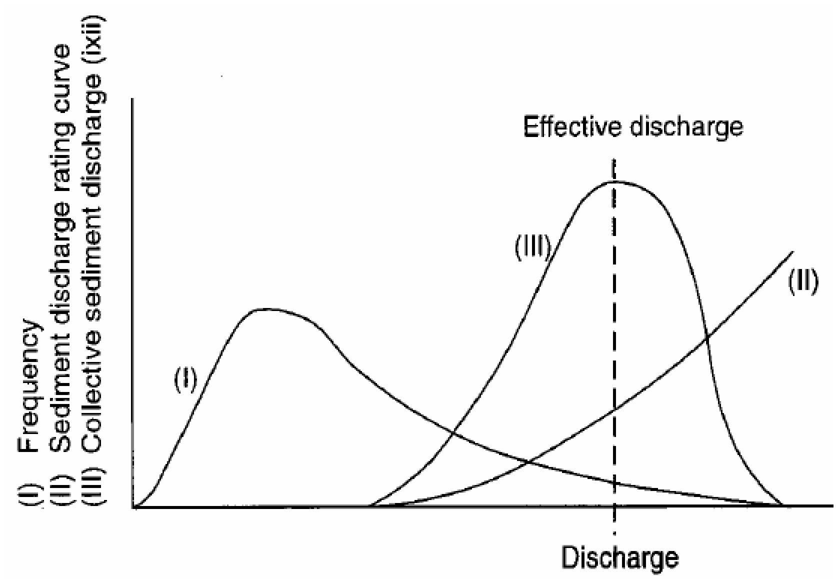

Figure 67. Derivation of Bed Material Load-discharge Histogram (III) From Flow Frequency (I) and Bed Material Load Rating Curves (II). (Watson, 1999)

Watson (1999) presents "A Practical Guide to Effective Discharge Calculation." This guide is Appendix A of the *Demonstration Erosion Control, Design Manual*, produced by the U.S. Army, Engineer Research and Development Center, Vicksburg, Mississippi. This, and the *Reservoir Sedimentation* Technical Guideline for Bureau of Reclamation (Strand, 1982), provide the methodology used in this analysis of the effective discharge.

GAGING STATION DESCRIPTIONS

The following section describes the USGS gaging stations from which daily mean discharges were used for calculating the discharge exceedance or flow duration curves. The descriptions come from the USGS (USGS, 2001) web pages for each particular station. Figure 68 shows the USGS gaging stations in the upper Gila River watershed.

STATION:--09466500 Gila River at Calva, AZ

LOCATION.--Lat 33°:11'08", long 110°:13'10", in SW1/4 sec.8, T.3 S., R.21 E. (unsurveyed), Graham County, Hydrologic Unit 15040005, in San Carlos Indian Reservation, on Southern Pacific Railroad bridge at head of San Carlos Reservoir, 2.0 mi west of Calva.

DRAINAGE AREA.--11,470 mi^2.

PERIOD OF RECORD.--October 1929 to current year.

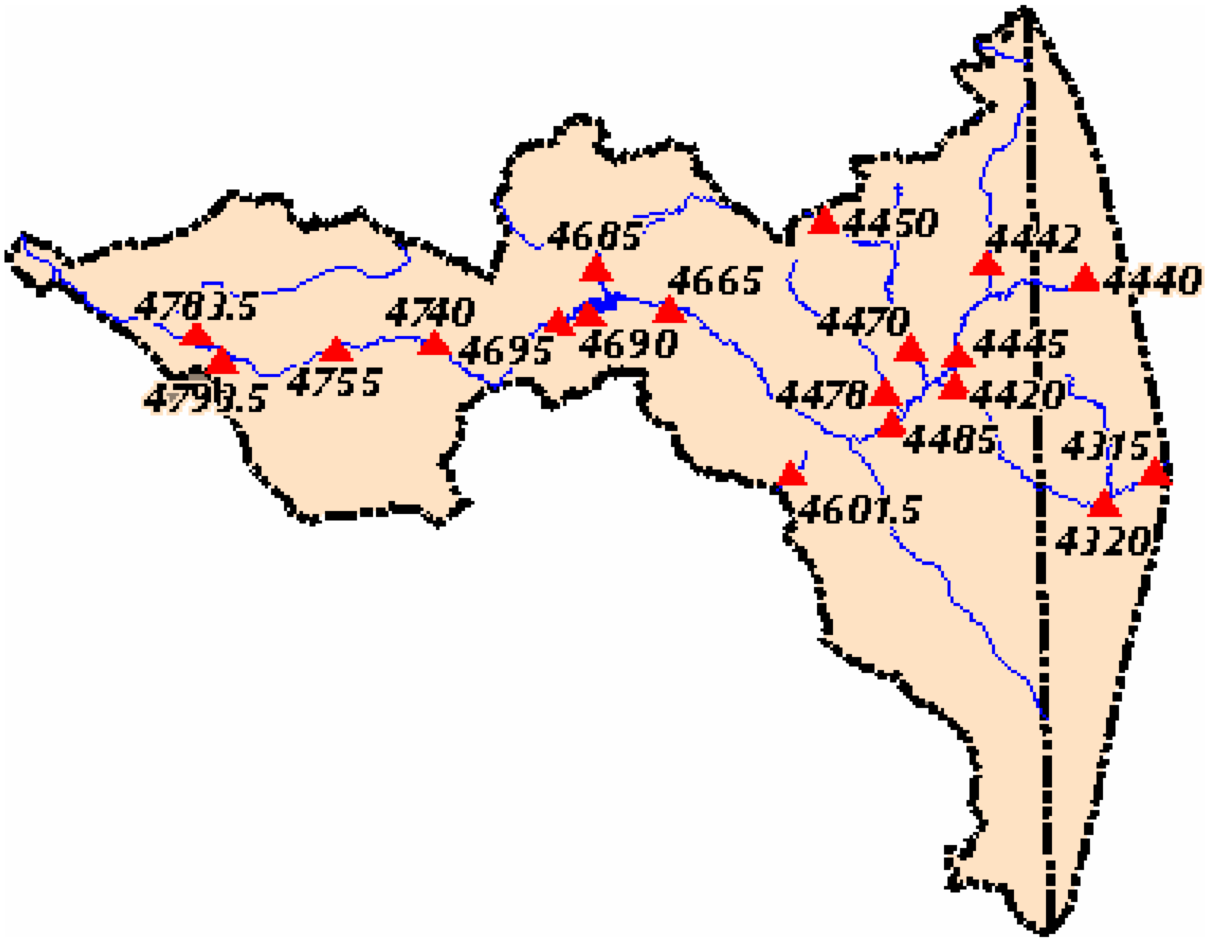

Figure 68. USGS gaging stations in the upper Gila River watershed. (Note: the gage numbers are proceeded by the digits “09” and followed a “00” when referenced in USGS records.)

GAGE.--Water-stage recorder. Datum of gage is 2,517.29 ft above sea level. Prior to Oct. 1, 1954, and Aug. 25, 1958, to Dec. 31, 1962, at datum 2.52 ft lower. Oct. 1, 1954, to Aug. 24, 1958, at datum 5.52 ft lower. Dec. 31, 1962, to Oct. 20, 1972, at site 530 ft downstream at datum 3.65 ft lower. Oct. 20, 1972, to Sept. 30, 1974, supplementary gage at bridge on U.S. Highway 70, 6.2 mi upstream at datum 2,560.19 ft, NGVD.

REMARKS.--Records good except for estimated daily discharges, which are fair. Diversion above station for irrigation of about 69,000 acres, metallurgical treatment of ores, and municipal uses.

STATION:--09458500 Gila River at Safford, AZ
LOCATION.--Lat 32°50’50”, Long 109°42’55” NAD27, Graham County, Arizona, Hydrologic Unit Code 15040005.

DRAINAGE AREA. --10,459.00 mi^2

GAGE DATUM. --2,880.07 feet above sea level NGVD29

STATION DATA: --Begin Date 1940-06-01; End Date 1965-09-30; Count 6268

STATION:--09451000 Gila River near Solomon, AZ
LOCATION.--Lat 32°52'00", Long 109°31'00" NAD27, Graham County, Arizona , Hydrologic Unit 15040005.

DRAINAGE AREA. --7,950.00 mi^2

STATION TYPE:--Surface Water

STATION DATA: --Begin Date 1914-04-01; End Date 1951-09-30; Count 10775

SITE OPERATION: Site is located in Arizona; record is maintained by Arizona

STATION:--09448500 Gila River at head of Safford Valley, near Solomon, AZ
LOCATION.--Lat 32°52'06", long 109°30'38", in SE1/4NE1/4 sec. 3l, T.6 S., R.28 E., Graham County, Hydrologic Unit 15040005, on left bank 0.6 mi downstream from intake of Brown Canal, 8 mi northeast of Solomon, and 17 mi downstream from San Francisco River. Records include flow of Brown Canal, which is measured 2,000 ft downstream from intake.

DRAINAGE AREA.--7,896 mi^2.

PERIOD OF RECORD.--April 1914 to current year. Monthly discharge only for some periods, published in WSP 1313. Prior to October 1932 and October 1940 to September 1949 published as "near Solomonsville" and October 1932 to October 1933 and May 1935 to September 1940 as "below Bonita Creek near Solomonsville."

REVISED RECORDS.--WSP 1059: 1914, 1916-17, 1923(M), 1924-25, 1927, 1929-31(M). WSP 1179: 1915, 1918-19(M). WSP 1313: 1934. WSP 1733: 1923.

GAGE.--Water-stage recorder. Datum of gage is 3,059.92 ft above sea level. Prior to July 8, 1980, at datum 4.96 ft higher. See WSP 1733 for history of changes prior to Jan. 1, 1941. Supplementary water-stage recorder and Parshall flume on Brown Canal.

REMARKS.--Records show water reaching head of Safford Valley and include water diverted to Brown Canal. Diversions above station for mining, municipal use, and for irrigation of about 17,500 acres, much of it by pumping from ground water.

COOPERATION.--Record for Brown Canal furnished by Gila Water Commissioner.

AVERAGE DISCHARGE.--80 years, 507 ft^3/s, 367,300 acre-ft/yr; median of yearly mean discharges, 340 ft^3/s, 246,000 acre-ft/yr.

STATION:--09444500 San Francisco River at Clifton, AZ
LOCATION.--Lat 33°02'58", long 109°17'43", in SW1/4SE1/4 sec. 30, T.4 S., R.30 E., Greenlee County, Hydrologic Unit 15040004, on downstream side of right pier at Railroad Boulevard Bridge (U.S. Highway 666), at Clifton, 9.9 mi upstream from mouth.

DRAINAGE AREA.--2,766 mi^2, of which 2 mi^2 is noncontributing.

PERIOD OF RECORD.--October 1910 to March 1911, July 1911 to June 1912, September 1912, November 1912 to March 1913, May 1913 to July 1918, July 1927 to current year. Monthly discharge only for some periods, published in WSP 1313. Published as "San Francisco River at dam above Clifton" in 1911 and under both names in 1912.

REVISED RECORDS.--WSP 1049: 1911, 1913-15, 1917. WSP 1283: Drainage area. WSP 1313: 1927-30(M), 1932(M), 1934(M). WRD Ariz. 1972: 1917(M).

GAGE.--Water-stage recorder. Datum of gage is 3,436.16 ft above sea level. See WSP 1713 or 1733 for history of changes prior to Apr. 7, 1959. Apr. 7, 1959, to Mar. 23, 1961, at site 1,140 ft downstream at datum 5.37 ft lower. July 18, 1980 to July 28, 1983, supplementary water-stage recorder 0.4 mi upstream on right bank at same datum and June 15, 1981 to Sept. 30, 1983, crest-stage gages at site. Aug. 4, 1983 to Mar. 1, 1985, supplementary water-stage recorder on right bank at main gage site at same datum, Oct. 1, 1992 at main gage site, at datum 10.00 ft higher.

REMARKS.--Diversions for mining, municipal use, and for irrigation of about 2,700 acres above station.

AVERAGE DISCHARGE.--71 years, 226 ft^3/s, 163,700 acre-ft/yr; median of yearly mean discharges 130 ft^3/s, 94,200 acre-ft/yr.

STATION:--09432000 Gila River below Blue Creek, near Virden, NM
LOCATION.--Lat 32°38’53”, long 108°50’43”, in SE1/4SW1/4 sec. 18, T.19 S., R.19 W., Grant County, Hydrologic Unit 15040002, on left bank at head of canyon, 1.4 mi downstream from Blue Creek, 10 mi east of Virden, and 16 mi upstream from New Mexico-Arizona State line.

DRAINAGE AREA.--3,203 mi^2, excluding Animas River basin.

PERIOD OF RECORD.--May to November 1914, March to September 1915, July 1927 to current year. July 1927 to May 1931 monthly discharge only, published in WSP 1313, computed as sum of flow at Virden Bridge, 9 mi downstream, and in Sunset Canal. Published as “Gila River near Duncan, Ariz.,” 1914-15 and as “Gila River at Fuller’s Ranch, near Duncan, Ariz.,” 1931-38.

REVISED RECORDS.--WSP 1283: Drainage area. WSP 1313: 1929, 1931-32(M).

GAGE.--Water-stage recorder. Elevation of gage is 3,875 ft above sea level, from river-profile map. May 11, 1914, to Sept. 30, 1915, at site 6 mi downstream, 1,000 ft upstream from intake of Sunset Canal. June 1 to July 7, 1931, non-recording gage at present site and datum. Since April 18, 1980, supplementary gage on left bank 800 ft downstream at same datum. Since June 1980, crest-stage gages at supplementary gage site. Since Nov. 1990, water-stage recorder at supplementary gage.

REMARKS.--Records fair. Station is above all Duncan Valley diversions. Diversions for irrigation of about 6,200 acres above station.

AVERAGE DISCHARGE.--68 (water years 1928-95), 216 ft^3/s, 156,500 acre-ft/yr; median of yearly mean discharges, 150 ft^3/s, 109,000 acre-ft/yr.

FLOW DURATION

Flow duration curves represent the cumulative probability of exceeding a mean daily discharge for a given period of record at a gaging station. For this analysis the period in question follows the mid 1960’s. The following flow duration curves come from analyzing the records of several gaging stations using the procedures outlined in the Demonstration Erosion Control, Design Manual (Watson, 1999) and the Reservoir Sedimentation Technical Guideline for Bureau of Reclamation (Strand, 1982). All of the curves are here, including the entire record, the period prior to the mid 1960’s, and the period since the mid 1960’s. Appendix C contains the tabular data for these curves.

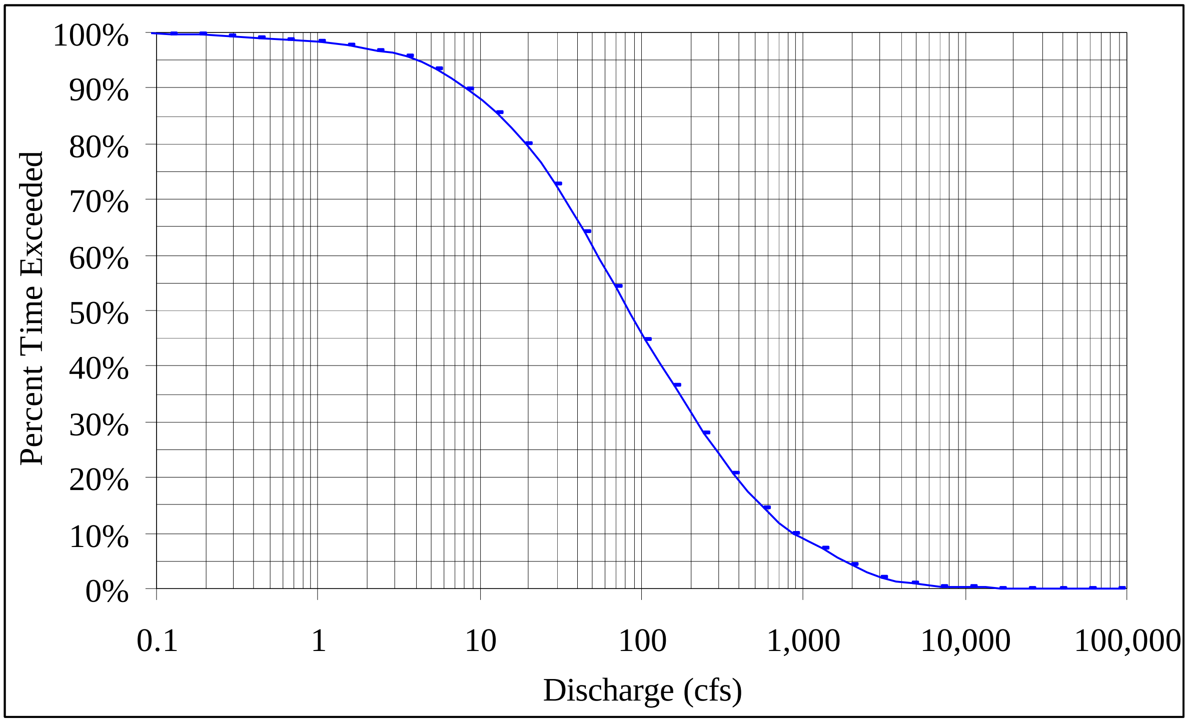

Figure 69. Discharge exceedance curve for Gila River at Calva, AZ. 1929-2000.

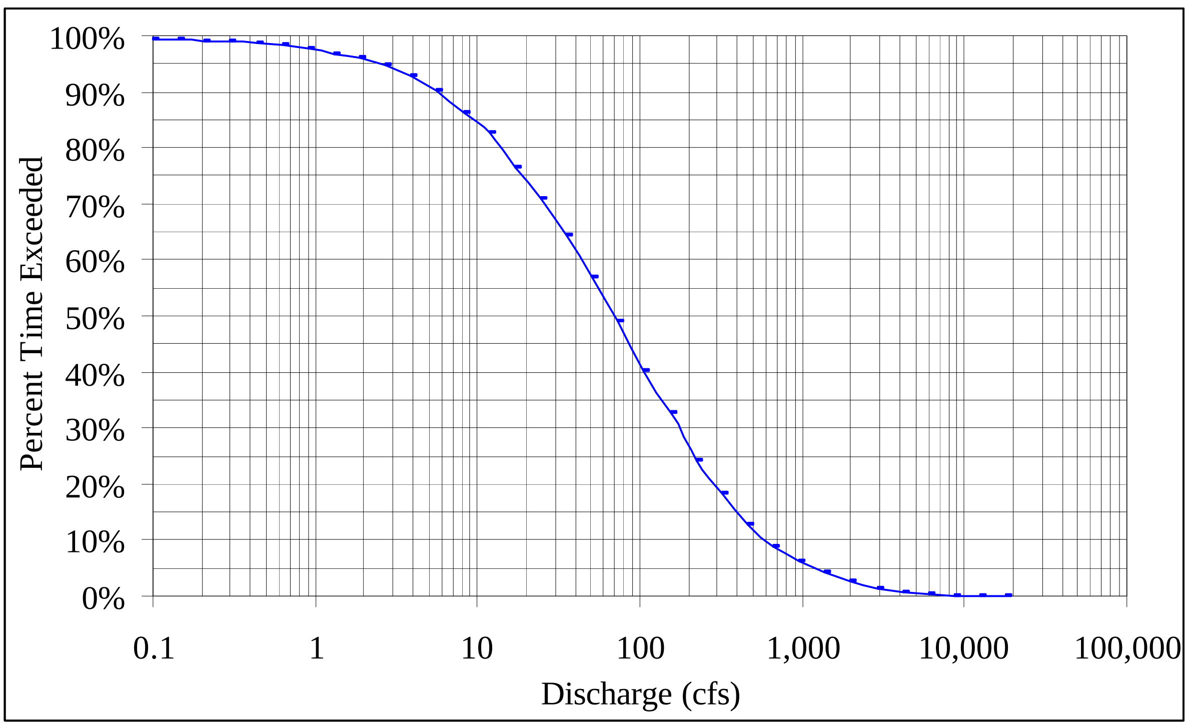

Figure 70. Discharge exceedance curve for Gila River at Calva, AZ. 1929-1964.

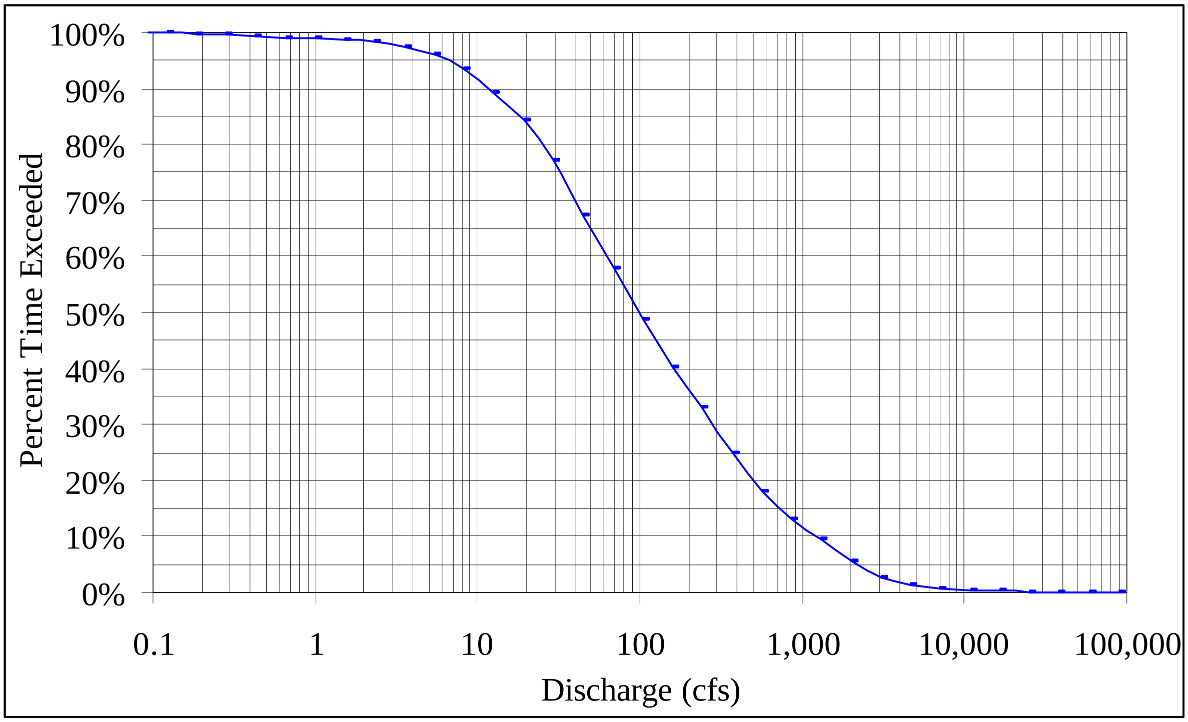

Figure 71. Discharge exceedance curve for Gila River at Calva, AZ. 1965-2000.

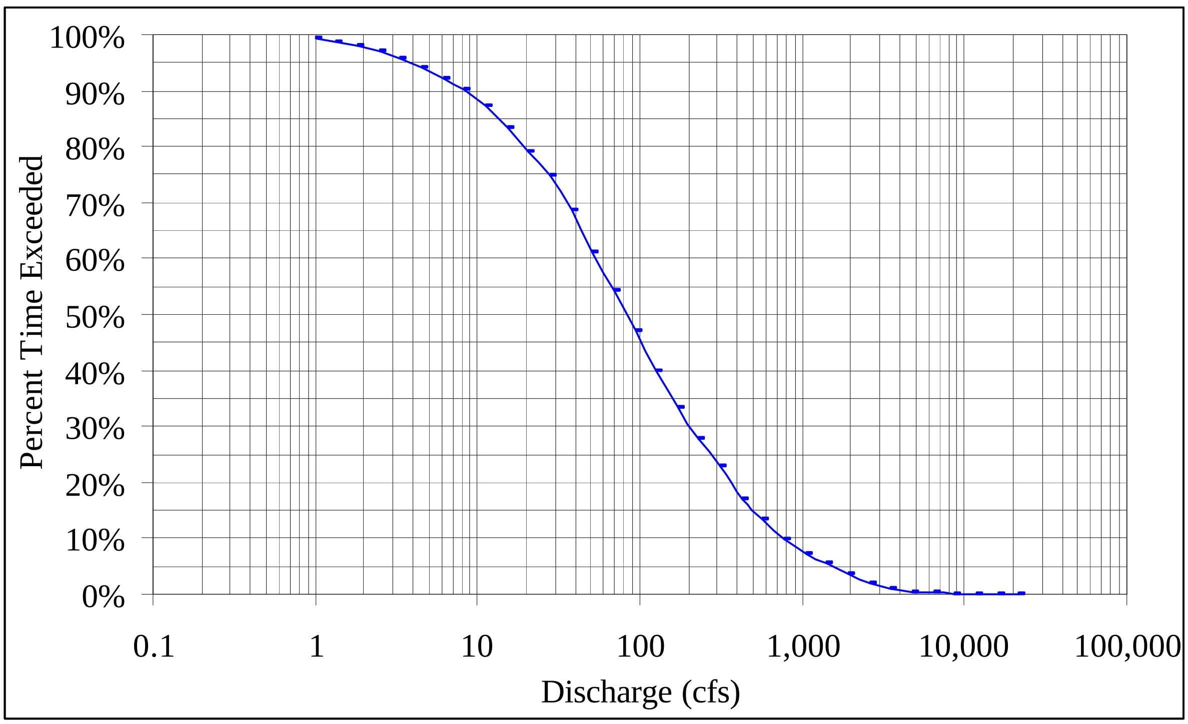

Figure 72. Discharge exceedance curve for Gila River at Safford, AZ. 1940-1965

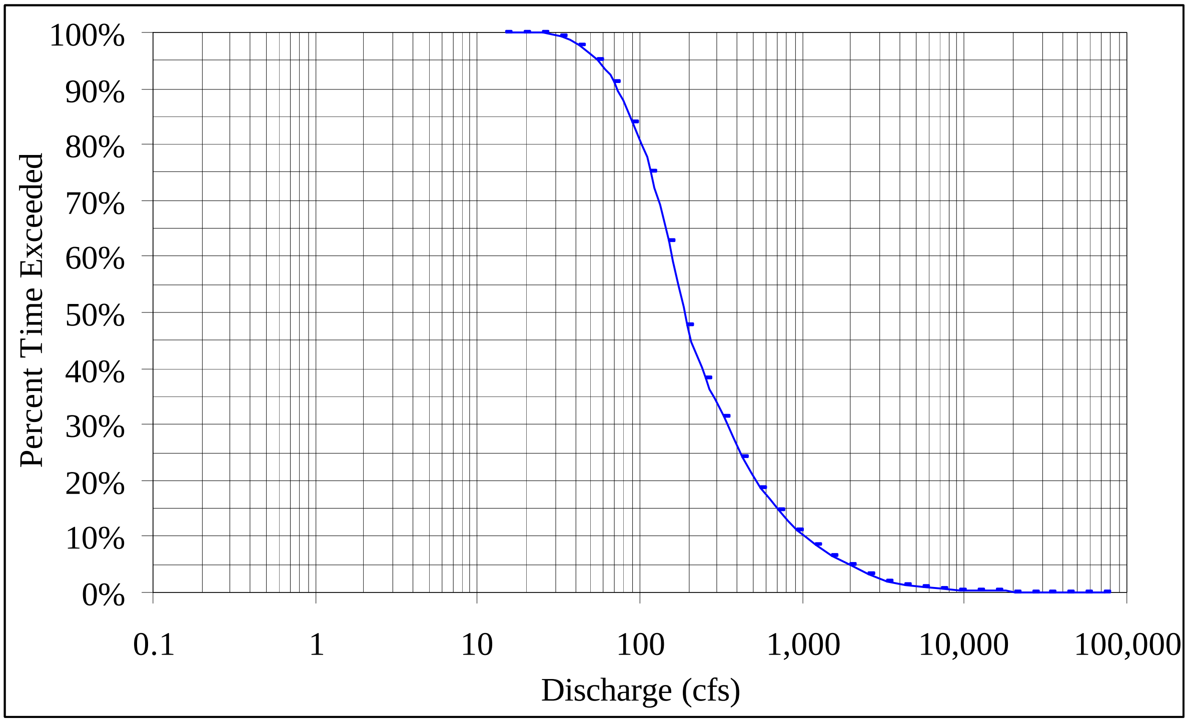

Figure 73. Discharge exceedance curve for Gila River near Solomon, AZ. 1914-1951

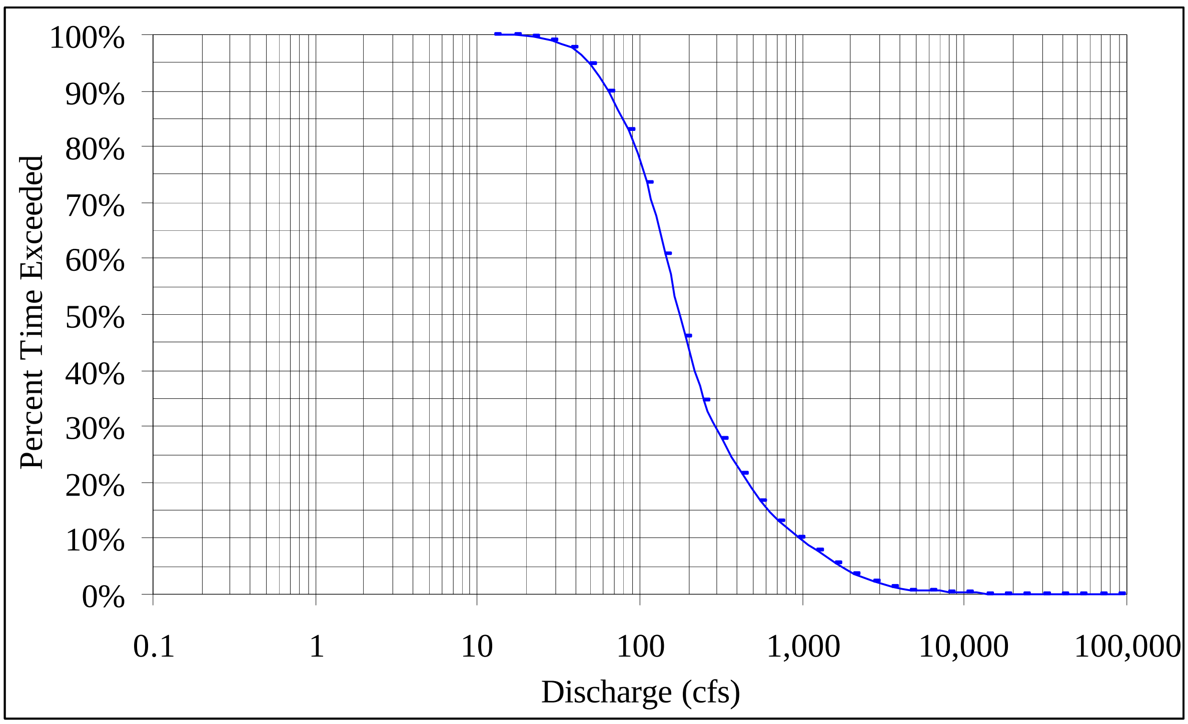

Figure 74. Discharge exceedance curve for Gila River at Head of Safford Valley, 1920-2000.

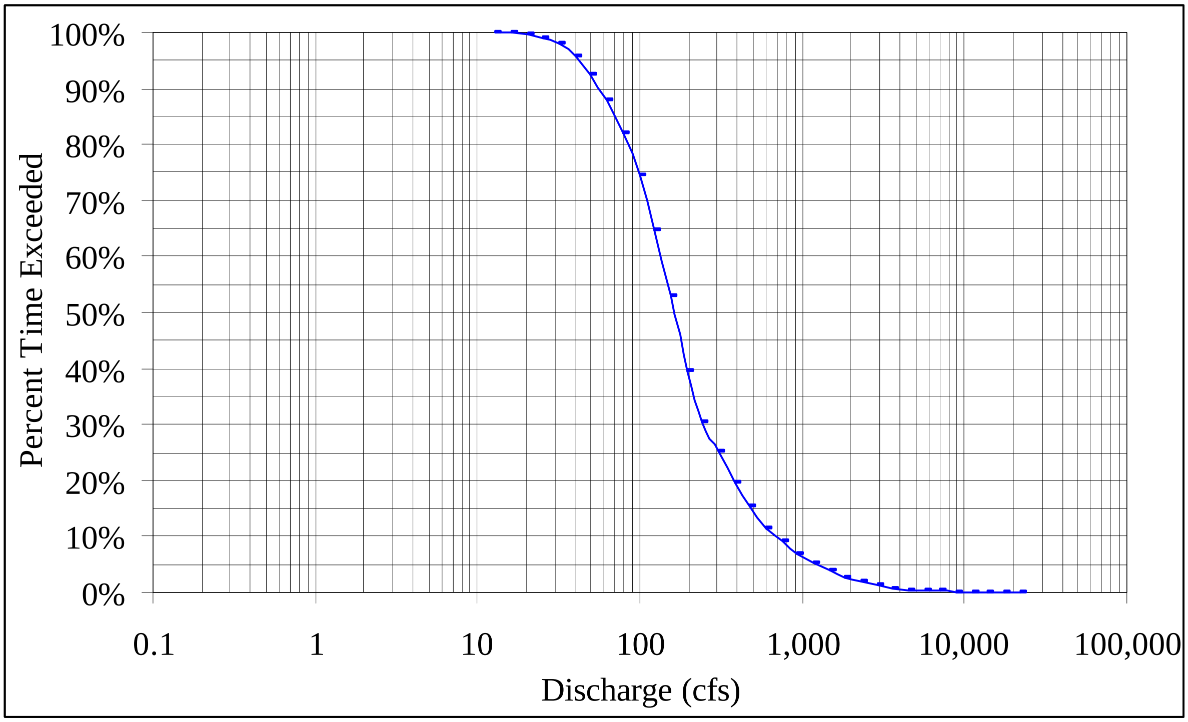

Figure 75. Discharge exceedance curve for Gila River at Head of Safford Valley, 1920-1964.

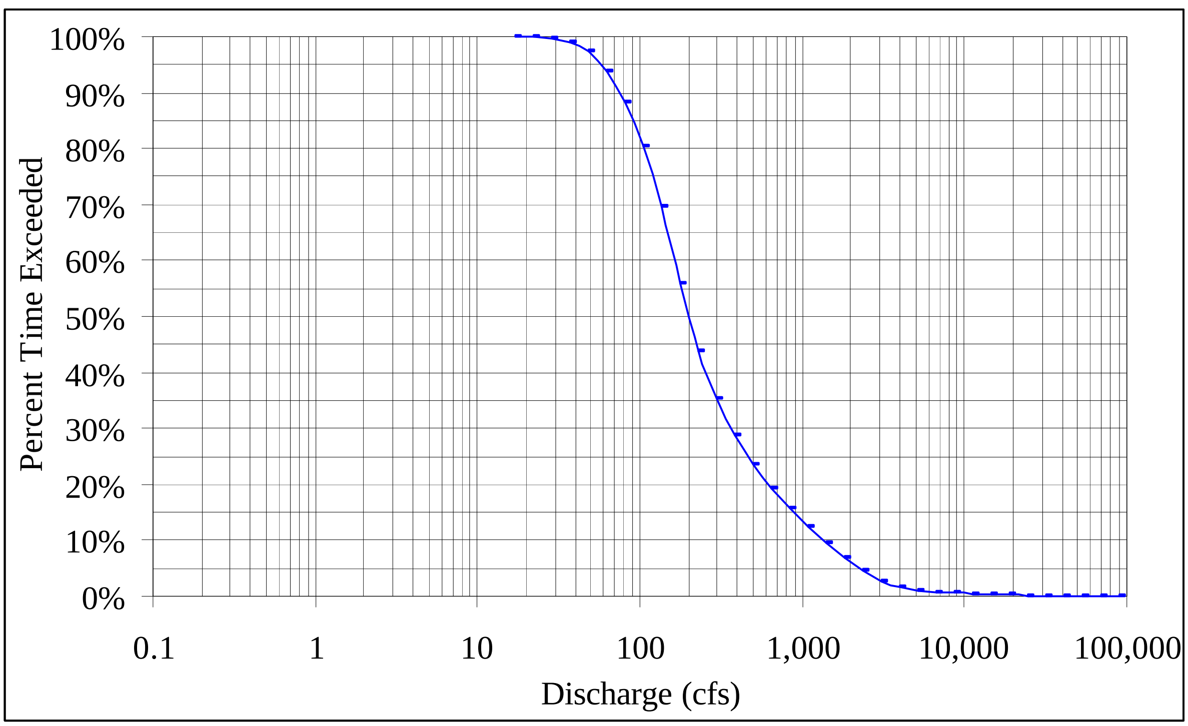

Figure 76. Discharge exceedance curve for Gila River at Head of Safford Valley, 1965-2000.

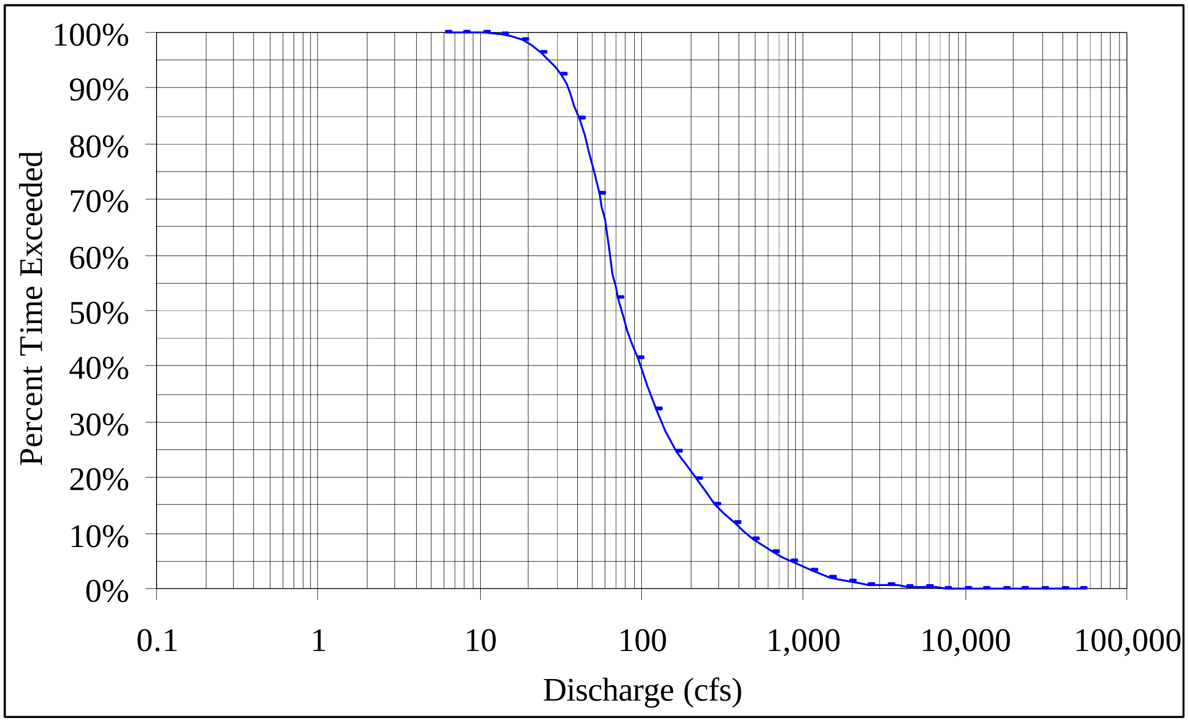

Figure 77. Discharge exceedance curve for San Francisco River at Clifton, AZ. 1911-2000.

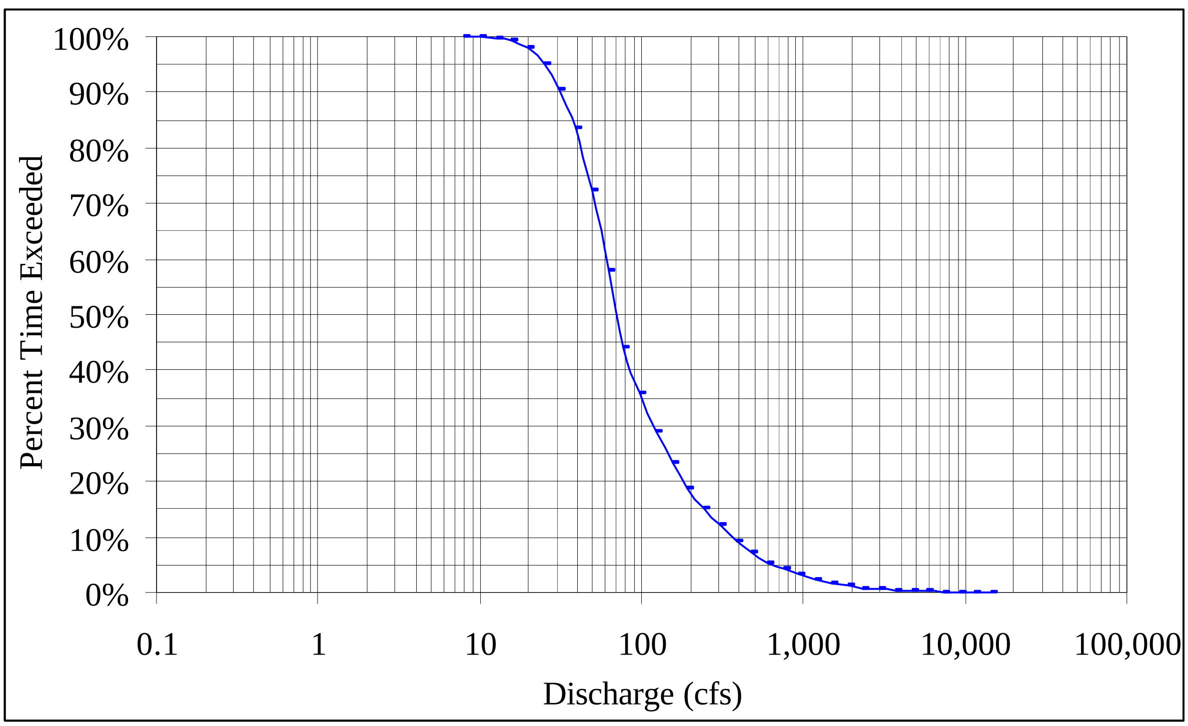

Figure 78. Discharge exceedance curve for San Francisco River at Clifton, AZ. 1911-1964.

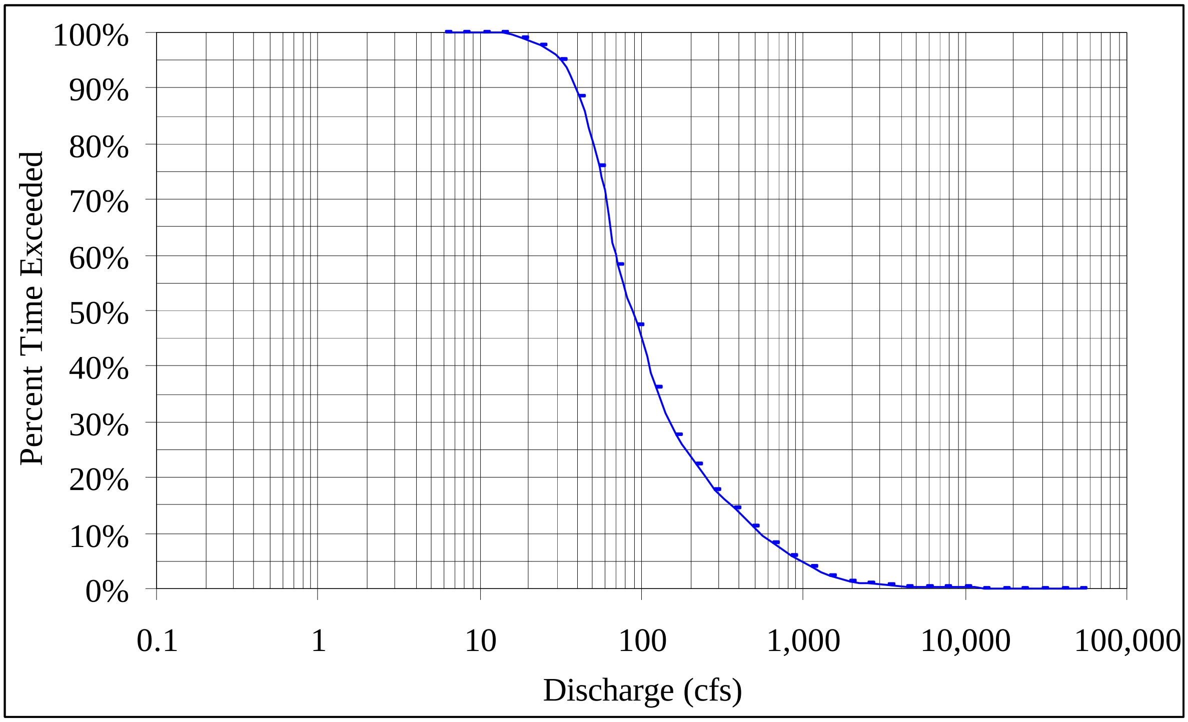

Figure 79. Discharge exceedance curve for San Francisco River at Clifton, AZ. 1965-1999.

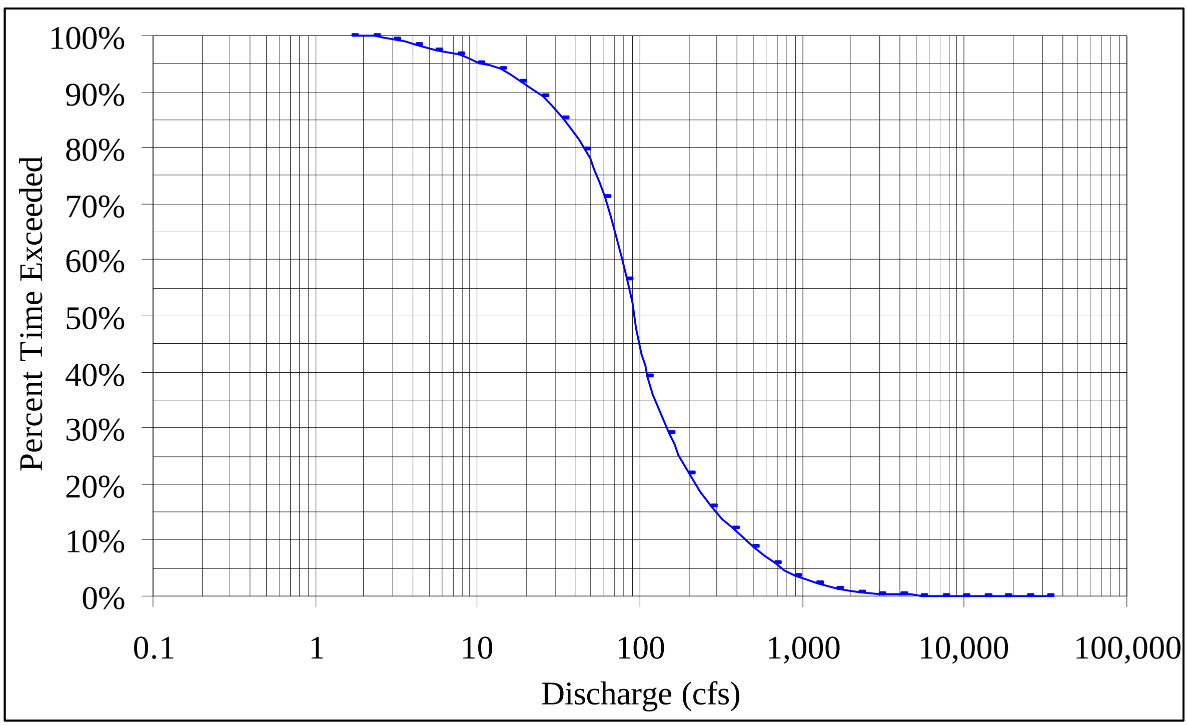

Figure 80. Discharge exceedance curve for Gila River below Blue Creek, near Virden, NM. 1927-2000.

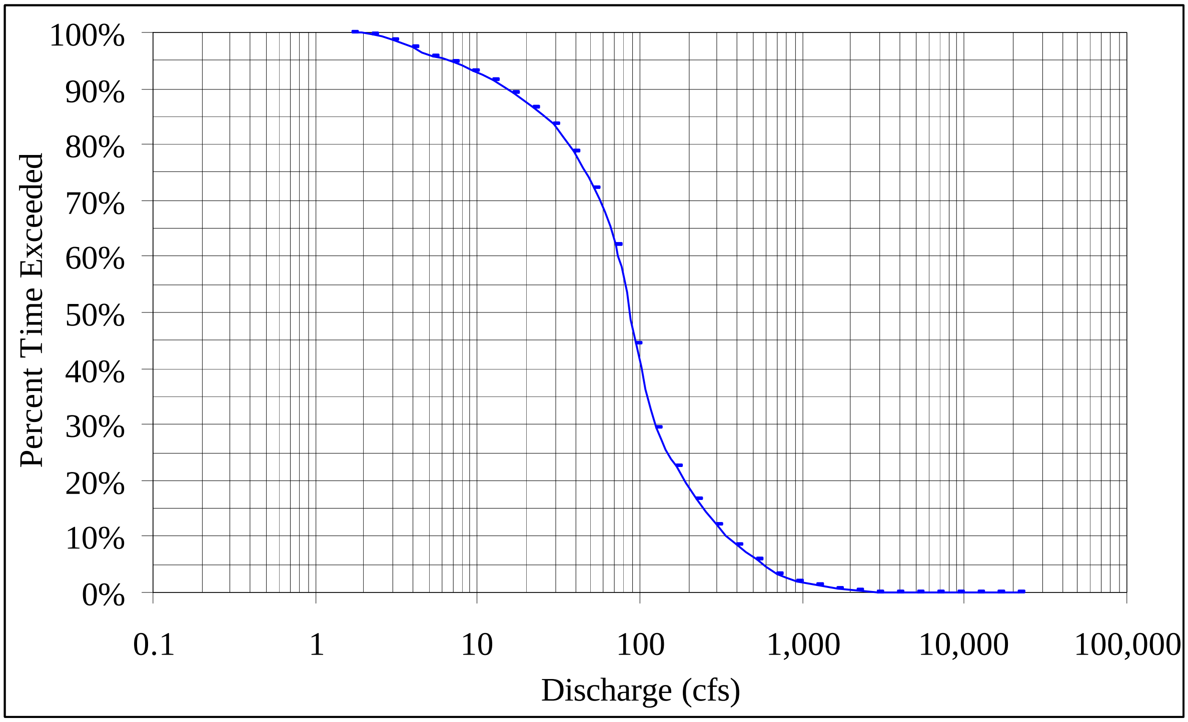

Figure 81. Discharge exceedance curve for Gila River below Blue Creek, near Virden, NM. 1927-1964.

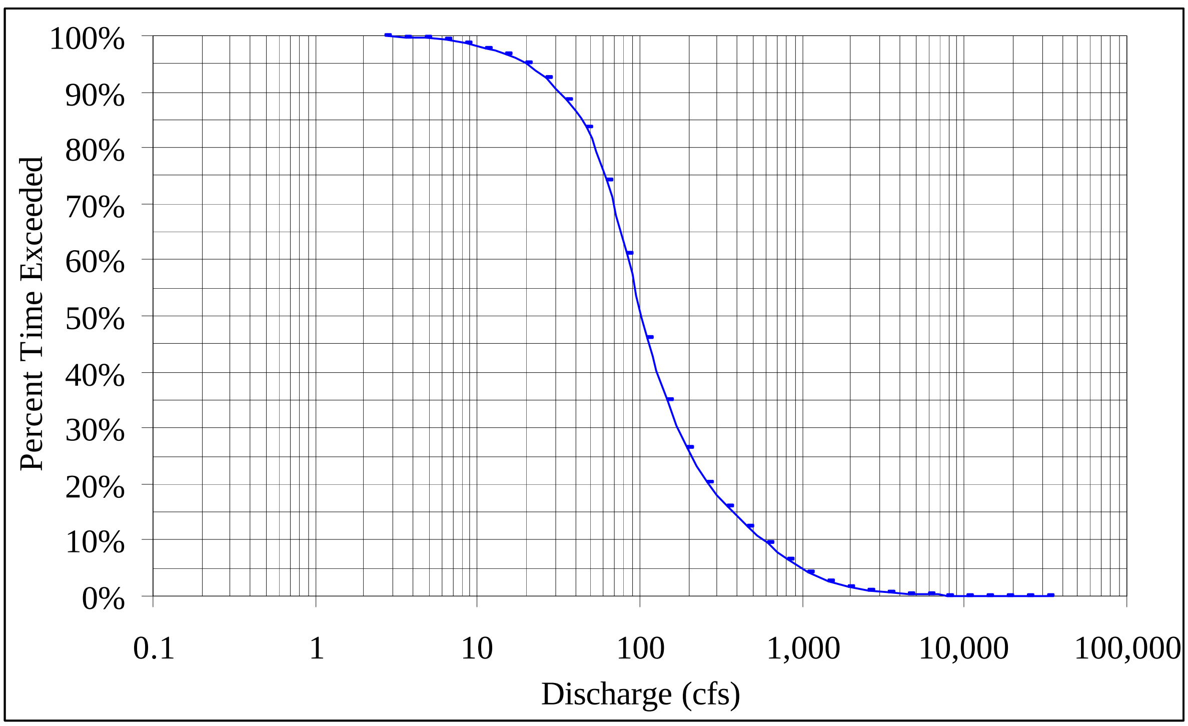

Figure 82. Discharge exceedance curve for Gila River below Blue Creek, near Virden, NM. 1965-2000.

SEDIMENT TRANSPORT

The Yang (Yang, 1973) sediment transport equations are used exclusively for the effective discharge calculations. Details on the calculation methods are available in Stream Channel Design for Sandbed Streams (Delcau, 1997).

EFFECTIVE DISCHARGE CALCULATIONS

This section presents the results of the effective discharge calculations. Those calculations are made for Lower Reach 1, Lower Reach 4, and the Upper Reach only. The effective discharge in Lower Reach 1 is applied to Lower Reach 2, while the effective discharge in Lower Reach 4 is applied to Lower Reach 3. The procedure follows that specified in Reservoir Sedimentation – Technical Guideline for Bureau of Reclamation (Strand, 1982), pg. 12, Table 2.

Lower Reach 1

Cross section 631.06 from the HEC-RAS model of Lower Reach 1 was selected to estimate the effective discharge. Figure 83 shows the graphical results of the tabulated calculations shown in Table 16. The effective discharge in Lower Reach 1 is roughly 1,191.6 m^3/s (42,082 ft^3/s) for the period 1965 to 2000.

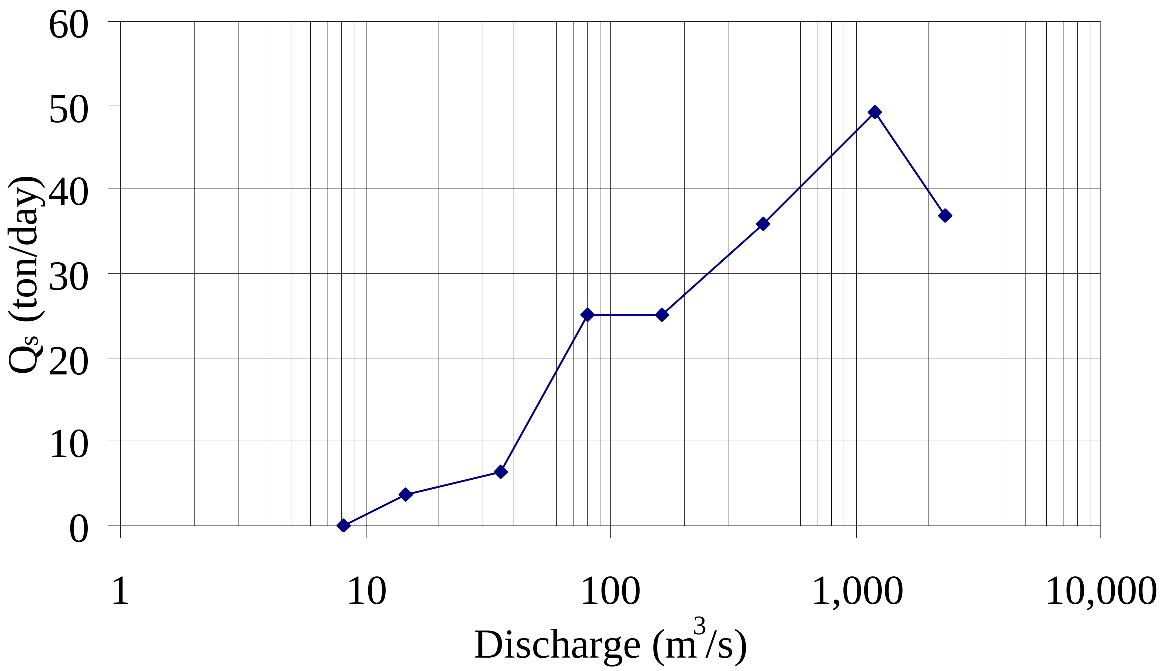

Figure 83. Gila River At Calva, AZ, USGS Gage # 09466500, 1965-2000, XS 631.06.

Table 16. Gila River At Calva, AZ, USGS Gage # 09466500, 1965-2000, XS 631.06.

1 Limits %	2 Interval %	3 Middle Ordinate	4 Q ft^3/s	Q m^3/s	5 Q_s tons/day	2 x 4 Q ft^3/s	2 x 5 Q_s tons/day
0.00-0.02	0.02	0.01	82,252.68	2,329.14	1850.2953	16.45	37.01
0.02 - 0.1	0.08	0.06	42,082.06	1,191.63	613.8718	33.67	49.11
0.1 - 0.5	0.4	0.3	14,907.88	422.14	89.6207	59.63	35.85
0.5 - 1.5	1	1	5,765.94	163.27	25.1359	57.66	25.14
1.5 - 5.0	3.5	3.25	2,867.35	81.19	7.2013	100.36	25.20
5.0 - 15	10	10	1,266.87	35.87	0.6397	126.69	6.40
15 - 25	10	20	513.91	14.55	0.3758	51.39	3.76
25 - 35	10	30	290.23	8.22	0.0000	29.02	0.00
35 - 45	10	40	163.16	4.62	0.0000	16.32	0.00
45 - 55	10	50	99.33	2.81	0.0000	9.93	0.00
55 - 65	10	60	62.93	1.78	0.0000	6.29	0.00
65 - 75	10	70	40.71	1.15	0.0000	4.07	0.00

1 Limits %	2 Interval %	3 Middle Ordinate	4 Q ft³/s	 Q m³/s	5 Q_s tons/day	2 x 4 Q ft³/s	2 x 5 Q_s tons/day
75 - 85	10	80	25.52	0.72	0.0000	2.55	0.00
85 - 95	10	90	11.87	0.34	0.0000	1.19	0.00
95 - 96.5	3.5	96.75	4.53	0.13	0.0000	0.16	0.00
98.5 - 99.5	1	99	0.91	0.03	0.0000	0.01	0.00
99.5 - 99.9	0.4	99.7	0.27	0.01	0.0000	0.00	0.00
99.9 - 99.98	0.08	99.94	0.10	0.003	0.0000	0.00	0.00
99.98 - 100	0.02	99.99	0.08	0.002	0.0000	0.00	0.00
					Total =	515.39	182.46
					Q_{annual} =	373,373	AF/year
					$Q_{s\ annual}$ =	66,598	tons/year

Figure 84 shows the graphical results of the tabulated calculations shown in Table 17. The effective discharge in Lower Reach 1 is roughly 94.58 m³/s (3,340 ft³/s) during the period of 1930 to 1965.

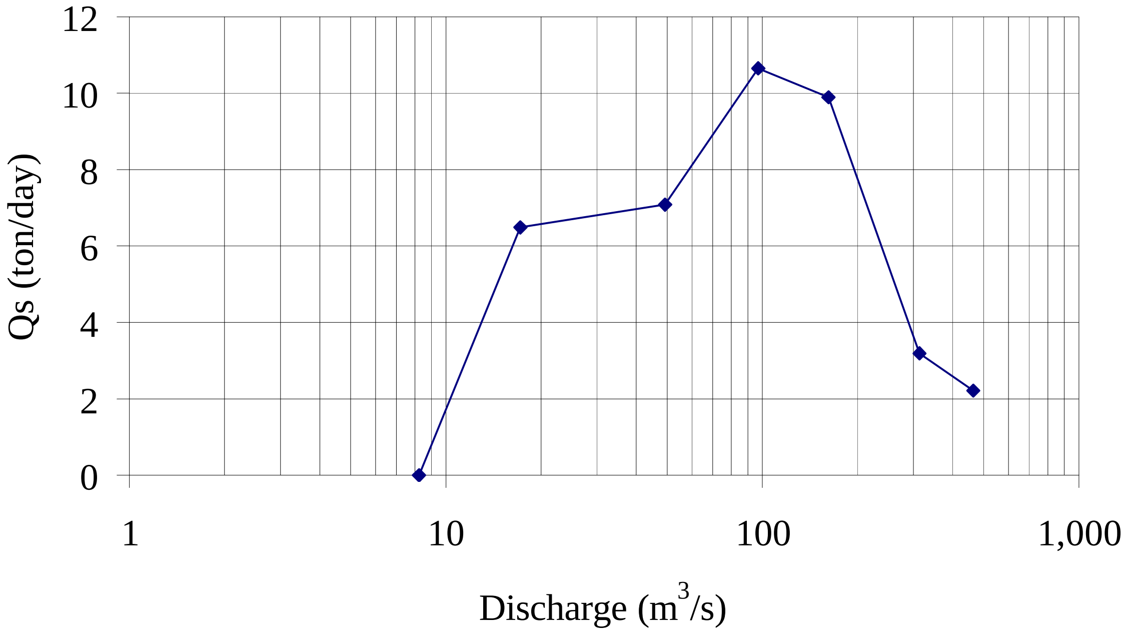

Figure 84. Gila River At Calva, AZ, USGS Gage # 09466500, 1930-1965, XS 631.06.

Table 17. Gila River At Calva, AZ, USGS Gage # 09466500, 1930-1965, XS 631.06.

1 Limits %	2 Interval %	3 Middle Ordinate	4 Q ft³/s	 Q m³/s	5 Q_s tons/day	2 x 4 Q ft³/s	2 x 5 Q_s tons/day
0.00 - 0.02	0.02	0.01	16,476.83	466.57	112.1537	3.30	2.24
0.02 - 0.1	0.08	0.06	11,093.23	314.13	40.0424	8.87	3.20
0.1 - 0.5	0.4	0.3	5,687.60	161.06	24.7957	22.75	9.92
0.5 - 1.5	1	1	3,430.27	97.13	10.6553	34.30	10.66
1.5 - 5.0	3.5	3.25	1,745.22	49.42	2.0296	61.08	7.10
5.0 - 15	10	10	607.93	17.21	0.6462	60.79	6.46
15 - 25	10	20	289.66	8.20	0.0000	28.97	0.00
25 - 35	10	30	174.53	4.94	0.0000	17.45	0.00
35 - 45	10	40	108.41	3.07	0.0000	10.84	0.00

1 Limits %	2 Interval %	3 Middle Ordinate	4 Q ft³/s	Q m³/s	5 Q_s tons/day	2 x 4 Q ft³/s	2 x 5 Q_s tons/day
45 - 55	10	50	71.02	2.01	0.0000	7.10	0.00
55 - 65	10	60	44.43	1.26	0.0000	4.44	0.00
65 - 75	10	70	25.86	0.73	0.0000	2.59	0.00
75 - 85	10	80	14.06	0.40	0.0000	1.41	0.00
85 - 95	10	90	5.78	0.16	0.0000	0.58	0.00
95 - 96.5	3.5	96.75	1.37	0.04	0.0000	0.05	0.00
98.5 - 99.5	1	99	0.26	0.01	0.0000	0.00	0.00
99.5 - 99.9	0.4	99.7	0.05	0.0016	0.0000	0.00	0.00
99.9 - 99.98	0.08	99.94	0.01	0.0003	0.0000	0.00	0.00
99.98 - 100	0.02	99.99	0.00	0.0001	0.0000	0.00	0.00
					Total =	264.52	39.59
					Q_{annual} =	191,635	AF/year
					$Q_{s\ annual}$ =	14,449	tons/year

Lower Reach 4

Cross section 17110.88 from the HEC-RAS model of Lower Reach 4 was selected to estimate the effective discharge. Figure 85 shows the graphical results of the tabulated calculations shown in Table 18. The effective discharge in Lower Reach 4 is roughly 426 m³/s (15,046 ft³/s) for the period 1965 to 2000.

Figure 86 shows the graphical results of the tabulated calculations shown in Table 19. The effective discharge in Lower Reach 1 is roughly 47.5 m³/s (1,679 ft³/s) during the period of 1920 to 1965.

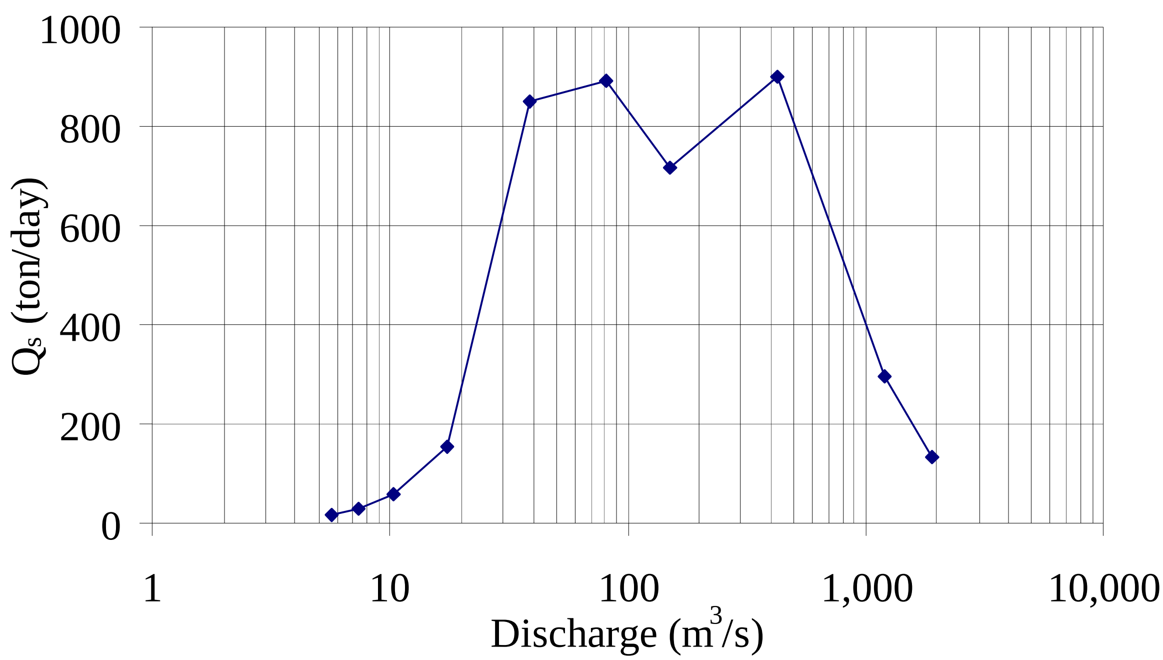

Figure 85. Gila River At Head Of Safford Valley, Near Solomon, AZ, USGS Gage # 09448500, 1965-2000, XS 17110.88.

Table 18. Gila River At Head Of Safford Valley, Near Solomon, AZ, USGS Gage #09448500, 1965-2000, XS 17110.88.

1 Limits %	2 Interval %	3 Middle Ordinate	4 Q ft^3/s	Q m^3/s	5 Q_s tons/day	2 x 4 Q ft^3/s	2 x 5 Q_s tons/day
0.00-0.02	0.02	0.01	67,932.73	1,923.64	6734.1177	13.59	134.68
0.02-0.1	0.08	0.06	42,286.92	1,197.43	3722.8172	33.83	297.83
0.1-0.5	0.4	0.3	15,045.98	426.05	2253.7201	60.18	901.49
0.5-1.5	1	1	5,336.17	151.10	715.1645	53.36	715.16
1.5-5.0	3.5	3.25	2,872.69	81.35	254.5001	100.54	890.75
5.0-15	10	10	1,366.60	38.70	85.1594	136.66	851.59
15-25	10	20	618.64	17.52	15.2676	61.86	152.68
25-35	10	30	366.40	10.38	5.6936	36.64	56.94
35-45	10	40	257.96	7.30	2.9410	25.80	29.41
45-55	10	50	201.25	5.70	1.7372	20.13	17.37
55-65	10	60	163.89	4.64	1.1597	16.39	11.60
65-75	10	70	134.66	3.81	0.7519	13.47	7.52
75-85	10	80	106.09	3.00	0.4319	10.61	4.32
85-95	10	90	74.75	2.12	0.1647	7.48	1.65
95-96.5	3.5	96.75	50.48	1.43	0.0166	1.77	0.06
98.5-99.5	1	99	37.05	1.05	0.0000	0.37	0.00
99.5-99.9	0.4	99.7	28.71	0.81	0.0000	0.11	0.00
99.9-99.98	0.08	99.94	23.10	0.65	0.0000	0.02	0.00
99.98-100	0.02	99.99	18.40	0.52	0.0000	0.00	0.00
					Total=	592.81	4073.04
					Q_{annual}=	429,460	AF/year
					$Q_{sannual}$=	1,486,660	tons/year

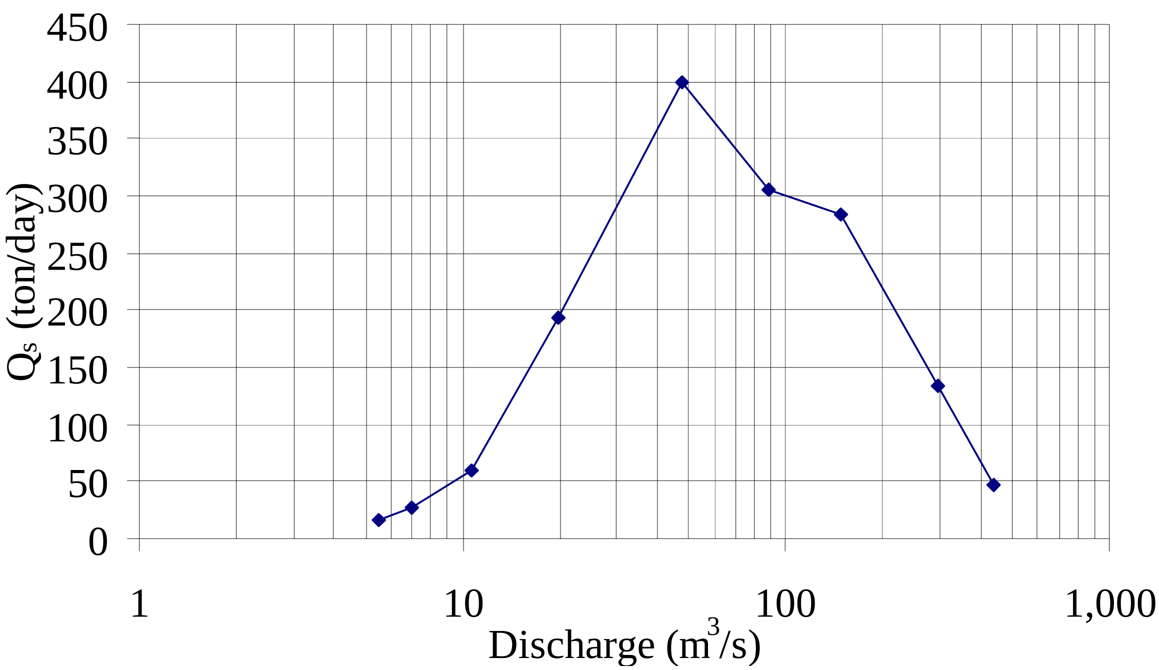

Figure 86. Gila River At Head Of Safford Valley, Near Solomon, AZ, USGS Gage # 09448500, 1920-1965, XS 17110.88.

Table 19. Gila River At Head Of Safford Valley, Near Solomon, AZ, USGS Gage #09448500, 1920-1965, XS 17110.88.

1 Limits %	2 Interval %	3 Middle Ordinate	4 Q ft^3/s	Q m^3/s	5 Q_s tons/day	2 x 4 Q ft^3/s	2 x 5 Q_s tons/day
0.00 - 0.02	0.02	0.01	15,616.48	442.21	2314.9791	3.12	46.30
0.02 - 0.1	0.08	0.06	10,451.85	295.96	1661.3147	8.36	132.91
0.1 - 0.5	0.4	0.3	5,240.37	148.39	711.3945	20.96	284.56
0.5 - 1.5	1	1	3,131.66	88.68	304.9383	31.32	304.94
1.5 - 5.0	3.5	3.25	1,678.90	47.54	114.3138	58.76	400.10
5.0 - 15	10	10	695.89	19.71	19.3864	69.59	193.86
15 - 25	10	20	377.97	10.70	5.9807	37.80	59.81
25 - 35	10	30	246.32	6.97	2.6220	24.63	26.22
35 - 45	10	40	192.98	5.46	1.6029	19.30	16.03
45 - 55	10	50	163.52	4.63	1.1572	16.35	11.57
55 - 65	10	60	136.12	3.85	0.7593	13.61	7.59
65 - 75	10	70	110.27	3.12	0.4802	11.03	4.80
75 - 85	10	80	84.29	2.39	0.2404	8.43	2.40
85 - 95	10	90	57.29	1.62	0.0415	5.73	0.41
95 - 96.5	3.5	96.75	36.33	1.03	0.0000	1.27	0.00
98.5 - 99.5	1	99	26.35	0.75	0.0000	0.26	0.00
99.5 - 99.9	0.4	99.7	20.43	0.58	0.0000	0.08	0.00
99.9 - 99.98	0.08	99.94	15.48	0.44	0.0000	0.01	0.00
99.98 - 100	0.02	99.99	13.16	0.37	0.0000	0.00	0.00
					Total =	330.62	1491.50
					Q_{annual} =	239,520	AF/year
					$Q_{s\ annual}$ =	544,399	tons/year

Upper Reach

Cross section 24238.64 from the HEC-RAS model of the Upper Reach was selected to estimate the effective discharge. Figure 87 shows the graphical results of the tabulated calculations shown in Table 20. The effective discharge in the Upper Reach is roughly 152.47 m^3/s (5,384 ft^3/s) during the period of 1965 to 2000.

Figure 88 shows the graphical results of the tabulated calculations shown in Table 21. The effective discharge in the Upper Reach is roughly 20.5 m^3/s (725 ft^3/s) during the period of 1927 to 1964.

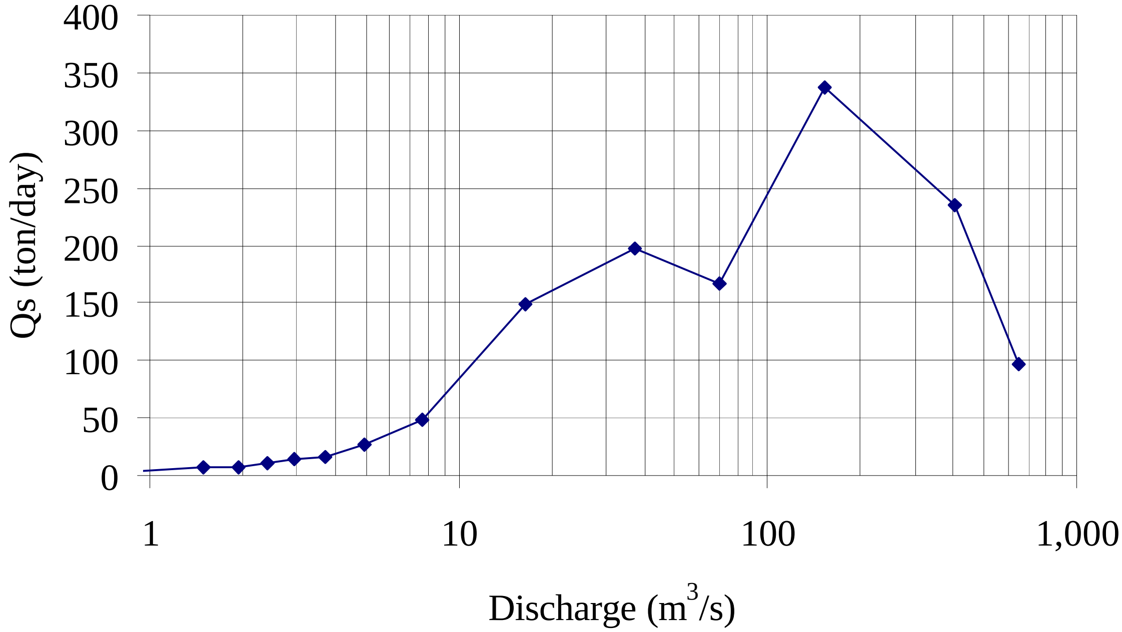

Figure 87. Gila River Below Blue Creek, Near Virden, NM, USGS Gage # 09432000, 1965-2000, XS 24238.64.

Table 20. Gila River Below Blue Creek, Near Virden, NM, USGS Gage # 09432000, 1965-2000, XS 24238.64.

1 Limits %	2 Interval %	3 Middle Ordinate	4 Q ft³/s	Q m³/s	5 Q_s tons/day	2 x 4 Q ft³/s	2 x 5 Q_s tons/day
0.00-0.02	0.02	0.01	23034.46	652.26	4849.6050	4.61	96.99
0.02-0.1	0.08	0.06	14221.95	402.72	2935.7243	11.38	234.86
0.1-0.5	0.4	0.3	5384.36	152.47	840.9313	21.54	336.37
0.5-1.5	1	1	2470.03	69.94	167.0932	24.70	167.09
1.5-5.0	3.5	3.25	1309.41	37.08	56.5859	45.83	198.05
5.0-15	10	10	582.62	16.50	14.8565	58.26	148.57
15-25	10	20	267.34	7.57	4.8827	26.73	48.83
25-35	10	30	174.88	4.95	2.6453	17.49	26.45
35-45	10	40	130.31	3.69	1.5987	13.03	15.99
45-55	10	50	103.17	2.92	1.3462	10.32	13.46
55-65	10	60	84.64	2.40	1.0511	8.46	10.51
65-75	10	70	68.91	1.95	0.7983	6.89	7.98
75-85	10	80	52.94	1.50	0.6471	5.29	6.47
85-95	10	90	31.66	0.90	0.4207	3.17	4.21
95-96.5	3.5	96.75	15.13	0.43	0.1152	0.53	0.40
98.5-99.5	1	99	7.04	0.20	0.0094	0.07	0.01
99.5-99.9	0.4	99.7	4.29	0.12	0.0000	0.02	0.00
99.9-99.98	0.08	99.94	2.91	0.08	0.0000	0.00	0.00
99.98-100	0.02	99.99	1.17	0.03	0.0000	0.00	0.00
					Total=	258.32	1316.25
					Q_{annual}=	187,140	AF/year
					$Q_{sannual}$=	480,430	tons/year

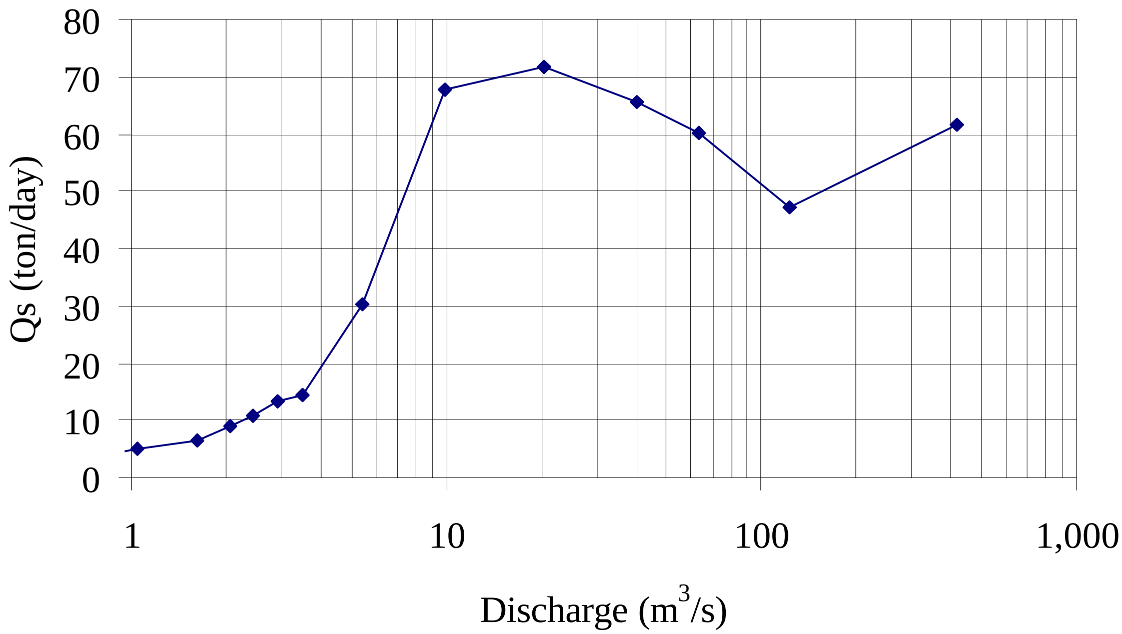

Figure 88. Gila River Below Blue Creek, Near Virden, NM, USGS Gage # 09432000, 1927-1964, XS 24238.64.

Table 21. Gila River Below Blue Creek, Near Virden, NM, USGS Gage # 09432000, 1927-1964, XS 24238.64.

1 Limits %	2 Interval %	3 Middle Ordinate	4 Q ft^3/s	Q m^3/s	5 Q_s tons/day	2 x 4 Q ft^3/s	2 x 5 Q_s tons/day
0.00 - 0.02	0.02	0.01	14830.16	419.94	3078.0348	2.97	61.56
0.02 - 0.1	0.08	0.06	4363.46	123.56	591.4365	3.49	47.31
0.1 - 0.5	0.4	0.3	2236.01	63.32	150.5934	8.94	60.24
0.5 - 1.5	1	1	1426.32	40.39	65.6738	14.26	65.67
1.5 - 5.0	3.5	3.25	725.38	20.54	20.4699	25.39	71.64
5.0 - 15	10	10	349.65	9.90	6.7727	34.96	67.73
15 - 25	10	20	190.80	5.40	3.0132	19.08	30.13
25 - 35	10	30	123.96	3.51	1.4475	12.40	14.48
35 - 45	10	40	103.33	2.93	1.3508	10.33	13.51
45 - 55	10	50	86.62	2.45	1.0667	8.66	10.67
55 - 65	10	60	73.25	2.07	0.8870	7.33	8.87
65 - 75	10	70	56.84	1.61	0.6662	5.68	6.66
75 - 85	10	80	37.22	1.05	0.4943	3.72	4.94
85 - 95	10	90	15.48	0.44	0.1257	1.55	1.26
95 - 96.5	3.5	96.75	4.49	0.13	0.0000	0.16	0.00
98.5 - 99.5	1	99	2.82	0.08	0.0000	0.03	0.00
99.5 - 99.9	0.4	99.7	2.26	0.06	0.0000	0.01	0.00
99.9 - 99.98	0.08	99.94	1.76	0.05	0.0000	0.00	0.00
99.98 - 100	0.02	99.99	0.58	0.02	0.0000	0.00	0.00
					Total =	158.96	464.67
					Q_{annual} =	115,162	AF/year
					$Q_{s\ annual}$ =	169,606	tons/year

SUMMARY OF HYDRAULIC, HYDROLOGIC, AND BED MATERIAL DATA

Table 22 summarizes the effective discharge calculations for each period of record at particular gaging stations, as well as listing the results of other calculations and comparisons. The table organizes much of the input necessary for RISAD and the stable channel analysis. The results from the Gila River at Calva, AZ, gage during the period of 1965 to 2000 will be used in the stable channel analysis in Lower Reach 1 and 2. The results from the Gila River at Head of Safford Valley Near Solomon, AZ, gage during the period of 1965 to 2000 will be used in the stable channel analysis in Lower Reach 3 and 4. The results from the Gila River below Blue Creek near Virden, NM, gage during the period 1965 to 2000 will be used in the stable channel analysis in the Upper Reach.

Table 22. Summary of periods of record and resulting hydrologic and sediment transport analysis.

Period	Calculated Mean AF/yr	USGS Mean AF/yr	Δ	Q_{eff} ft³/s	Ratio	Q_s t/d	Q_s PPM
GILA RIVER AT CALVA, AZ USGS Gage # 09466500							
1930-2000	284,410	277,456	2.5%				
1930-1964	191,635	176,205	8.8%	3,430		11	1.1
1965-2000	373,373	384,664	-2.9%	42,082	12.3	614	5.4
GILA RIVER AT SAFFORD, AZ USGS Gage # 09458500							
1940-1965	229,121	206,640	10.9%				
GILA RIVER NEAR SOLOMON, AZ USGS Gage # 09451000							
1914-1951	360,932	359,490	0.4%				
GILA RIVER AT HEAD OF SAFFORD VALLEY NEAR SOLOMON, AZ USGS Gage # 09448500							
1920-2000	325,435	342,418	-5.0%				
1920-1964	239,520	251,304	-4.7%	1,679		114	25.2
1965-2000	429,460	443,945	-3.3%	15,046	9.0	2254	55.5
SAN FRANCISCO RIVER AT CLIFTON, AZ USGS Gage # 09444500							
1911-1999	157,053	161,865	-3.0%				
1911-1964	131,472	130,034	1.1%				
1965-1999	184,421	195,516	-5.7%				
GILA RIVER BELOW BLUE CREEK NEAR VIRDEN, NM USGS Gage # 09432000							
1927-2000	150,728	154,683	-2.6%				
1927-1964	115,162	117,291	-1.8%	725		20	10.5
1965-2000	187,140	196,608	-4.8%	5,384	7.4	841	57.8

Table 23 summarizes the channel side slopes at each of the sections in the analysis. Cross section 631.06 will represent both Lower Reach 1 and 2.

Table 23. Summary of channel side slopes and seed widths for RISAD.

Reach	X-Section	Right Bank Z	Left Bank Z	Ratio	Top Width (ft)
Lower Reach 1 & 2	631.06	39	20	1.96	2073
Lower Reach 4 & 3	17110.88	23	44	1.86	1064
Upper Reach	24238.64	20	13	1.58	324

Cross section 17110.88 will represent both Lower Reach 3 and 4. Cross Section 24238.64 will represent the Upper Reach. In each case, the top-width, from the HEC-RAS model, of the main channel was selected as the 'seed' width for the RISAD model. RISAD solves water continuity, roughness, and sediment transport continuity at a section, based upon the geometry of the section, i.e. the bank slopes, and the top width. It satisfies those three conditions simultaneously at various widths, based upon the 'seed' width. It calculates at twenty intervals, beginning at one-tenth of the 'seed' width, and proceeding up to twice the 'seed' width. In each case, the exception being the Upper Reach, the Myer-Peter Muller equation was used for the sediment transport. In the Upper Reach Brownlie was used because the D_{50} was sand size.

STABLE CHANNEL ANALYSIS

This section presents the stable channel analysis. The analysis consists primarily of a chart plotting the slope of the energy grade line versus top width of the channel. The metric for stability is the relative proximity of the channel values to the RISAD developed curve. Points above the stable channel curve are in a zone that generally degrades. Points below the stable channel curve are in a zone that generally aggrades. Points in proximity to the stable channel curve, above and below, as well as dead-on, are in the zone of stability. It is best to take a collective look at the points from a reach. Outliers usually indicate either sections with 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.

LOWER REACHES 1 & 2

Figure 89 shows the input screen for the Stable Channel Design: Lower Reach 1. The results are also applied to Lower Reach 2.

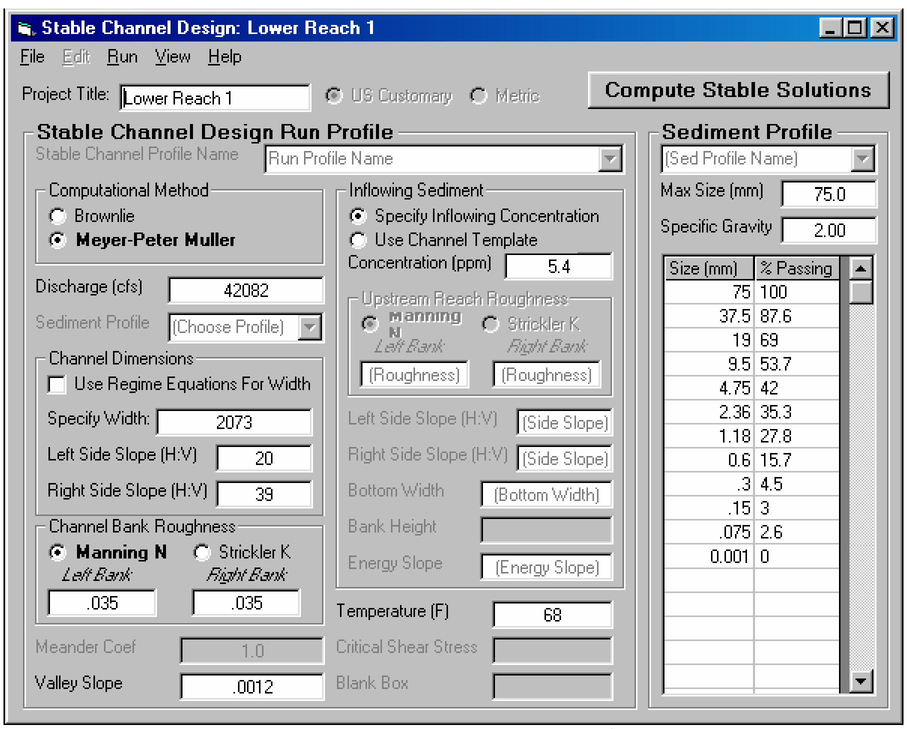

Figure 89. Stable Channel Design (RISAD) input screen for Lower Reaches 1 & 2.

Figure 90 presents the stable channel relationship produced by RISAD for Lower Reaches 1 & 2. Values for the Energy Grade Line (EGL) slope are at each HEC-RAS cross section in the respective reach, and are calculated by the HEC-RAS model.

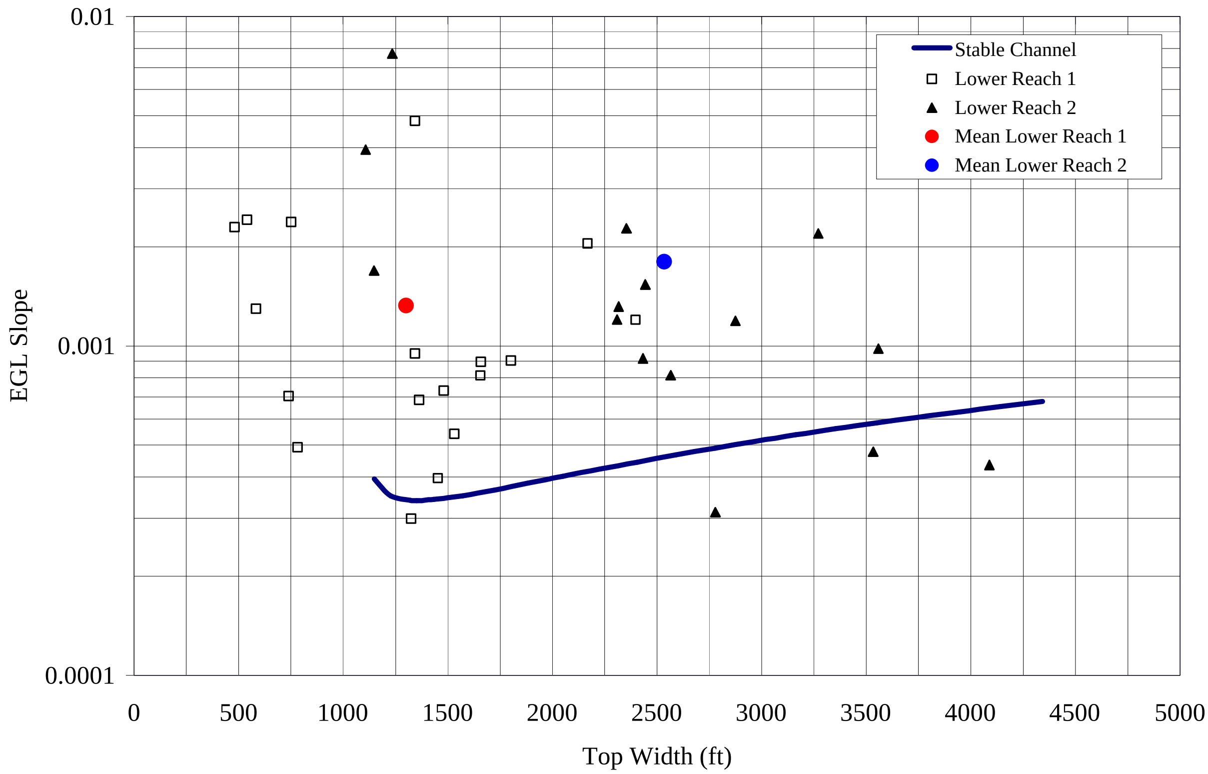

Figure 90. Stable channel analysis in Lower Reach 1 and 2.

Model results show that both reaches are relatively unstable. Some sections in Lower Reach 2 might be stable. The implications of the extremal hypothesis (trend towards the minimum slope on the stable channel curve) indicate that the channel is generally too steep, and many sections, especially in Lower Reach 2, are too wide. This parallels the conclusions of the Catalog of Historical Changes (Klawon, 2001), in that the channel in the upper Safford Valley is nearly at record width, over the period of 1935-1997, and may have been narrowing since 1997. The channel may reduce its slope in two ways: aggradation or increasing sinuosity. Local observation indicates that there may be local aggradation below Fort Thomas. The RISAD results do not indicate aggradation (points below the curve). The instability is probably due to increasing sinuosity, manifesting itself in bank instability and retreat.

LOWER REACHES 3 & 4

Figure 91 shows the input screen for the Stable Channel Design: Lower Reach 4. The results are also applied to Lower Reach 3.

Figure 92 presents the stable channel relationship produced by RISAD for Lower Reaches 3 & 4. Values for the Energy Grade Line (EGL) slope are at each HEC-RAS cross section in the respective reach, and are calculated by the HEC-RAS model.

Model results show that both reaches are relatively stable by virtue of the distribution of points about the stable channel curve. However, many points are a significant distance away from the curve and the minimum, extremal hypothesis, point on the curve. Observations from bridges in the valley reveal no obvious bed degradation. However, there has been significant lateral movement of the stream in several areas, due both to channel straightening projects and the river response to those, and the hydrologic regime since the mid 1960’s.

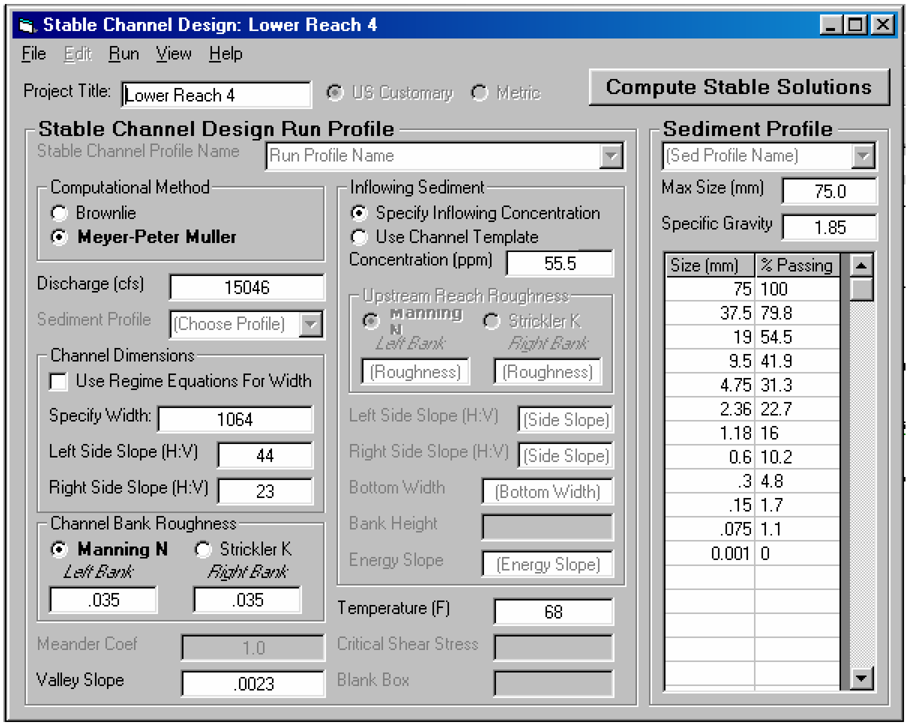

Figure 91. Stable Channel Design (RISAD) input screen for Lower Reaches 3 & 4.

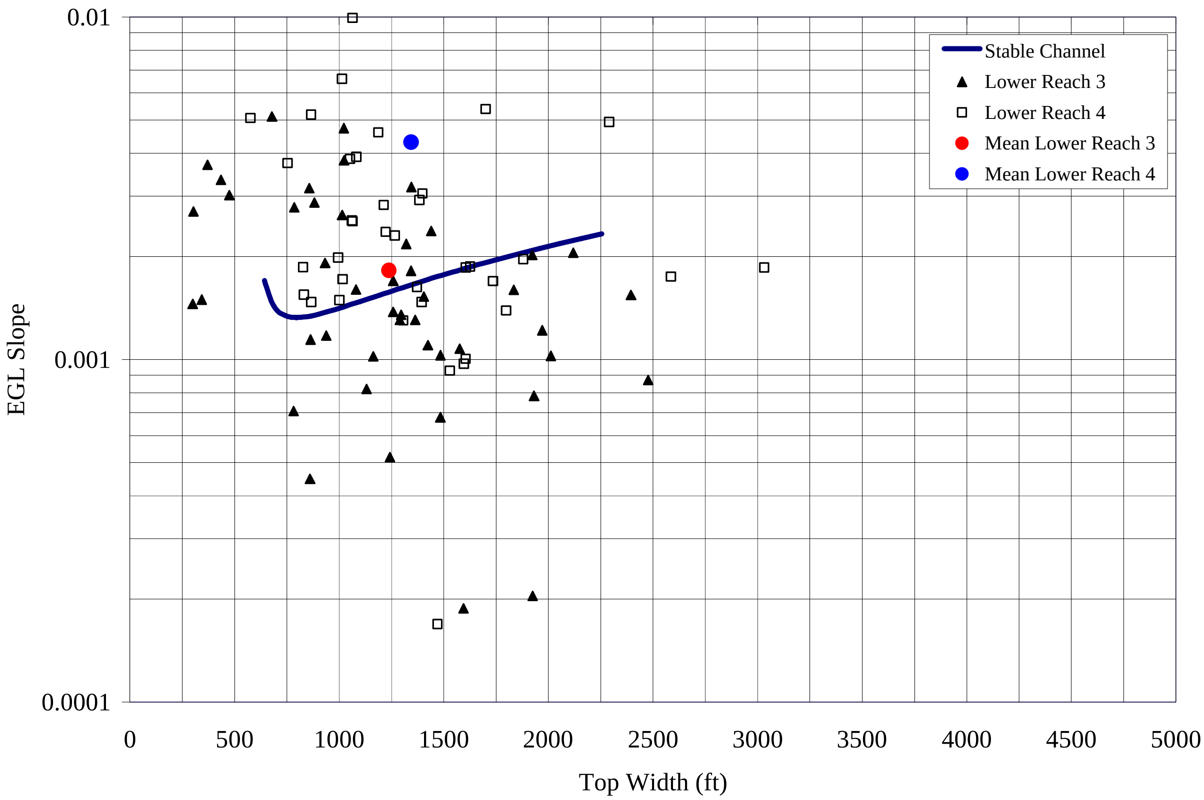

Figure 92. Stable channel analysis in Lower Reach 3 and 4.

UPPER REACH

Figure 93 shows the input screen for the Stable Channel Design: Upper Reach.

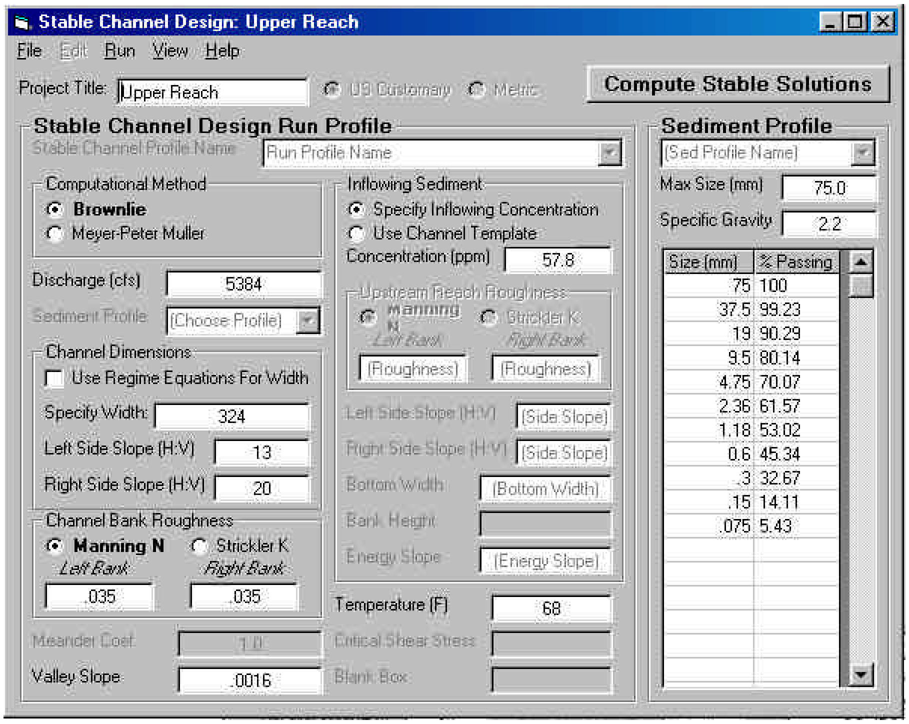

Figure 93. Stable Channel Design (RISAD) input screen for the Upper Reach.

Figure 94 presents the stable channel relationship produced by RISAD for the Upper Reach. Values for the Energy Grade Line (EGL) slope are at each HEC-RAS cross section in the reach, and are calculated by the HEC-RAS model.

Model results show that most of the sections in the Upper Reach are in the degradational range of the stable channel plot. Observations by Klawon indicate recent aggradation that the channel is now degrading. Implications of the extremal hypothesis are that the channel is indeed degrading, by lowering the bed and widening. Also, as the channel attempts to lower the slope, sinuosity will increase, resulting in bank instability and retreat. There are ample observations of that phenomenon in the Virden and Duncan areas.

There is evidence (Klawon, 2001) of bed rock controls in the lower portion of the Upper Reach. There also appear to be areas of hydraulic control that are not alluvial. The stable channel analysis does not apply to reaches in these areas, and likely produces outliers on the stable channel curve.

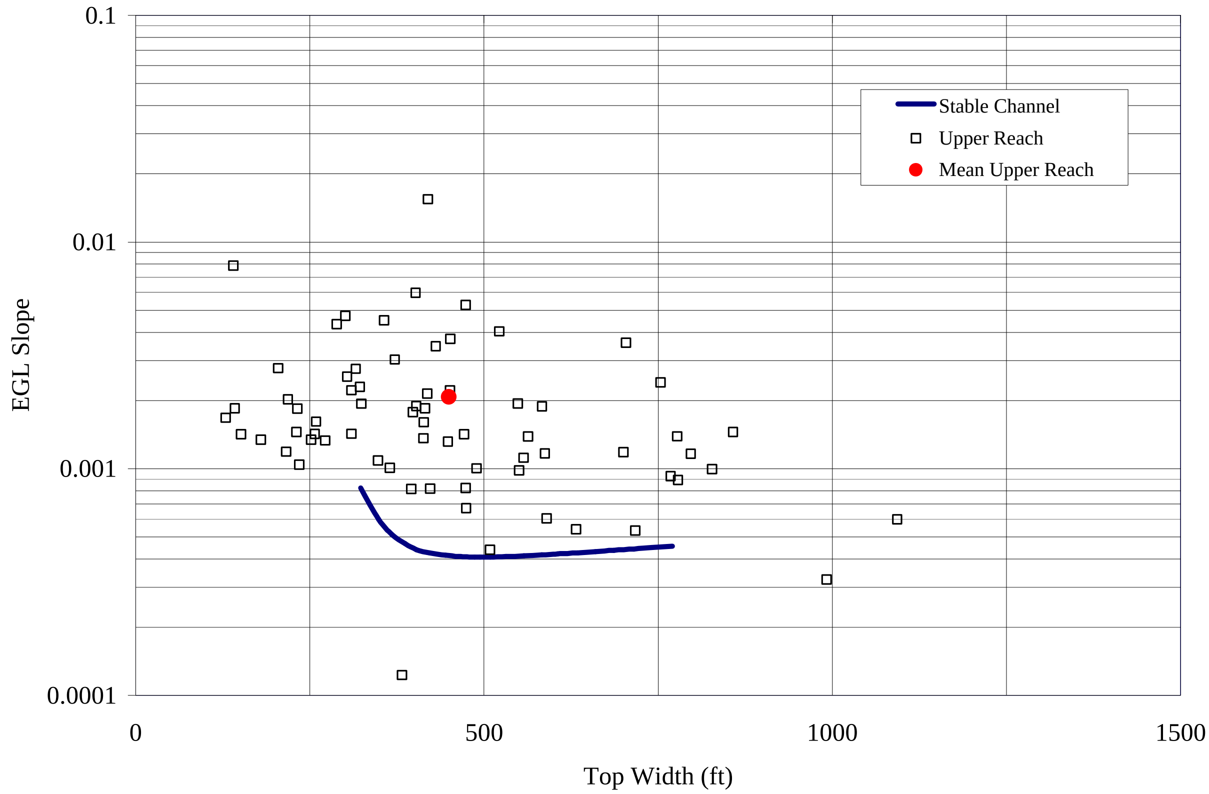

Figure 94. Stable channel analysis in the Upper Reach.

In general, since 1965 the study area is experiencing larger and more frequent floods compared to the 50 year preceding period. During the period from 1935 to 1965 the channel narrowed (Klawon, 2001). Since 1965 the channel is responding to the change in hydrology. The response includes widening, degrading in some reaches, aggrading in others, and increasing sinuosity. These are all normal geomorphic responses to an increase in the magnitude and frequency of floods in the channel forming flow range.

CONCLUSIONS

This analysis indicates that the results of the stable channel modeling are consistent with the geometry of the Gila River in the study area. The modeling indicates that the river is moderately unstable at the effective discharge in many sub-reaches, mostly in the area downstream of Safford and upstream of Sheldon. The modeling shows that the river is stable in a few sub-reaches, mostly between York and Sheldon, possibly due to the lack of levees in this area. The instability is greatest with respect to the width and sinuosity of the stream, manifested in a general aggradational position of channel geometries on the stable channel curves. In general the channel has widened in response to an increase in the magnitude and frequency of floods since 1965. Without large floods in the future, the channel will narrow and may locally aggrade, similar to the 1935-1965 period.

LOWER REACHES 1 & 2

Model results show that Lower Reach 1 and Lower Reach 2 are relatively unstable. Some sections in Lower Reach 2 might be stable. The channel in the Safford Valley is nearly the same as in 1935, the widest measured over the period of 1935-1997 (Klawon, 2001). Model results indicate that if the channel trends towards the minimum slope on the stable channel curve, Lower Reach 2 will experience the most channel narrowing. The process may include an increase in sinuosity causing widespread bank instability and retreat. Hypothetically, and separate from the stable channel analysis, a typical geomorphic response might include invasion of non-native vegetation, followed by bank encroachment and channel narrowing.

The stable channel analysis indicates that Lower Reach 1 may to be overly steep. If the channel reduces its slope by increasing sinuosity, bank instability and retreat will result. However, local observations indicate that the channel may be aggrading in the reach below Fort Thomas. More modeling and geomorphic investigation is necessary to determine the channel trends in this area.

LOWER REACHES 3 & 4

Model results show that both Lower Reach 3 and Lower Reach 4 are relative stable by virtue of the distribution of points about the stable channel curve. There has been significant lateral movement of the stream in several areas, due both to channel straightening projects and the river response to those and the hydrologic regime since the mid 1960's. Lower Reach 3 may undergo the most channel narrowing following invasion by non-native vegetation and bank encroachment.

UPPER REACH

Model results show that most of the sections in the Upper Reach are in the degradational range of the stable channel plot. Geomorphic evidence indicates that the river is in a period of degradation following a period of aggradation. There are ample observations of that phenomenon in the Virden and Duncan areas. There are several bedrock areas and hydraulic controls that are not alluvial in nature, invalidating the stable channel analysis in those reaches.

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APPENDIX A

HEC-RAS SECTION LOCATIONS

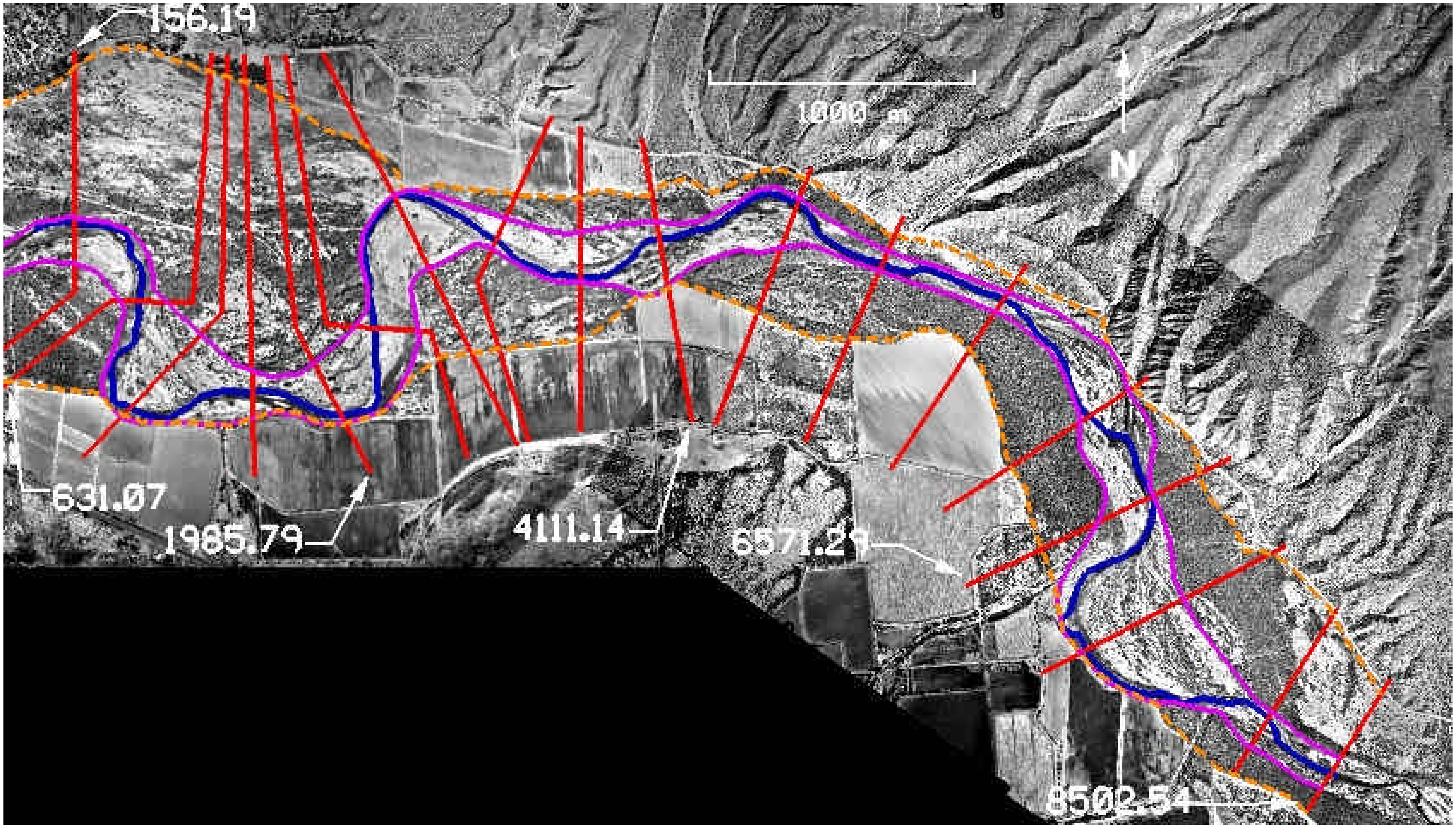


Figure 95. Lower Reach 1.

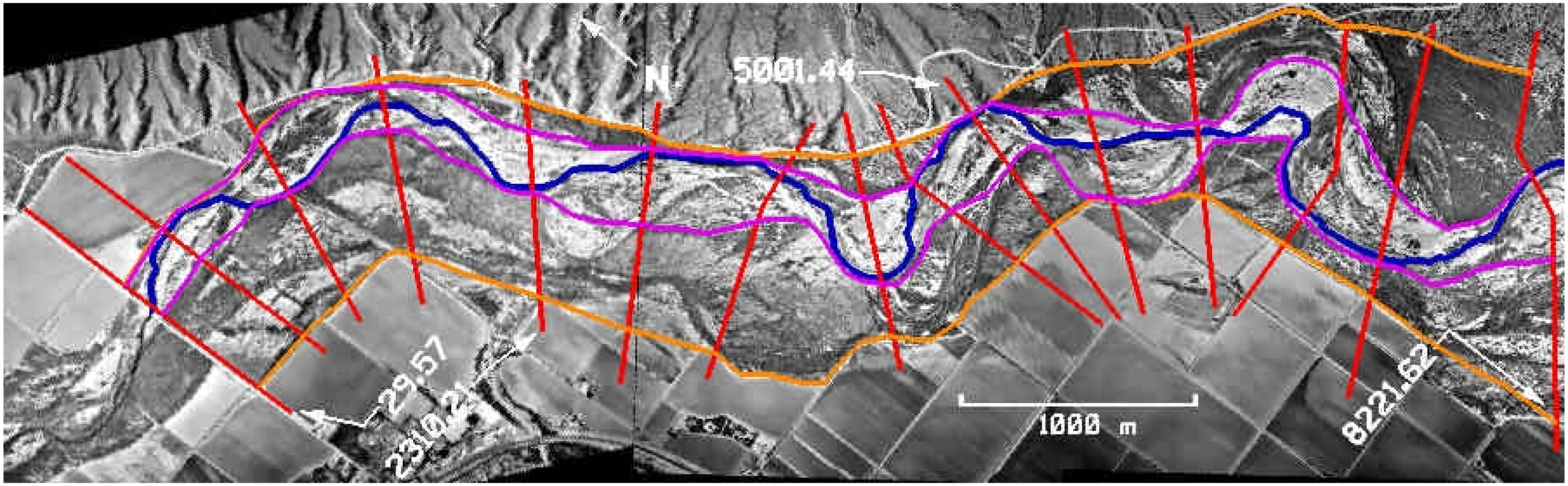


Figure 96. Lower Reach 2.

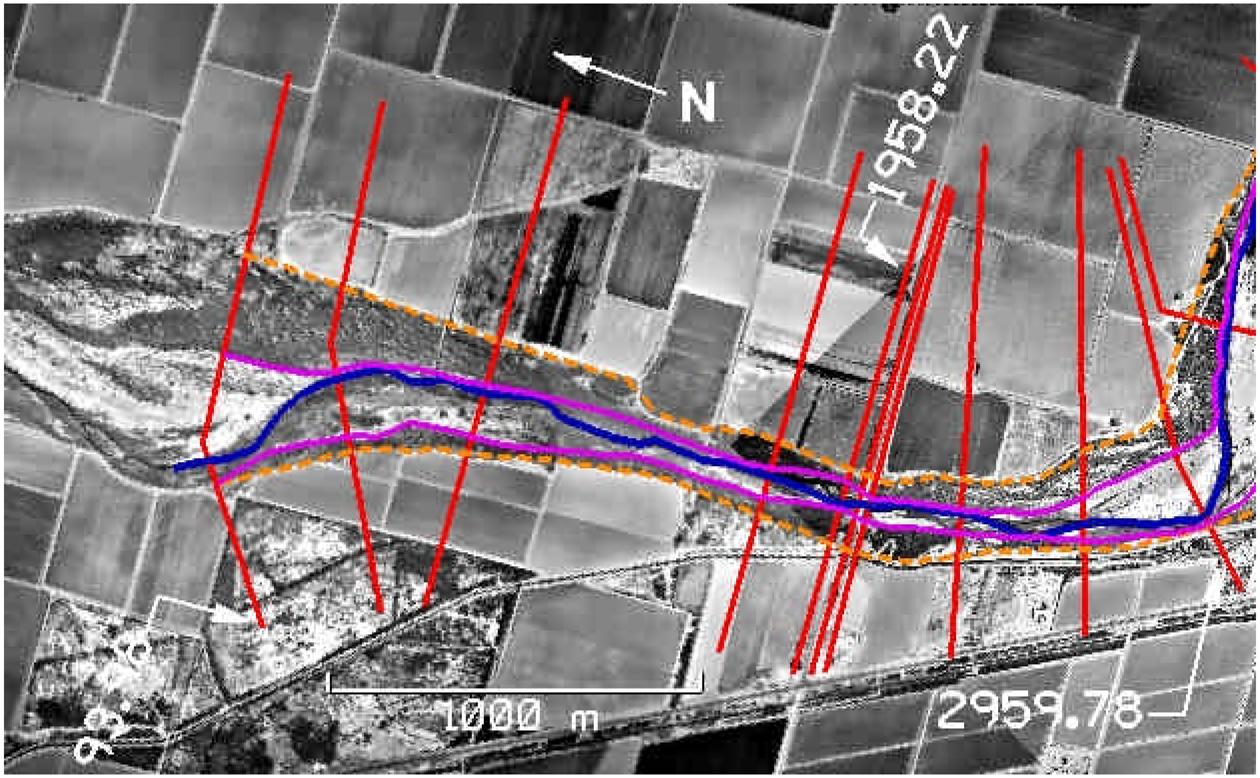


Figure 97. Lower Reach 3-A.

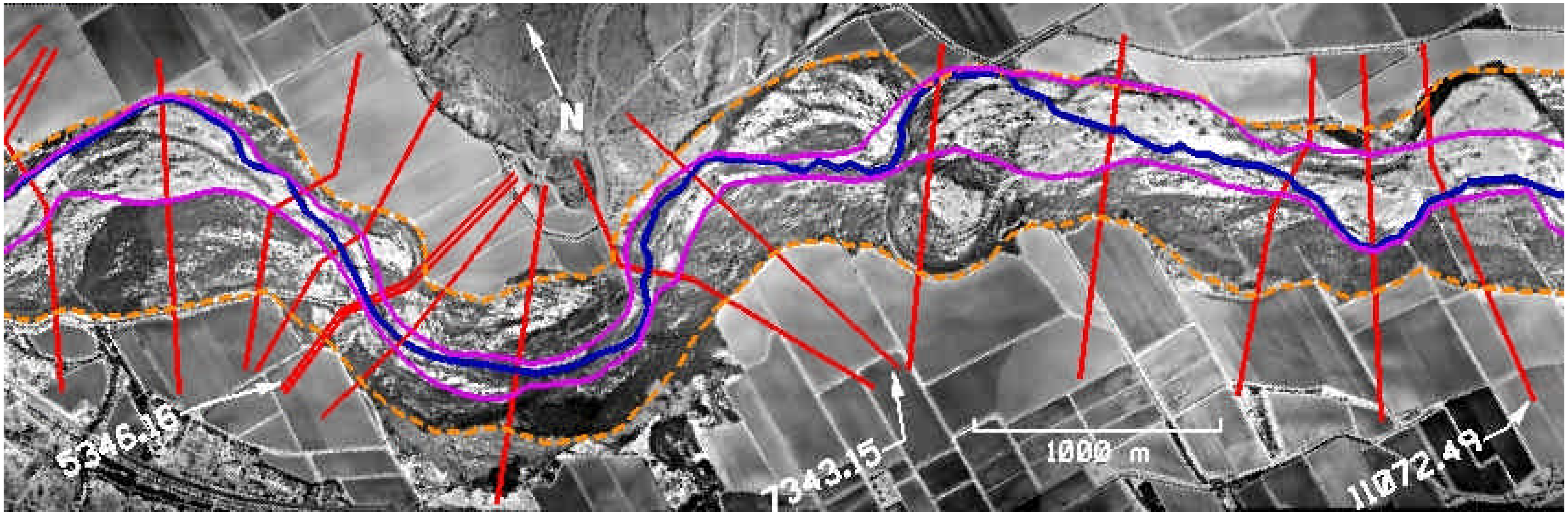


Figure 98. Lower Reach 3-B.

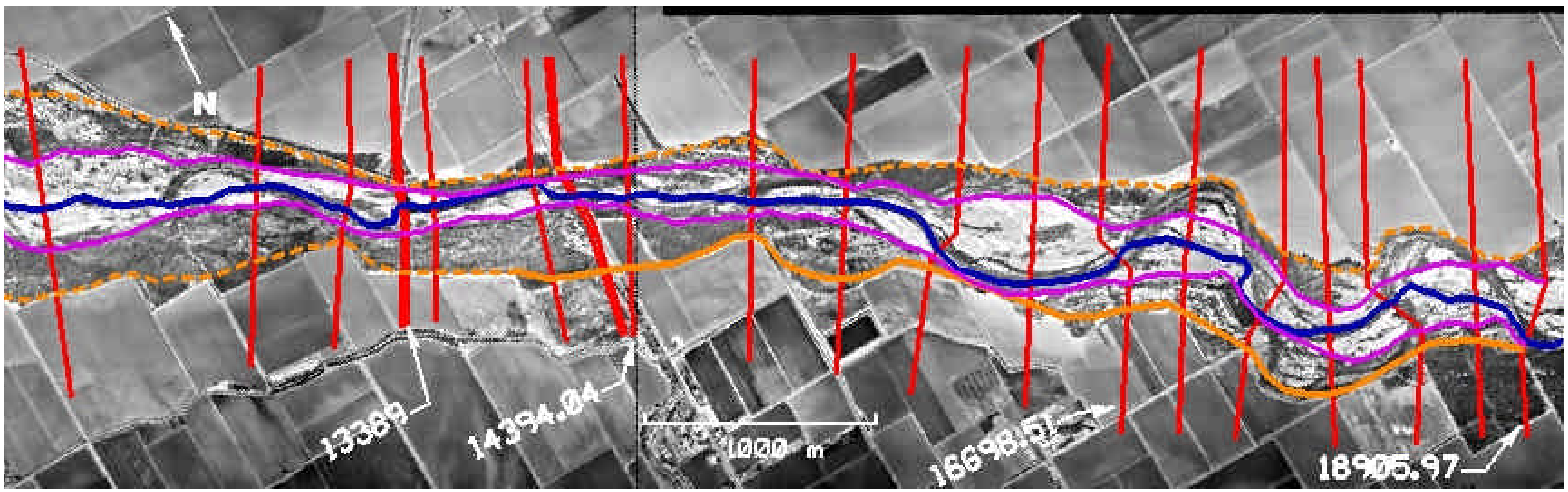


Figure 99. Lower Reach 3-C.

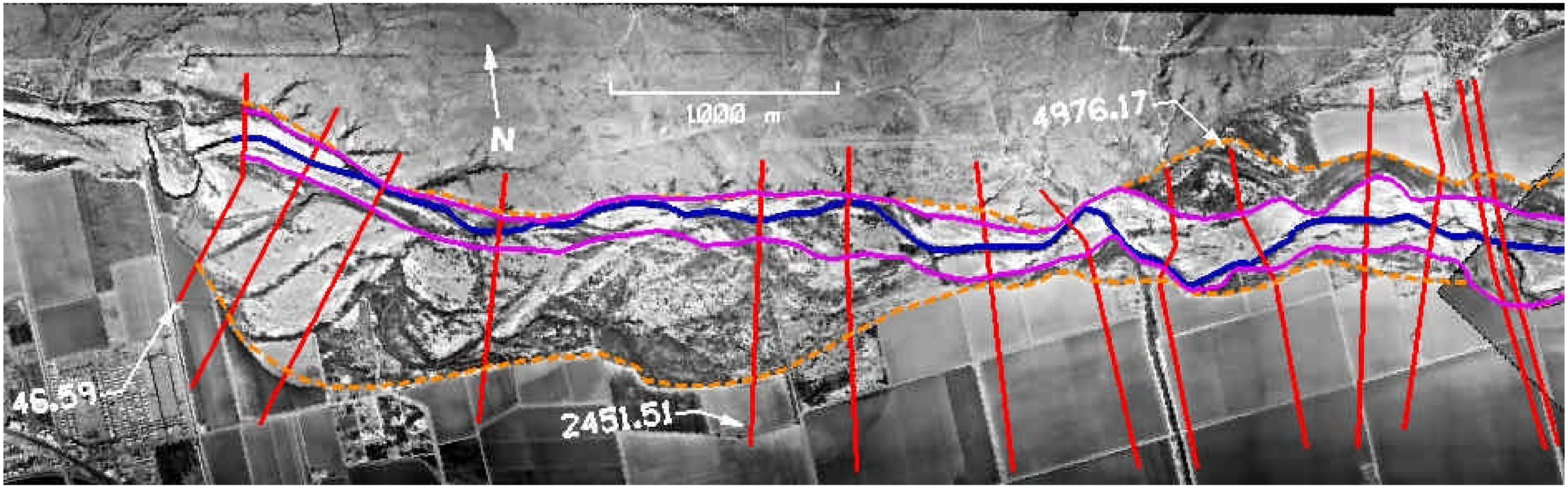


Figure 100. Lower Reach 4-A.

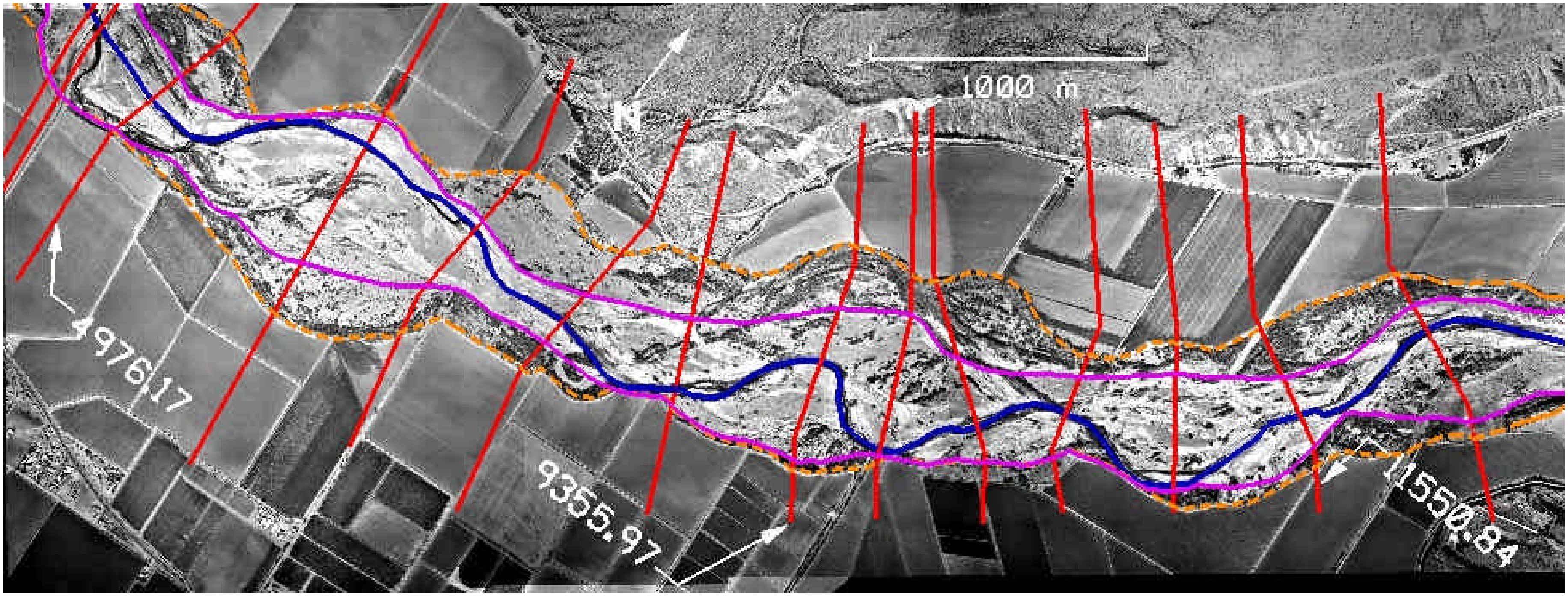


Figure 101. Lower Reach 4-B.

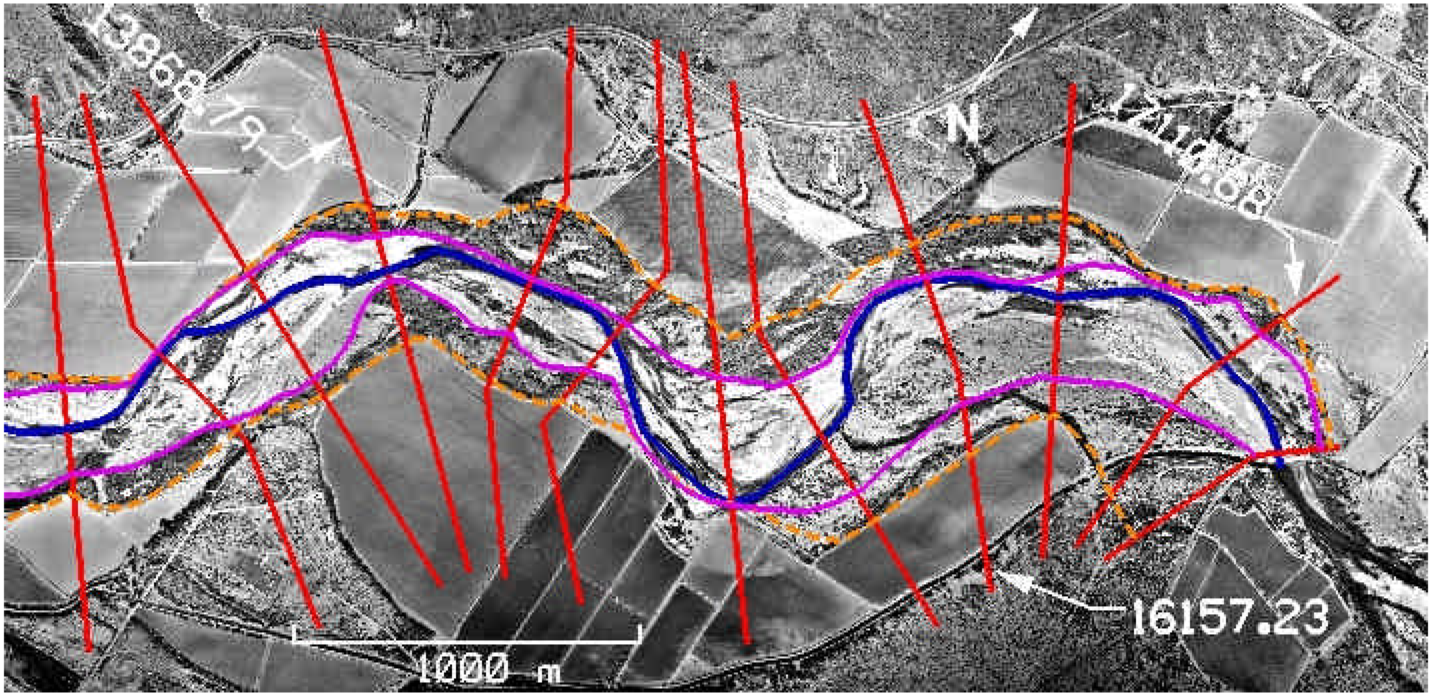


Figure 102. Lower Reach 4-C.

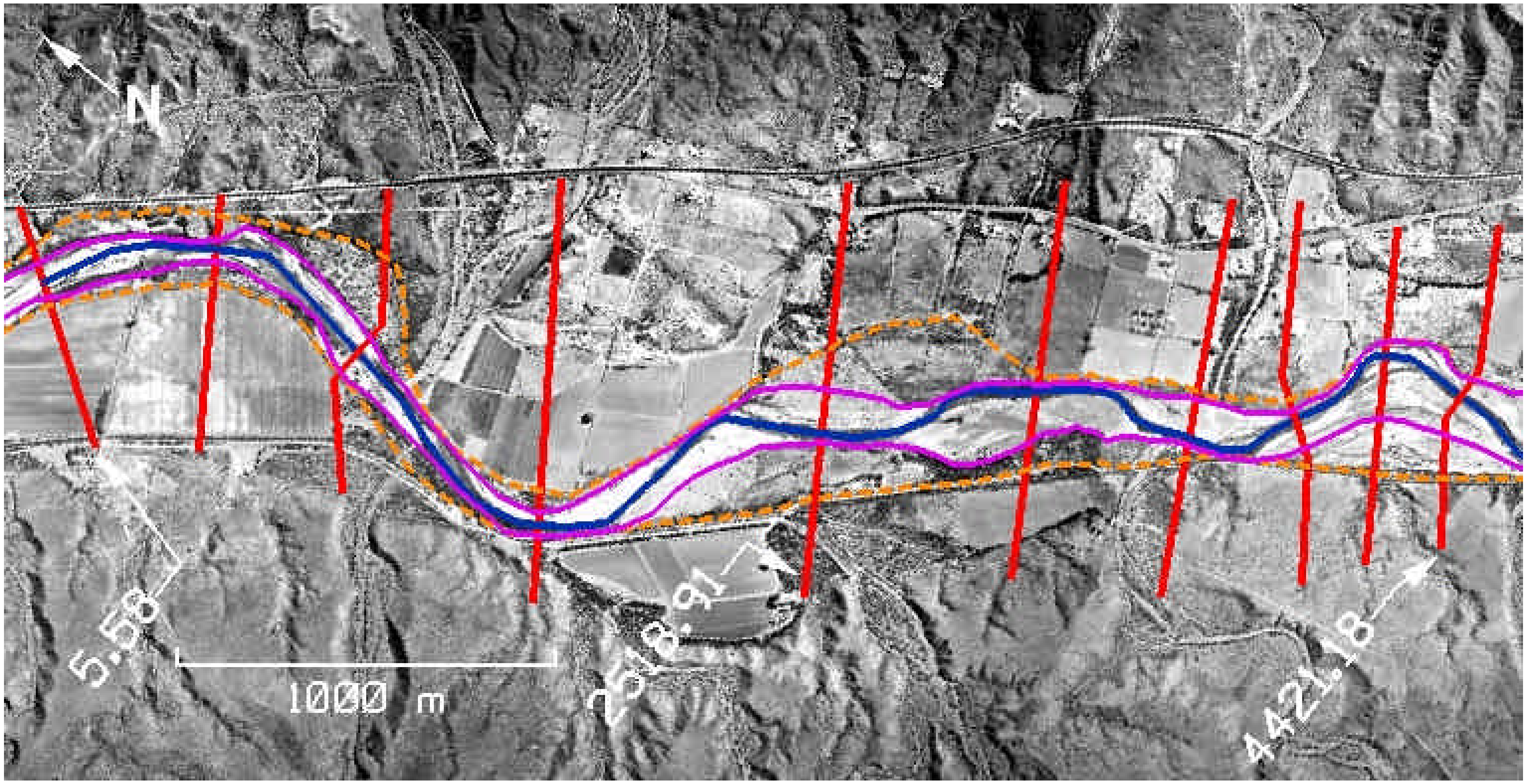


Figure 103. Upper Reach A.

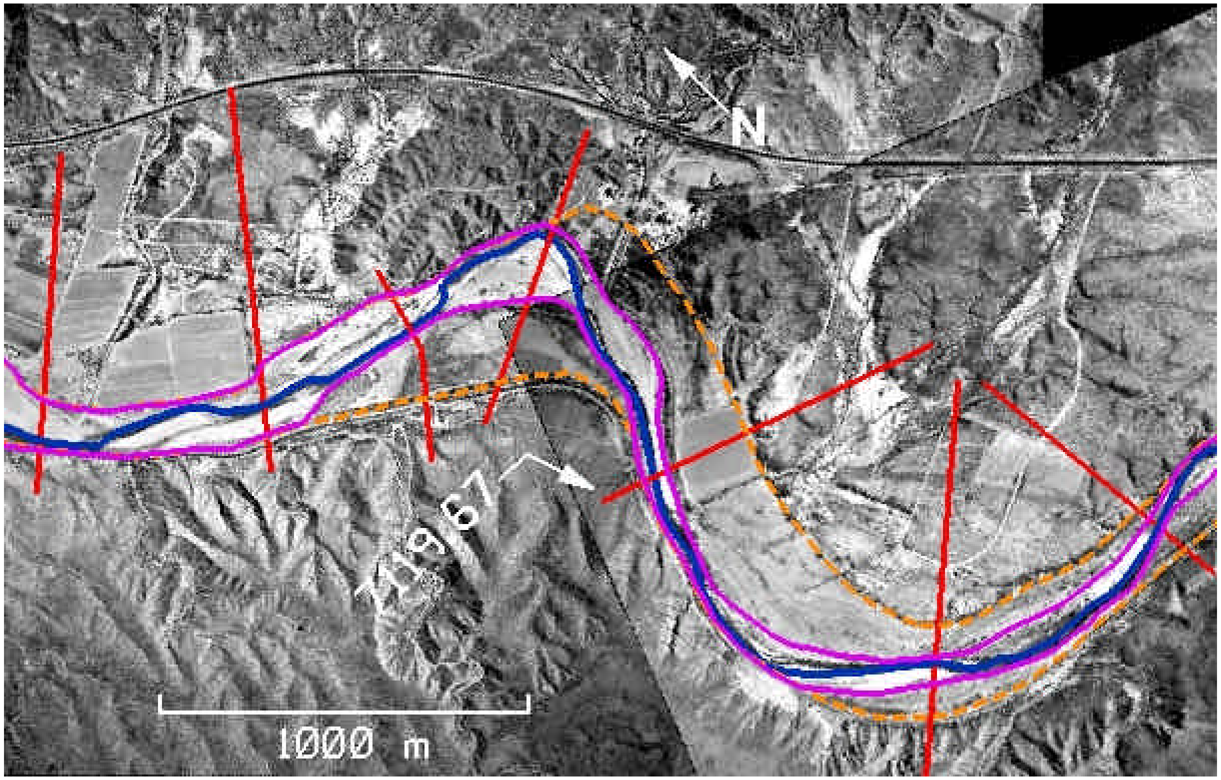


Figure 104. Upper Reach B.

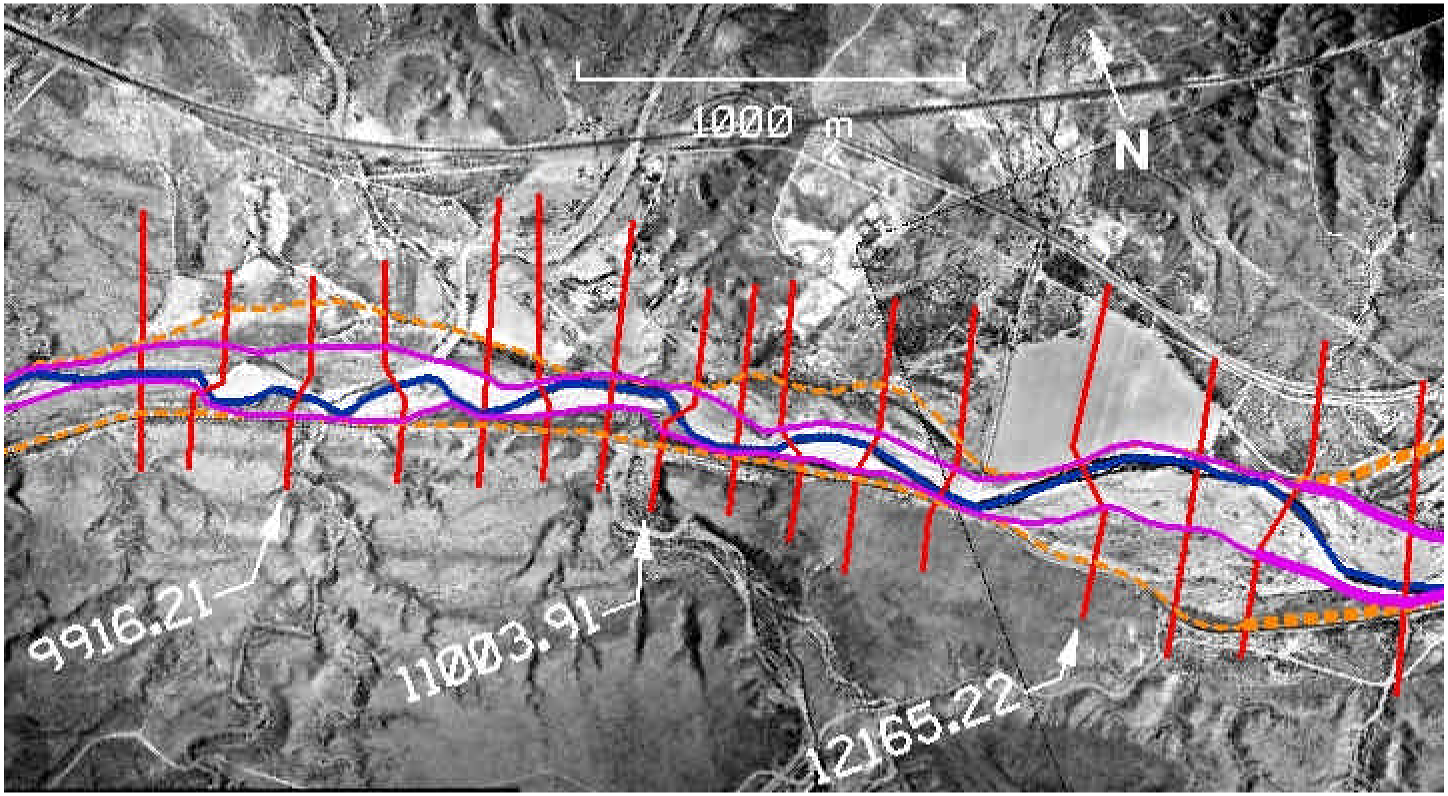


Figure 105. Upper Reach C.

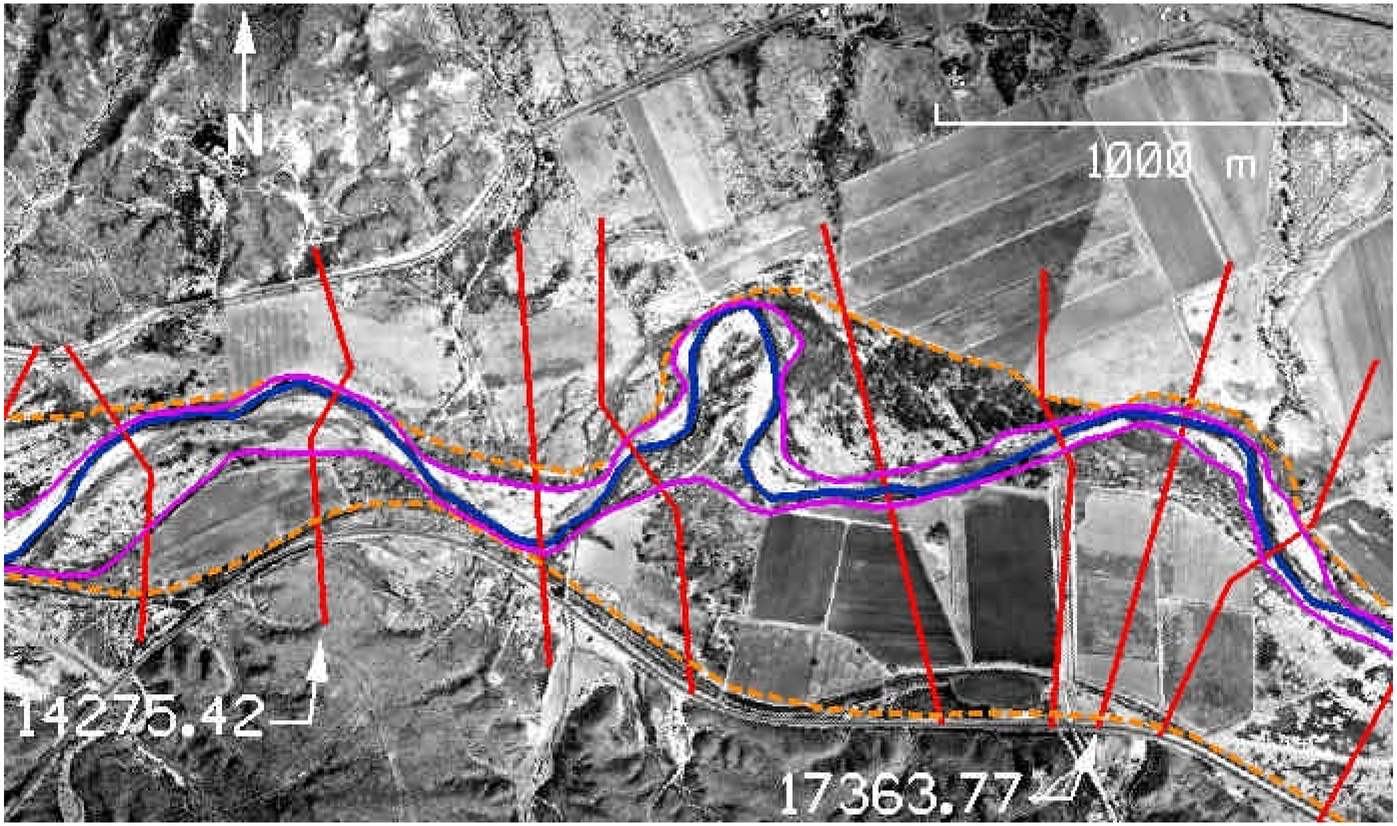


Figure 106. Upper Reach D.

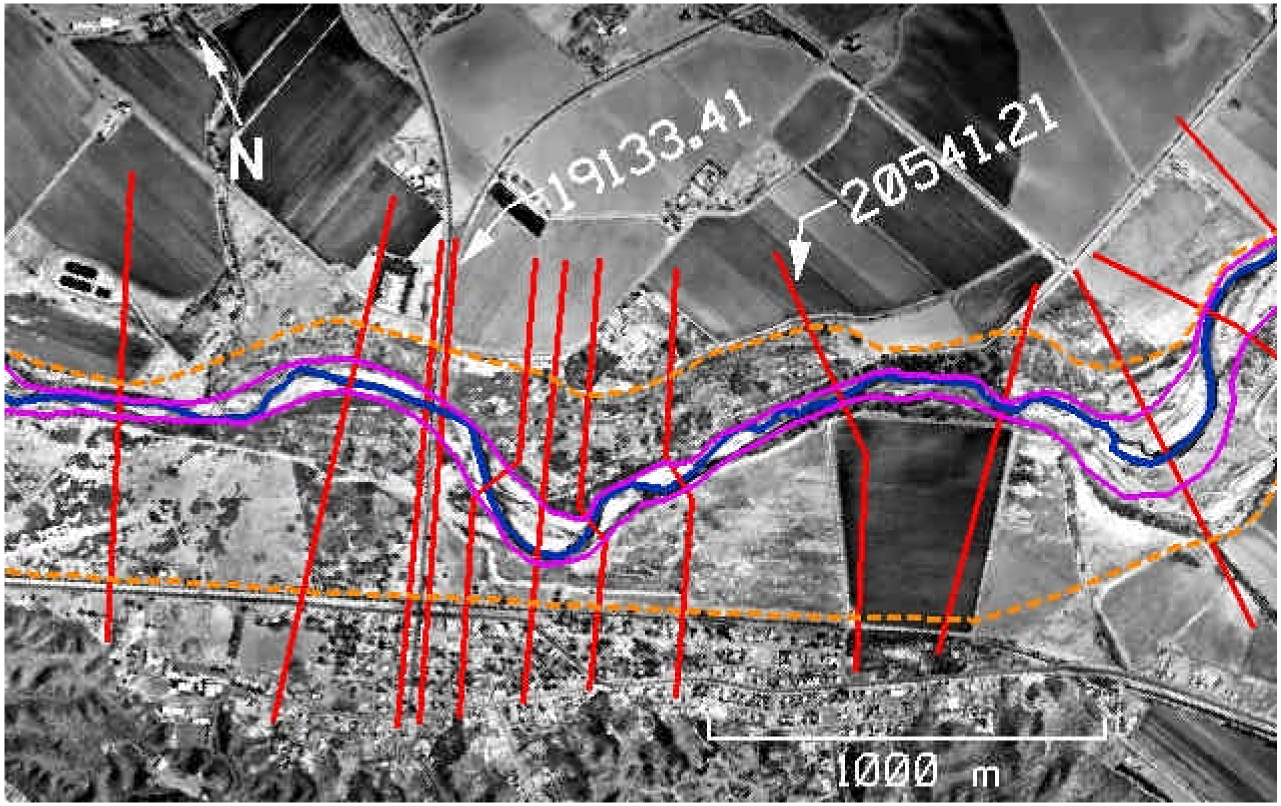


Figure 107. Upper Reach E.

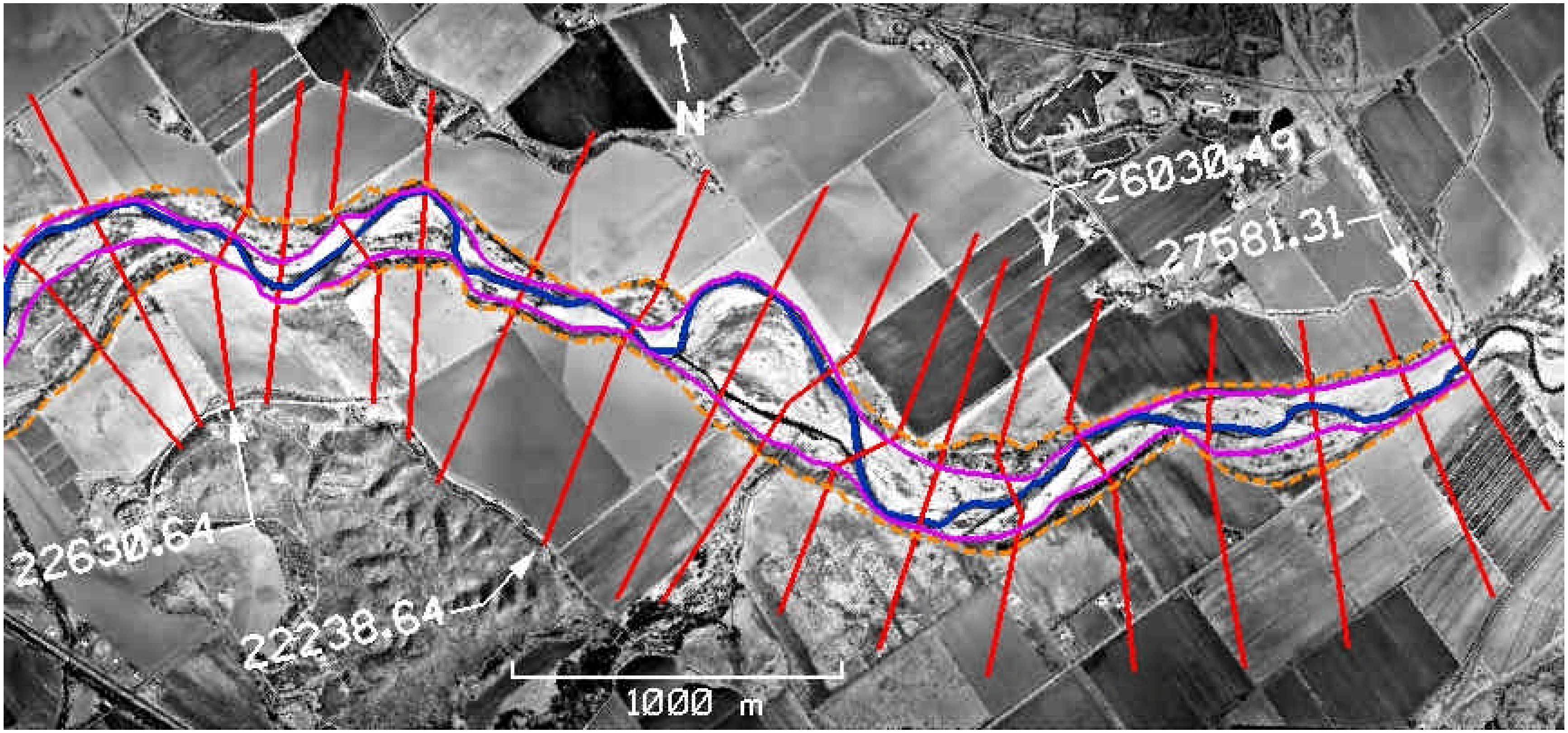


Figure 108. Upper Reach F.

APPENDIX B

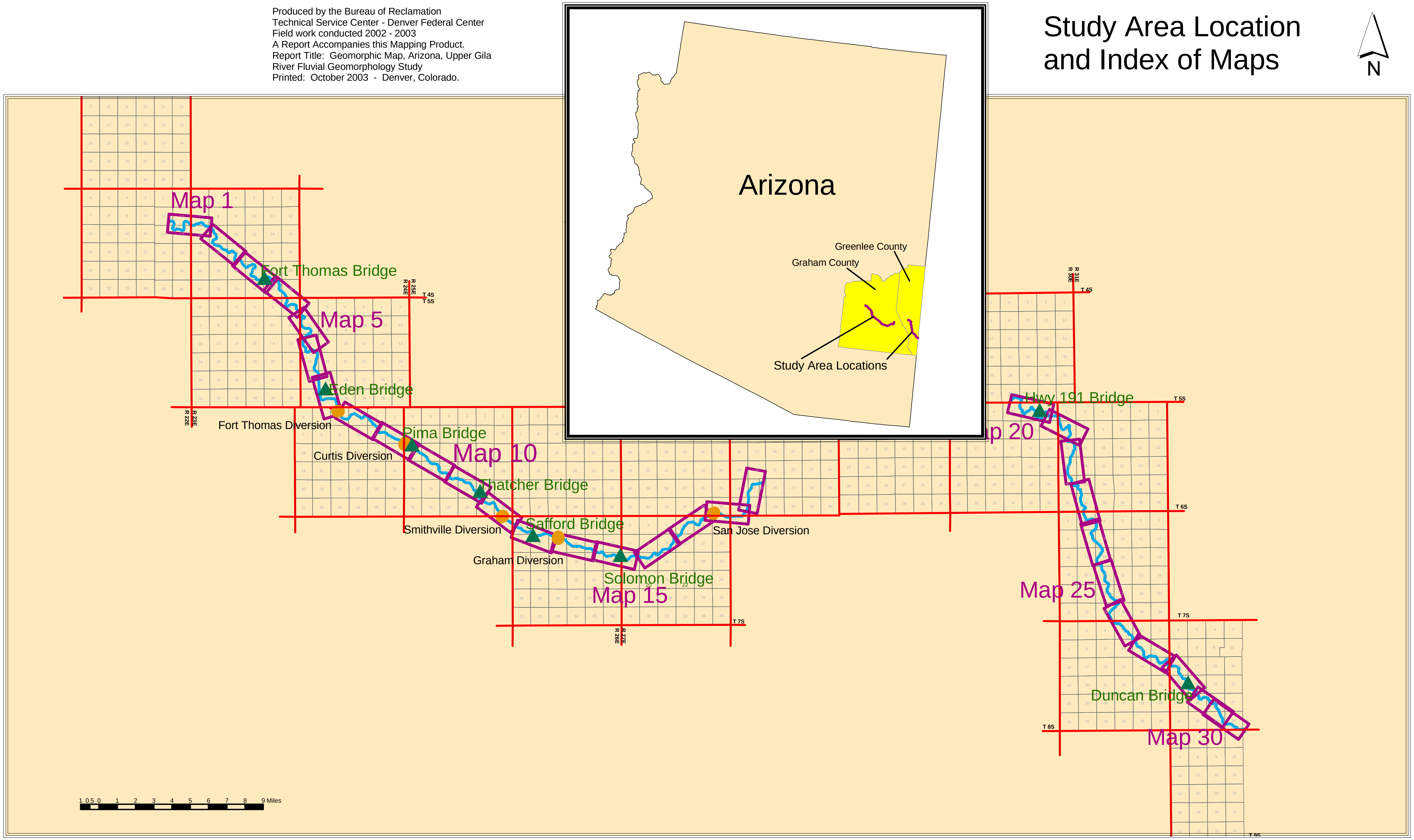
GEOMORPHIC MAP

Geomorphic Map of the Upper Gila River, Arizona

Produced by the Bureau of Reclamation
Technical Service Center - Denver Federal Center
Field work conducted 2002 - 2003
A Report Accompanies this Mapping Product.
Report Title: Geomorphic Map, Arizona, Upper Gila River Fluvial Geomorphology Study
Printed: October 2003 - Denver, Colorado.

Study Area Location and Index of Maps

N



BUREAU OF RECLAMATION
TECHNICAL SERVICE CENTER
6TH & KIPLING
DENVER, COLORADO 80225

UPPER GILA RIVER FLUVIAL GEOMORPHOLOGY STUDY

GEOMORPHIC MAP
ARIZONA

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, and sedimentation.
The team members are:

- Dr. Rodney J. Wittler, Team Leader, D-8560, (303) 445-2156
  Hydraulic Engineer (Hydraulics, Water Resources Management)
- Dr. Daniel R. Levish, Team Leader, D-8530, (303) 445-3175
  Geologist (Paleohydrology, Fluvial Geomorphology)
- Ms. Jeanne E. Klawon, Geomorphic Map Principal Investigator, D-8530, (303) 445-3164
  Geologist (Fluvial Geomorphology, Geology)
- Dr. Ralph E. Klinger, Geologist (Paleohydrology, Fluvial Geomorphology)
- Dr. Blair P. Greimann, Hydraulic Engineer (Hydraulics, Sediment Transport)
- Mr. Mitchell R. Delcau, Hydraulic Engineer (Hydraulic Modeling, Sediment Transport)

US Department of the Interior
Bureau of Reclamation

GRAHAM COUNTY, ARIZONA

COST SHARE AGREEMENT 00-GI 32-0054

Graham County, Arizona, 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 Graham County.

ARIZONA WATER PROTECTION FUND

GRANT NO. 98-054WPF

The Arizona Water Protection Fund Commission has funded all or a part of this report or project. The views or findings represented in this deliverable are the Grantees and do not necessarily represent those of the Commission or the Arizona Department of Water Resources.

REVISEDMARCH 4, 2004

Geomorphic Map of the Upper Gila River, AZ

Upper Gila River Fluvial Geomorphology Study

Map 1

Maps Produced by the Bureau of Reclamation Technical Service Center
Orthophoto images created with 40m DEM and 1:10,000 scale aerial photography
Photography dated February 2000 - Arizona State Plane East Zone NAD 83
Report Title: Geomorphic Map, Arizona

Legend:

- Property Loss
- Geomorphic Limit
- Geomorphic Limit +/- 200ft
- Pima Soil Boundary
- Pima Soil Boundary +/- 200ft
- Diversion Dam
- 1953 Levee
- 1967 Levee
- 1978 Levee
- 1981 Levee
- 1992 Levee

0 500 1,000 2,000 3,000 4,000 Feet

0 0.125 0.25 0.5 0.75 Miles

N

Geomorphic Map of the Upper Gila River, AZ

Upper Gila River Fluvial Geomorphology Study

Map 2

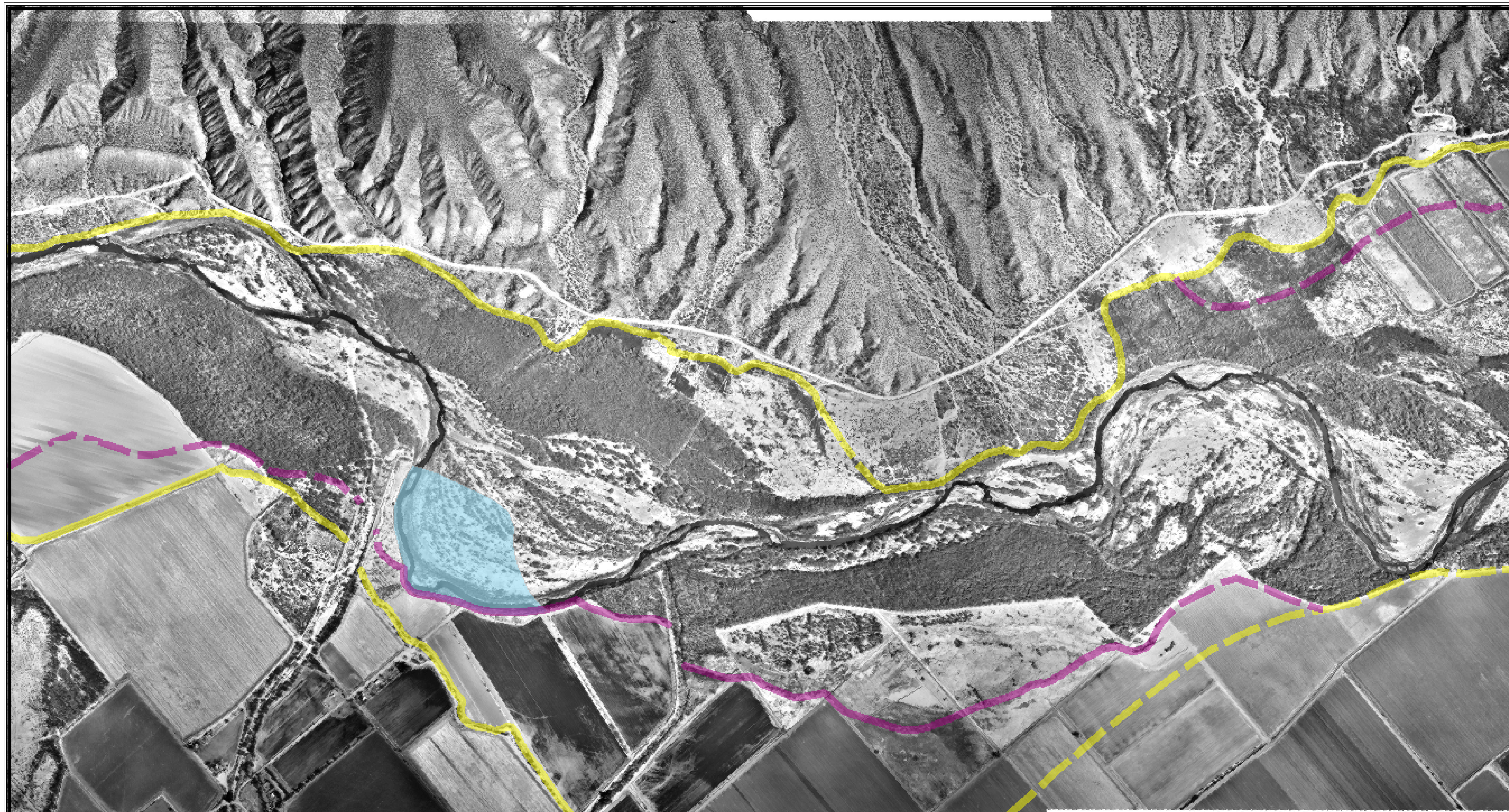
Legend:

- Property Loss
- Geomorphic Limit
- Geomorphic Limit +/- 200ft
- Pima Soil Boundary
- Pima Soil Boundary +/- 200ft
- Diversion Dam
- 1953 Levee
- 1967 Levee
- 1978 Levee
- 1981 Levee
- 1992 Levee

Maps Produced by the Bureau of Reclamation Technical Service Center
Orthophoto images created with 40m DEM and 1:10,000 scale aerial photography
Photography dated February 2000 - Arizona State Plane East Zone NAD 83
Report Title: Geomorphic Map, Arizona

Scale: 0 – 500 – 1,000 – 2,000 – 3,000 – 4,000 Feet; 0 – 0.125 – 0.25 – 0.5 – 0.75 Miles

N



Geomorphic Map of the Upper Gila River, AZ

Upper Gila River Fluvial Geomorphology Study

Map 3

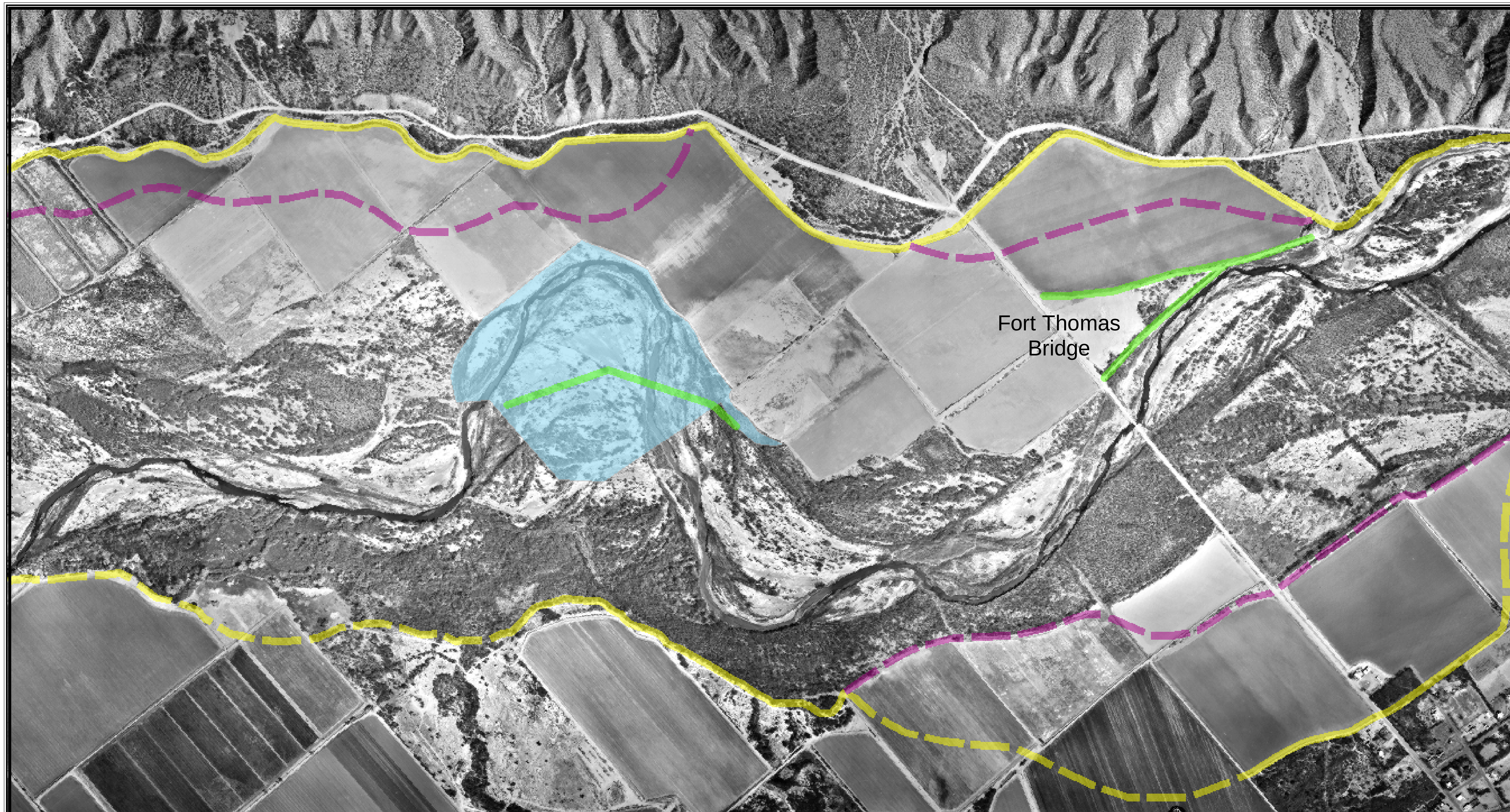
Legend:

- Property Loss
- Geomorphic Limit
- Geomorphic Limit +/- 200ft
- Pima Soil Boundary
- Pima Soil Boundary +/- 200ft
- Diversion Dam
- 1953 Levee
- 1967 Levee
- 1978 Levee
- 1981 Levee
- 1992 Levee

Maps Produced by the Bureau of Reclamation Technical Service Center
Orthophoto images created with 40m DEM and 1:10,000 scale aerial photography
Photography dated February 2000 - Arizona State Plane East Zone NAD 83
Report Title: Geomorphic Map, Arizona

Scale: 0, 500, 1,000, 2,000, 3,000, 4,000 Feet; 0, 0.125, 0.25, 0.5, 0.75 Miles

N



Geomorphic Map of the Upper Gila River, AZ

Upper Gila River Fluvial Geomorphology Study

Map 4

N

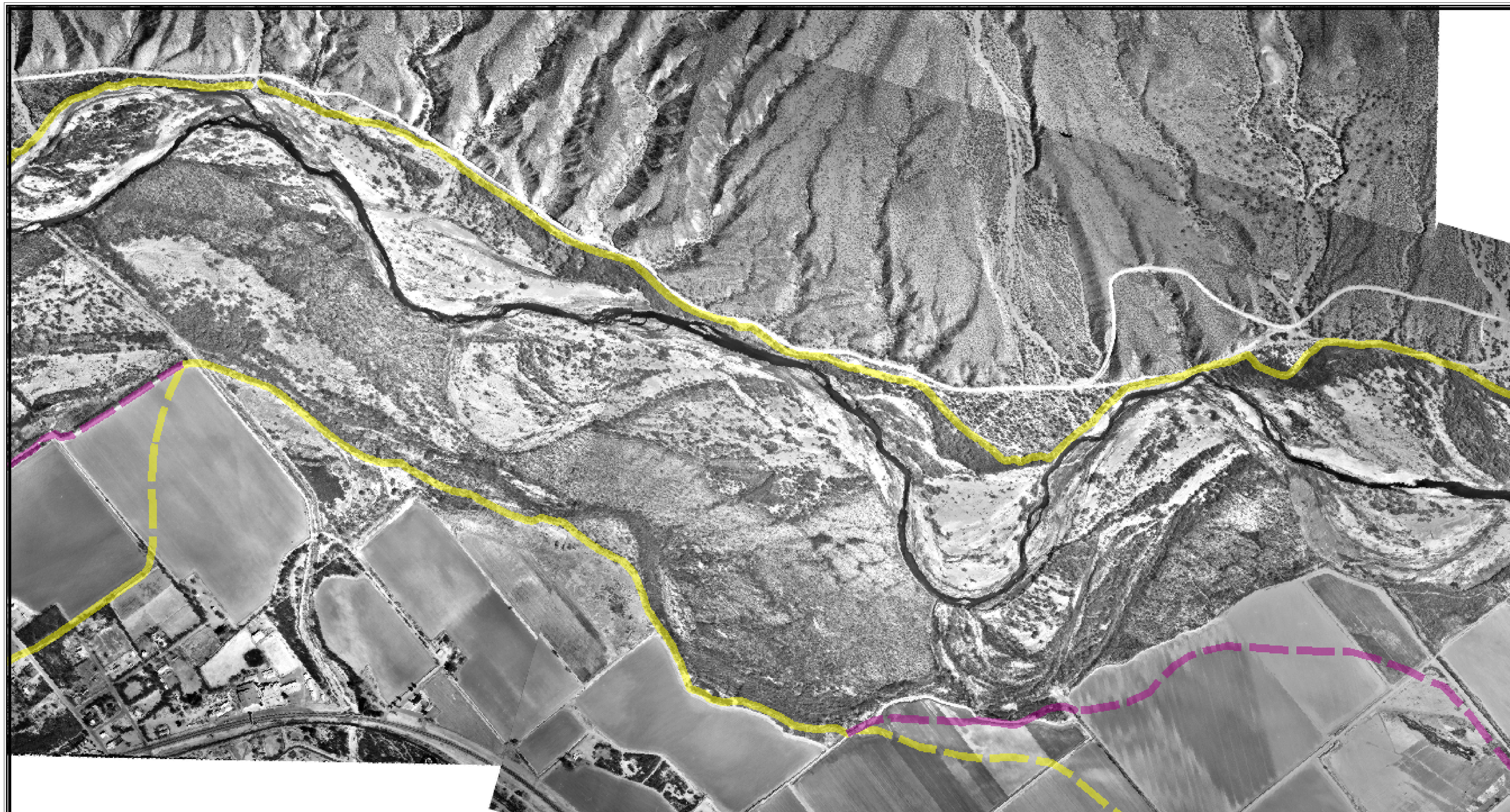
Legend:

- Property Loss
- Geomorphic Limit
- Geomorphic Limit +/- 200ft
- Pima Soil Boundary
- Pima Soil Boundary +/- 200ft
- Diversion Dam
- 1953 Levee
- 1967 Levee
- 1978 Levee
- 1981 Levee
- 1992 Levee

Maps Produced by the Bureau of Reclamation Technical Service Center
Orthophoto images created with 40m DEM and 1:10,000 scale aerial photography
Photography dated February 2000 - Arizona State Plane East Zone NAD 83
Report Title: Geomorphic Map, Arizona

0 500 1,000 2,000 3,000 4,000 Feet

0 0.125 0.25 0.5 0.75 Miles



Geomorphic Map of the Upper Gila River, AZ

Upper Gila River Fluvial Geomorphology Study

Map 5

Legend:

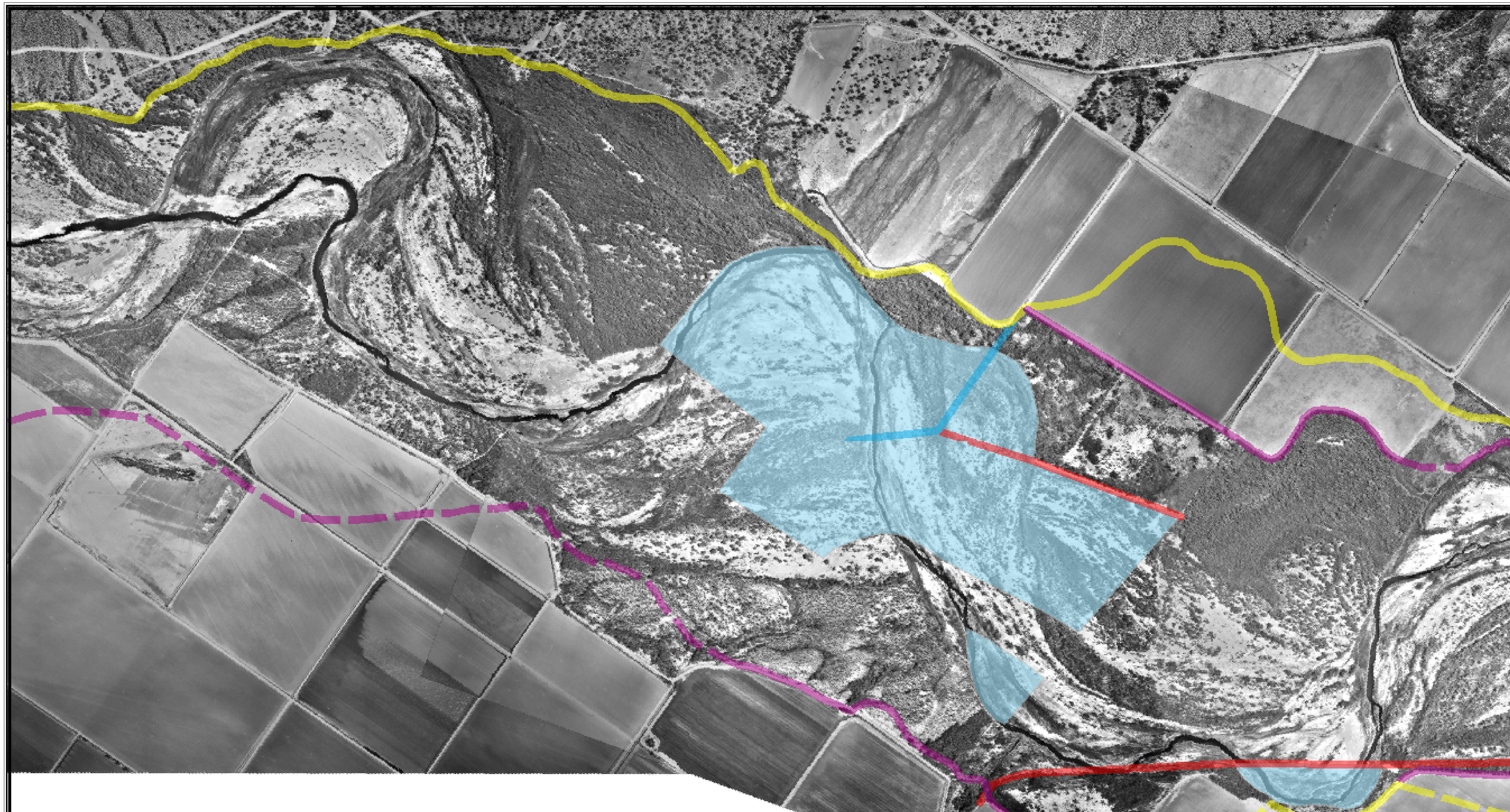
- Property Loss
- Geomorphic Limit
- Geomorphic Limit +/- 200ft
- Pima Soil Boundary
- Pima Soil Boundary +/- 200ft
- Diversion Dam
- 1953 Levee
- 1967 Levee
- 1978 Levee
- 1981 Levee
- 1992 Levee

Maps Produced by the Bureau of Reclamation Technical Service Center
Orthophoto images created with 40m DEM and 1:10,000 scale aerial photography
Photography dated February 2000 - Arizona State Plane East Zone NAD 83
Report Title: Geomorphic Map, Arizona

0 500 1,000 2,000 3,000 4,000 Feet

0 0.125 0.25 0.5 0.75 Miles

N



Geomorphic Map of the Upper Gila River, AZ

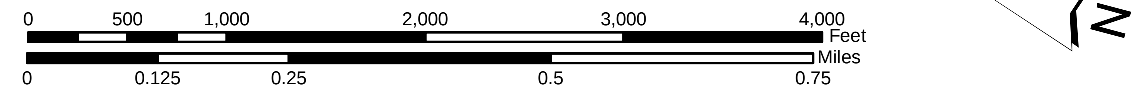
Upper Gila River Fluvial Geomorphology Study

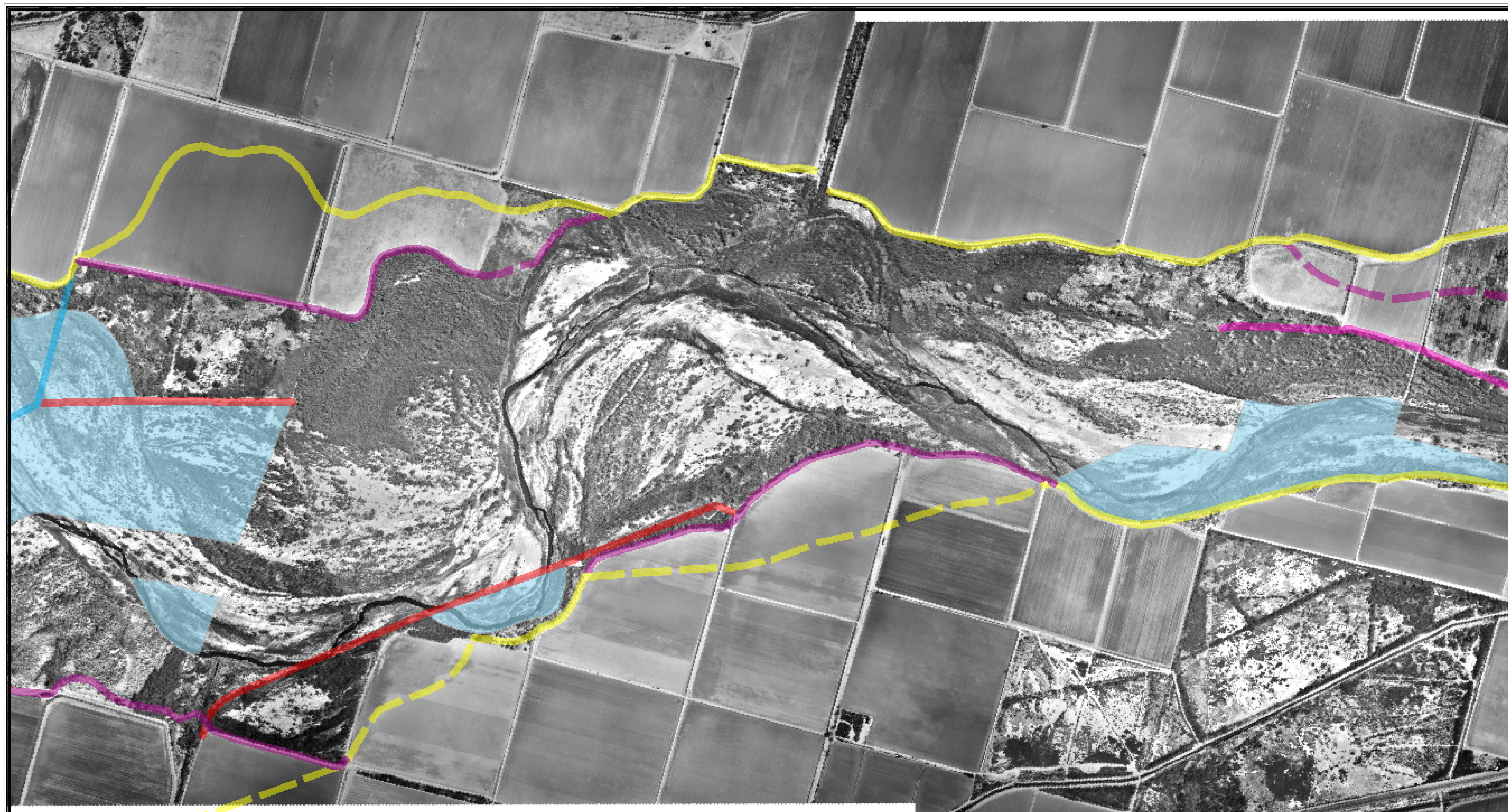
Map 6

Legend:

- Property Loss
- Geomorphic Limit
- Geomorphic Limit +/- 200ft
- Pima Soil Boundary
- Pima Soil Boundary +/- 200ft
- Diversion Dam
- 1953 Levee
- 1967 Levee
- 1978 Levee
- 1981 Levee
- 1992 Levee

Maps Produced by the Bureau of Reclamation Technical Service Center
Orthophoto images created with 40m DEM and 1:10,000 scale aerial photography
Photography dated February 2000 - Arizona State Plane East Zone NAD 83
Report Title: Geomorphic Map, Arizona





Geomorphic Map of the Upper Gila River, AZ

Upper Gila River Fluvial Geomorphology Study

Map 7

Legend:

- Property Loss
- Geomorphic Limit
- Geomorphic Limit +/- 200ft
- Pima Soil Boundary
- Pima Soil Boundary +/- 200ft
- Diversion Dam
- 1953 Levee
- 1967 Levee
- 1978 Levee
- 1981 Levee
- 1992 Levee

Maps Produced by the Bureau of Reclamation Technical Service Center
Orthophoto images created with 40m DEM and 1:10,000 scale aerial photography
Photography dated February 2000 - Arizona State Plane East Zone NAD 83
Report Title: Geomorphic Map, Arizona

Scale: 0 500 1,000 2,000 3,000 4,000 Feet
0 0.125 0.25 0.5 0.75 Miles

N

Geomorphic Map of the Upper Gila River, AZ

Upper Gila River Fluvial Geomorphology Study

Map 8

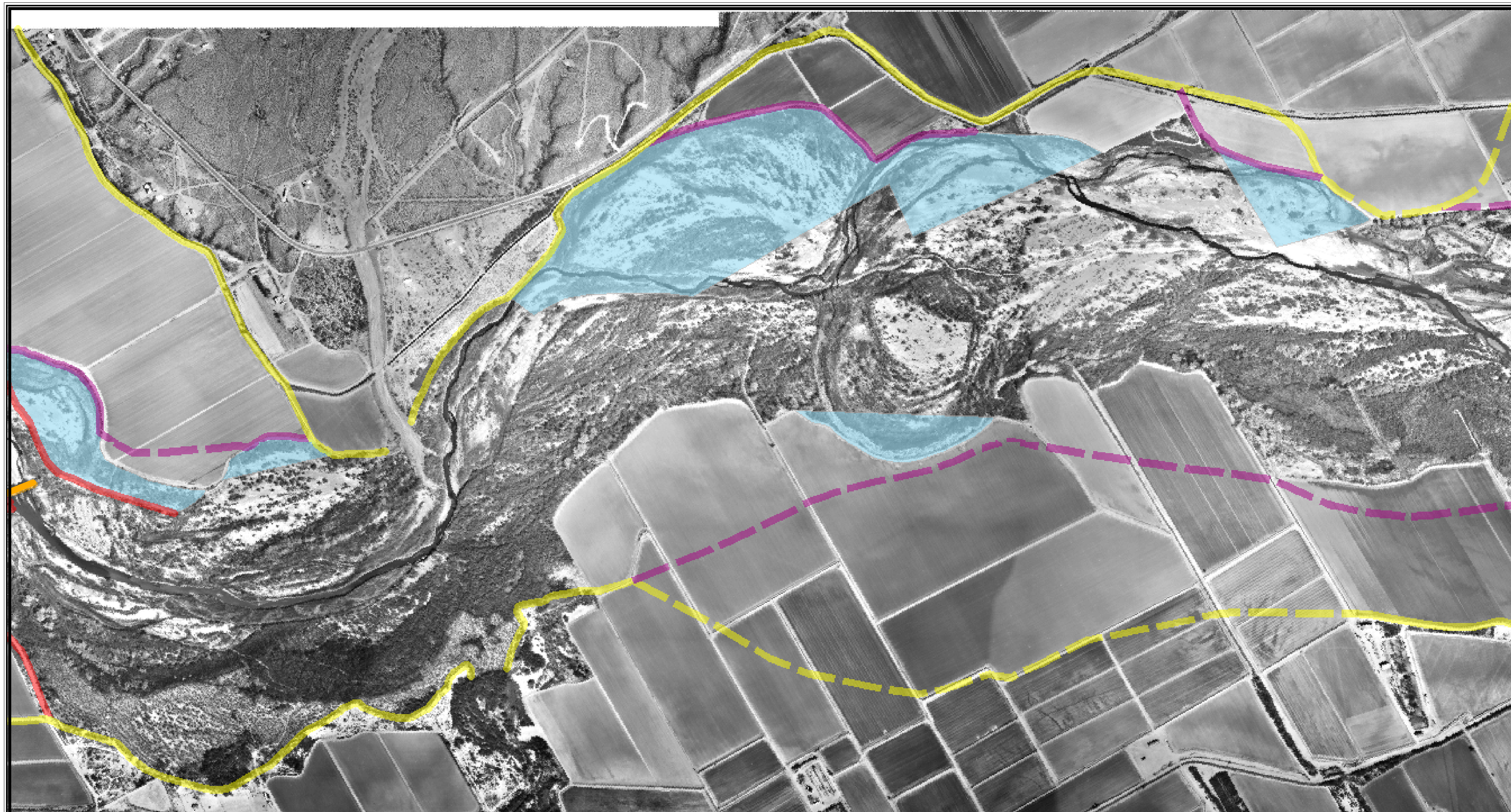
Legend:

- Property Loss
- Geomorphic Limit
- Geomorphic Limit +/- 200ft
- Pima Soil Boundary
- Pima Soil Boundary +/- 200ft
- Diversion Dam
- 1953 Levee
- 1967 Levee
- 1978 Levee
- 1981 Levee
- 1992 Levee

Maps Produced by the Bureau of Reclamation Technical Service Center
Orthophoto images created with 40m DEM and 1:10,000 scale aerial photography
Photography dated February 2000 - Arizona State Plane East Zone NAD 83
Report Title: Geomorphic Map, Arizona

Scale: 0, 500, 1,000, 2,000, 3,000, 4,000 Feet; 0, 0.125, 0.25, 0.5, 0.75 Miles

N



Geomorphic Map of the Upper Gila River, AZ

Upper Gila River Fluvial Geomorphology Study

Map 9

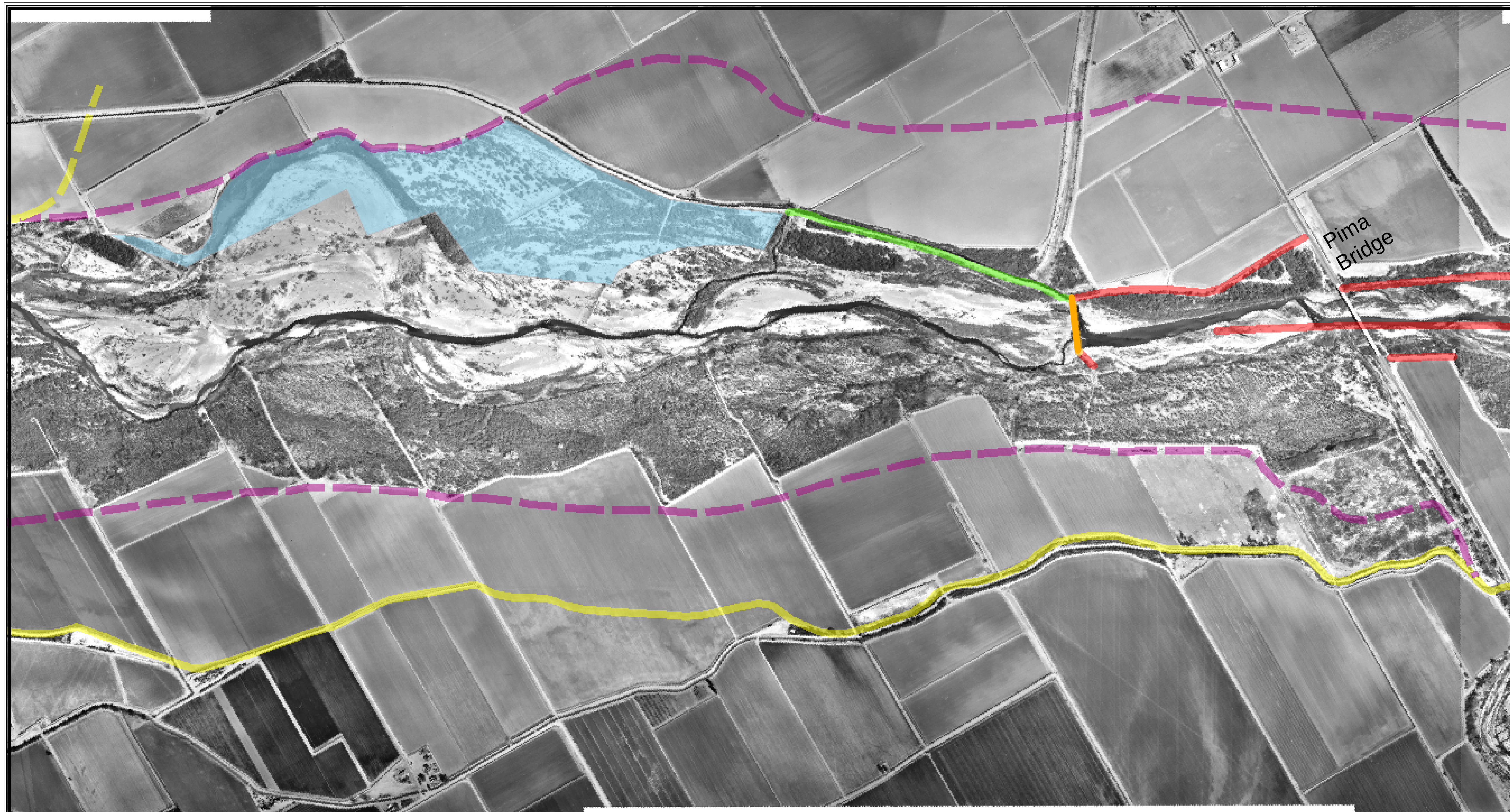
Legend:

- Property Loss
- Geomorphic Limit
- Geomorphic Limit +/- 200ft
- Pima Soil Boundary
- Pima Soil Boundary +/- 200ft
- Diversion Dam
- 1953 Levee
- 1967 Levee
- 1978 Levee
- 1981 Levee
- 1992 Levee

Maps Produced by the Bureau of Reclamation Technical Service Center
Orthophoto images created with 40m DEM and 1:10,000 scale aerial photography
Photography dated February 2000 - Arizona State Plane East Zone NAD 83
Report Title: Geomorphic Map, Arizona

0 500 1,000 2,000 3,000 4,000 Feet
0 0.125 0.25 0.5 0.75 Miles

N



Geomorphic Map of the Upper Gila River, AZ

Upper Gila River Fluvial Geomorphology Study

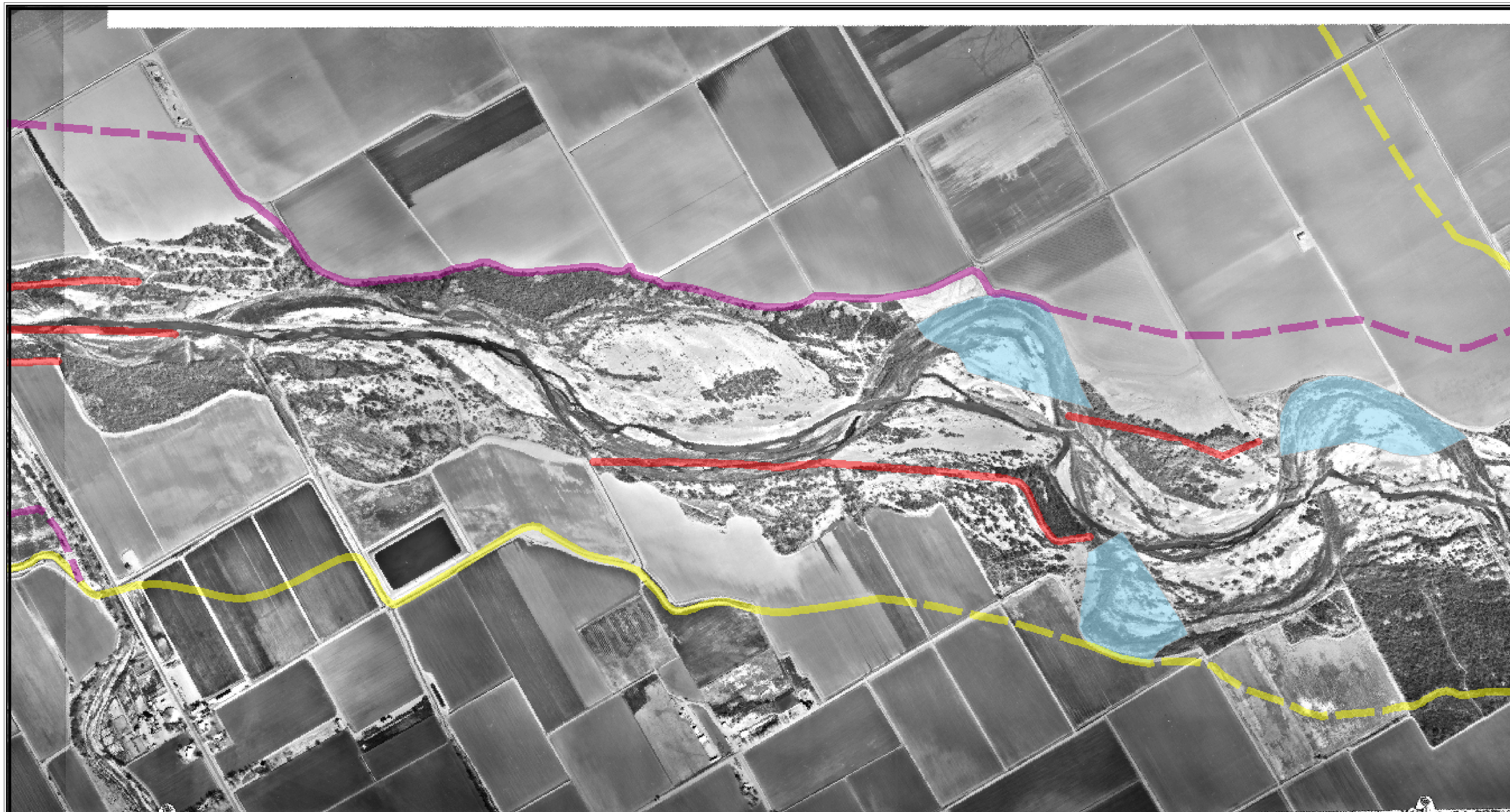
Map 10

Legend:
- Property Loss
- Geomorphic Limit
- Geomorphic Limit +/- 200ft
- Pima Soil Boundary
- Pima Soil Boundary +/- 200ft
- Diversion Dam
- 1953 Levee
- 1967 Levee
- 1978 Levee
- 1981 Levee
- 1992 Levee

Maps Produced by the Bureau of Reclamation Technical Service Center
Orthophoto images created with 40m DEM and 1:10,000 scale aerial photography
Photography dated February 2000 - Arizona State Plane East Zone NAD 83
Report Title: Geomorphic Map, Arizona

Scale: 0, 500, 1,000, 2,000, 3,000, 4,000 Feet; 0, 0.125, 0.25, 0.5, 0.75 Miles

N



Geomorphic Map of the Upper Gila River, AZ

Upper Gila River Fluvial Geomorphology Study

Map 11

Legend:

- Property Loss
- Geomorphic Limit
- Geomorphic Limit +/- 200ft
- Pima Soil Boundary
- Pima Soil Boundary +/- 200ft
- Diversion Dam
- 1953 Levee
- 1967 Levee
- 1978 Levee
- 1981 Levee
- 1992 Levee

Maps Produced by the Bureau of Reclamation Technical Service Center
Orthophoto images created with 40m DEM and 1:10,000 scale aerial photography
Photography dated February 2000 - Arizona State Plane East Zone NAD 83
Report Title: Geomorphic Map, Arizona

0 500 1,000 2,000 3,000 4,000 Feet
0 0.125 0.25 0.5 0.75 Miles

N

Geomorphic Map of the Upper Gila River, AZ

Upper Gila River Fluvial Geomorphology Study

Map 12

Legend:

- Property Loss
- Geomorphic Limit
- Geomorphic Limit +/- 200ft
- Pima Soil Boundary
- Pima Soil Boundary +/- 200ft
- Diversion Dam
- 1953 Levee
- 1967 Levee
- 1978 Levee
- 1981 Levee
- 1992 Levee

Maps Produced by the Bureau of Reclamation Technical Service Center
Orthophoto images created with 40m DEM and 1:10,000 scale aerial photography
Photography dated February 2000 - Arizona State Plane East Zone NAD 83
Report Title: Geomorphic Map, Arizona

0 500 1,000 2,000 3,000 4,000 Feet
0 0.125 0.25 0.5 0.75 Miles

N

Geomorphic Map of the Upper Gila River, AZ

Upper Gila River Fluvial Geomorphology Study

Map 13

Legend:

- Property Loss
- Geomorphic Limit
- Geomorphic Limit +/- 200ft
- Pima Soil Boundary
- Pima Soil Boundary +/- 200ft
- Diversion Dam
- 1953 Levee
- 1967 Levee
- 1978 Levee
- 1981 Levee
- 1992 Levee

Maps Produced by the Bureau of Reclamation Technical Service Center
Orthophoto images created with 40m DEM and 1:10,000 scale aerial photography
Photography dated February 2000 - Arizona State Plane East Zone NAD 83
Report Title: Geomorphic Map, Arizona

0 500 1,000 2,000 3,000 4,000 Feet
0 0.125 0.25 0.5 0.75 Miles

N

Geomorphic Map of the Upper Gila River, AZ

Upper Gila River Fluvial Geomorphology Study

Map 14

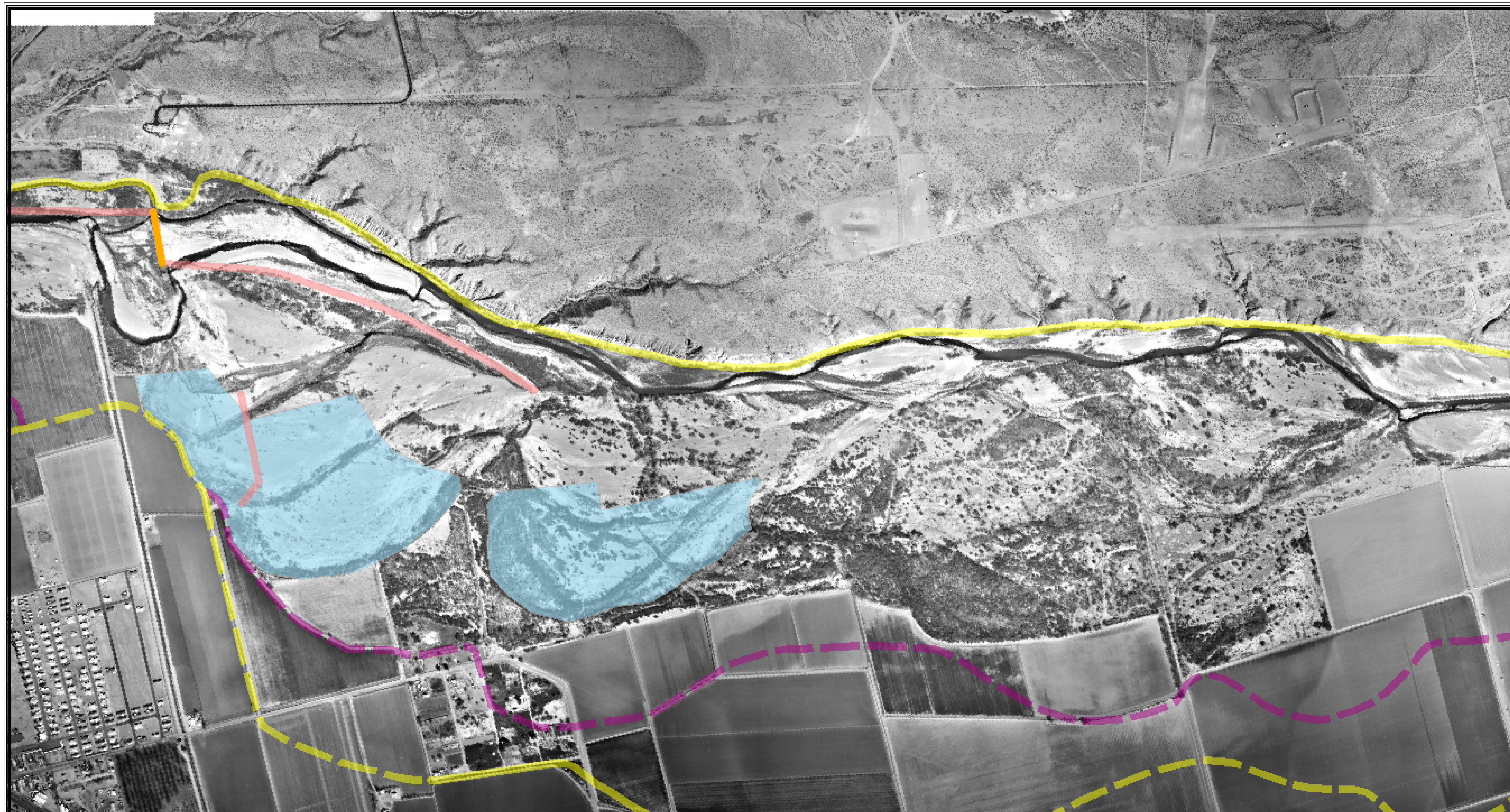
Legend:

- Property Loss
- Geomorphic Limit
- Geomorphic Limit +/- 200ft
- Pima Soil Boundary
- Pima Soil Boundary +/- 200ft
- Diversion Dam
- 1953 Levee
- 1967 Levee
- 1978 Levee
- 1981 Levee
- 1992 Levee

Maps Produced by the Bureau of Reclamation Technical Service Center
Orthophoto images created with 40m DEM and 1:10,000 scale aerial photography
Photography dated February 2000 - Arizona State Plane East Zone NAD 83
Report Title: Geomorphic Map, Arizona

Scale: 0, 500, 1,000, 2,000, 3,000, 4,000 Feet; 0, 0.125, 0.25, 0.5, 0.75 Miles

N



Legend:
- Property Loss
- Geomorphic Limit
- Geomorphic Limit +/- 200ft
- Pima Soil Boundary
- Pima Soil Boundary +/- 200ft
- Diversion Dam
- 1953 Levee
- 1967 Levee
- 1978 Levee
- 1981 Levee
- 1992 Levee

Geomorphic Map of the Upper Gila River, AZ

Upper Gila River Fluvial Geomorphology Study

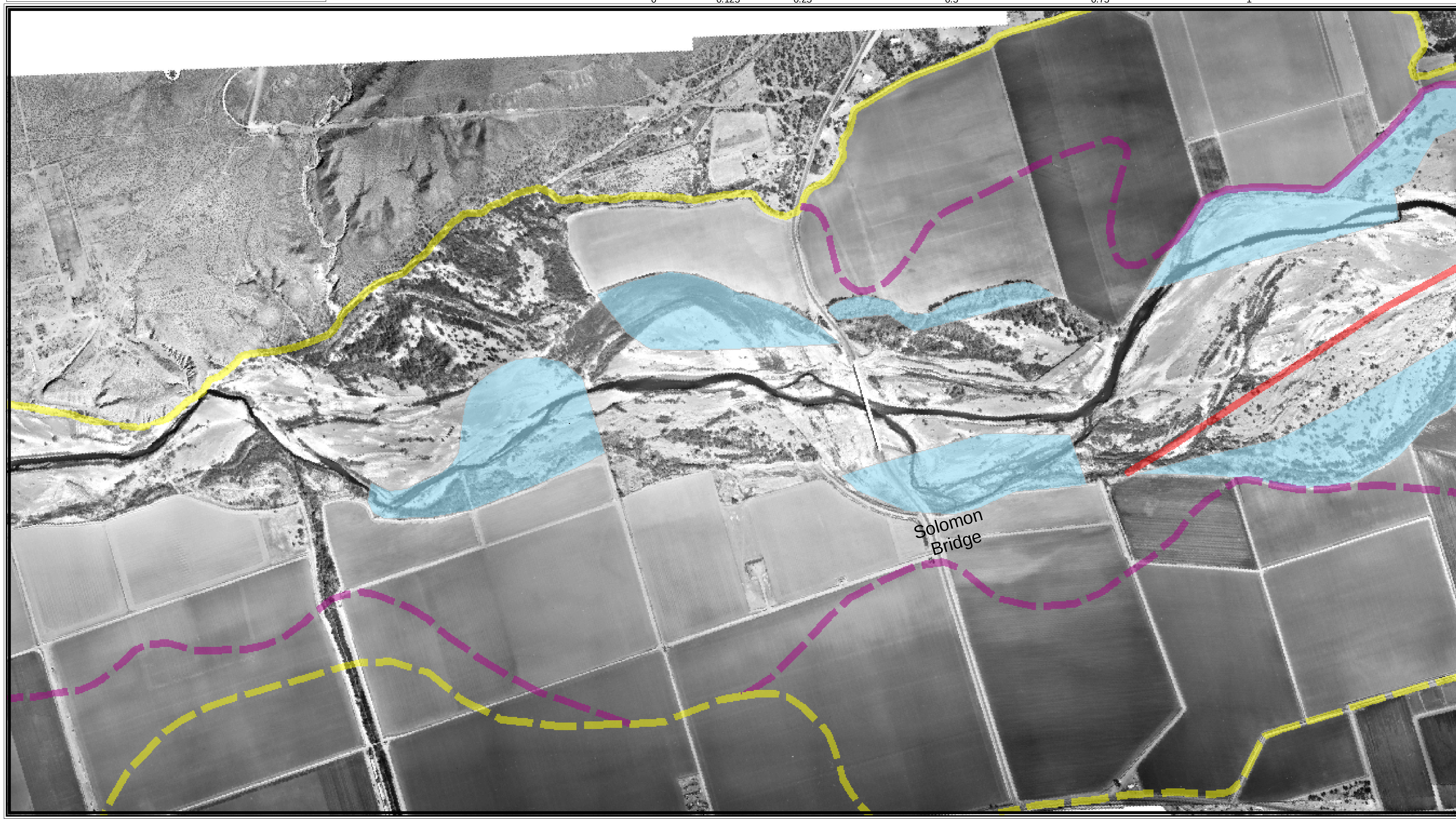
Maps Produced by the Bureau of Reclamation Technical Service Center
Orthophoto images created with 40m DEM and 1:10,000 scale aerial photography
Photography dated February 2000 - Arizona State Plane East Zone NAD 83
Report Title: Geomorphic Map, Arizona

0 500 1,000 2,000 3,000 4,000 5,000 Feet

0 0.125 0.25 0.5 0.75 1 Miles

N

Map 15



Geomorphic Map of the Upper Gila River, AZ

Upper Gila River Fluvial Geomorphology Study

Map 16

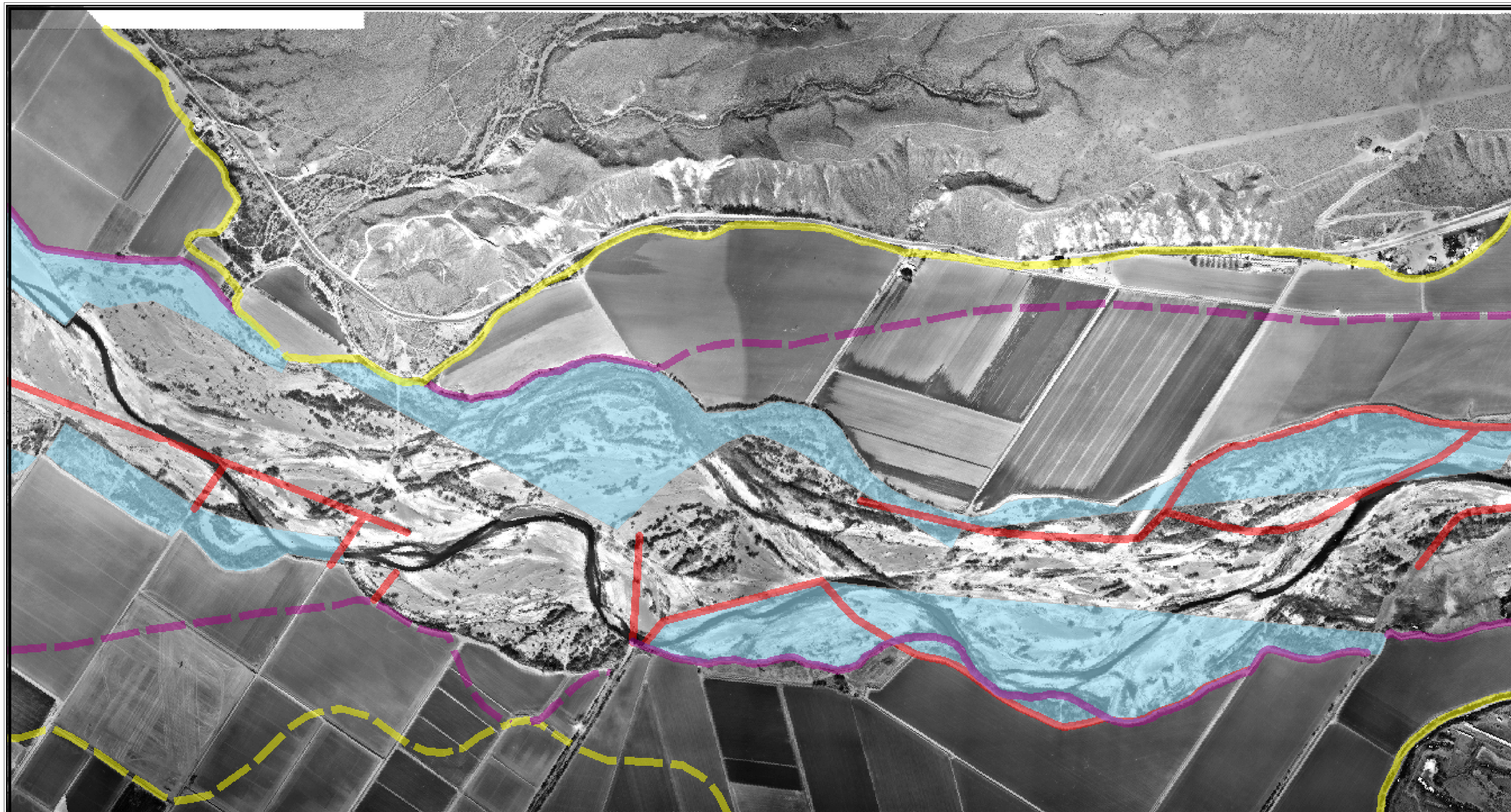
Legend:

- Property Loss
- Geomorphic Limit
- Geomorphic Limit +/- 200ft
- Pima Soil Boundary
- Pima Soil Boundary +/- 200ft
- Diversion Dam
- 1953 Levee
- 1967 Levee
- 1978 Levee
- 1981 Levee
- 1992 Levee

Maps Produced by the Bureau of Reclamation Technical Service Center
Orthophoto images created with 40m DEM and 1:10,000 scale aerial photography
Photography dated February 2000 - Arizona State Plane East Zone NAD 83
Report Title: Geomorphic Map, Arizona

Scale: 0, 500, 1,000, 2,000, 3,000, 4,000 Feet
0, 0.125, 0.25, 0.5, 0.75 Miles

N



Geomorphic Map of the Upper Gila River, AZ

Upper Gila River Fluvial Geomorphology Study

Map 17

Legend:

- Property Loss
- Geomorphic Limit
- Geomorphic Limit +/- 200ft
- Pima Soil Boundary
- Pima Soil Boundary +/- 200ft
- Diversion Dam
- 1953 Levee
- 1967 Levee
- 1978 Levee
- 1981 Levee
- 1992 Levee

Maps Produced by the Bureau of Reclamation Technical Service Center
Orthophoto images created with 40m DEM and 1:10,000 scale aerial photography
Photography dated February 2000 - Arizona State Plane East Zone NAD 83
Report Title: Geomorphic Map, Arizona

Scale: 0, 500, 1,000, 2,000, 3,000, 4,000 Feet; 0, 0.125, 0.25, 0.5, 0.75 Miles

N

Geomorphic Map of the Upper Gila River, AZ

Upper Gila River Fluvial Geomorphology Study

Map 18

Legend:

- Property Loss
- Geomorphic Limit
- Geomorphic Limit +/- 200ft
- Pima Soil Boundary
- Pima Soil Boundary +/- 200ft
- Diversion Dam
- 1953 Levee
- 1967 Levee
- 1978 Levee
- 1981 Levee
- 1992 Levee

Maps Produced by the Bureau of Reclamation Technical Service Center
Orthophoto images created with 40m DEM and 1:10,000 scale aerial photography
Photography dated February 2000 - Arizona State Plane East Zone NAD 83
Report Title: Geomorphic Map, Arizona

Scale: 0, 500, 1,000, 2,000, 3,000, 4,000 Feet; 0, 0.125, 0.25, 0.5, 0.75 Miles

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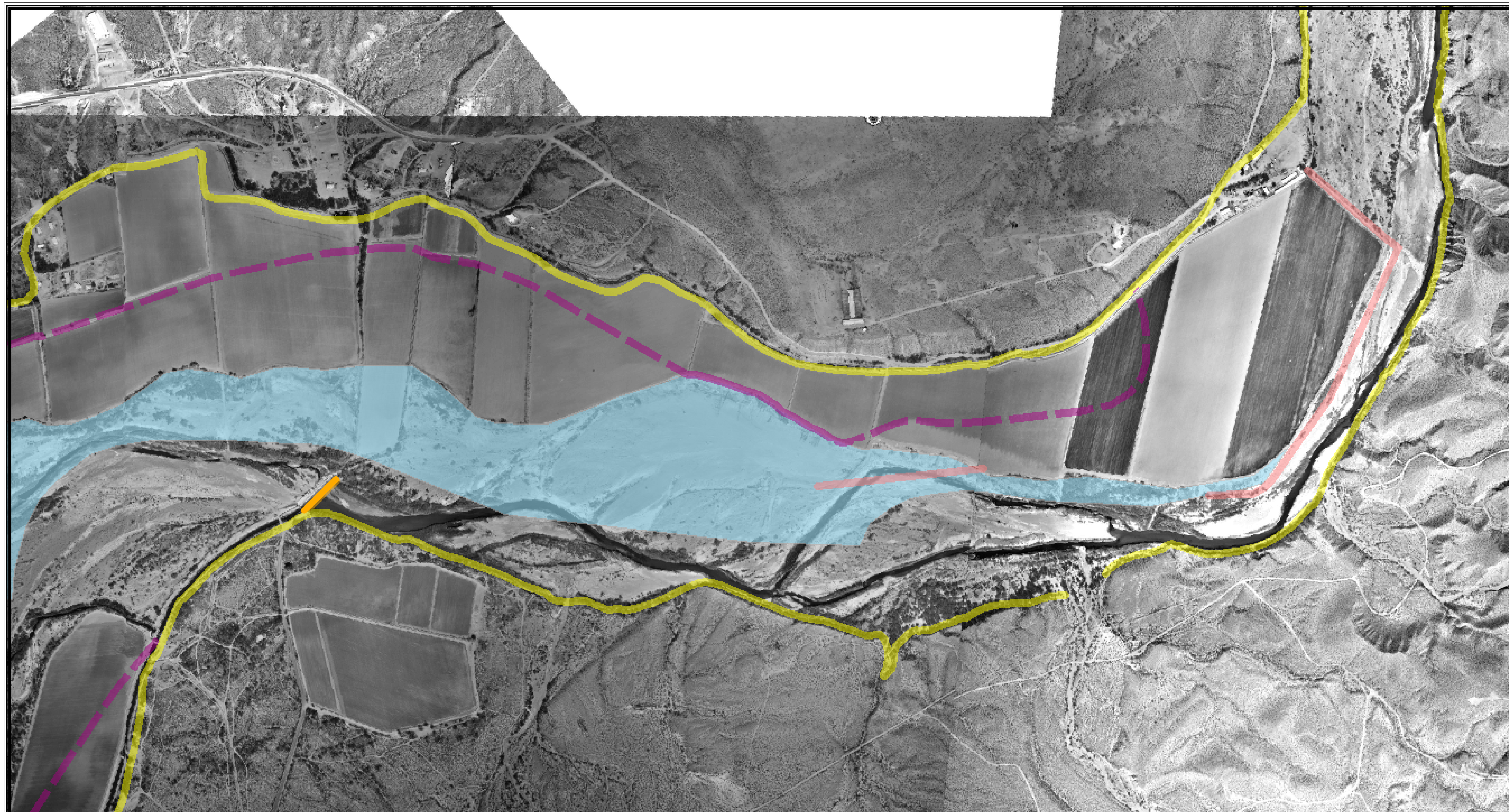


Geomorphic Map of the Upper Gila River, AZ

Upper Gila River Fluvial Geomorphology Study

Map 19

Legend:

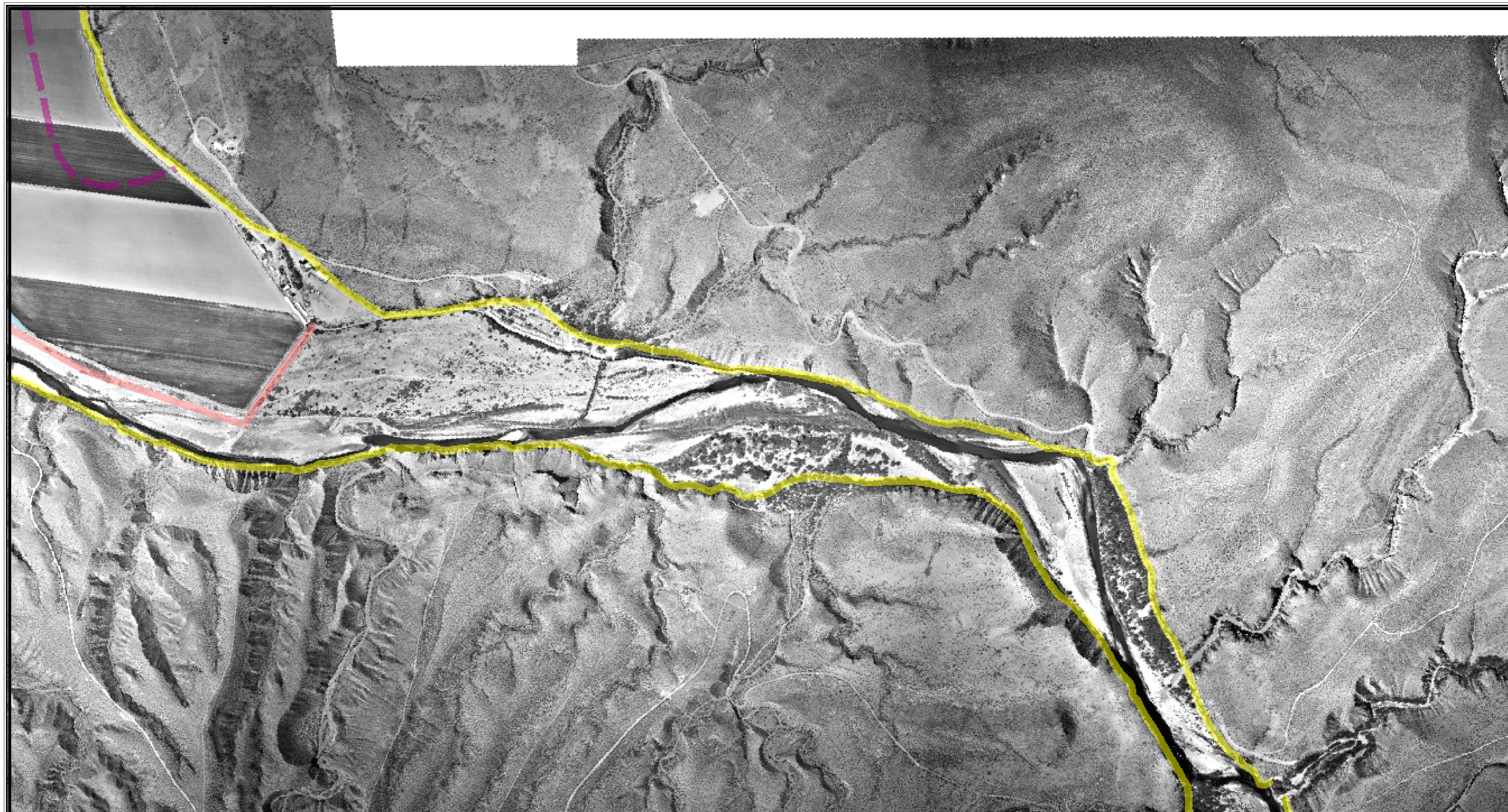
- Property Loss
- Geomorphic Limit
- Geomorphic Limit +/- 200ft
- Pima Soil Boundary
- Pima Soil Boundary +/- 200ft
- Diversion Dam
- 1953 Levee
- 1967 Levee
- 1978 Levee
- 1981 Levee
- 1992 Levee

Maps Produced by the Bureau of Reclamation Technical Service Center
Orthophoto images created with 40m DEM and 1:10,000 scale aerial photography
Photography dated February 2000 - Arizona State Plane East Zone NAD 83
Report Title: Geomorphic Map, Arizona

0 500 1,000 2,000 3,000 4,000 Feet

0 0.125 0.25 0.5 0.75 Miles

N



Geomorphic Map of the Upper Gila River, AZ

Upper Gila River Fluvial Geomorphology Study

Map 20

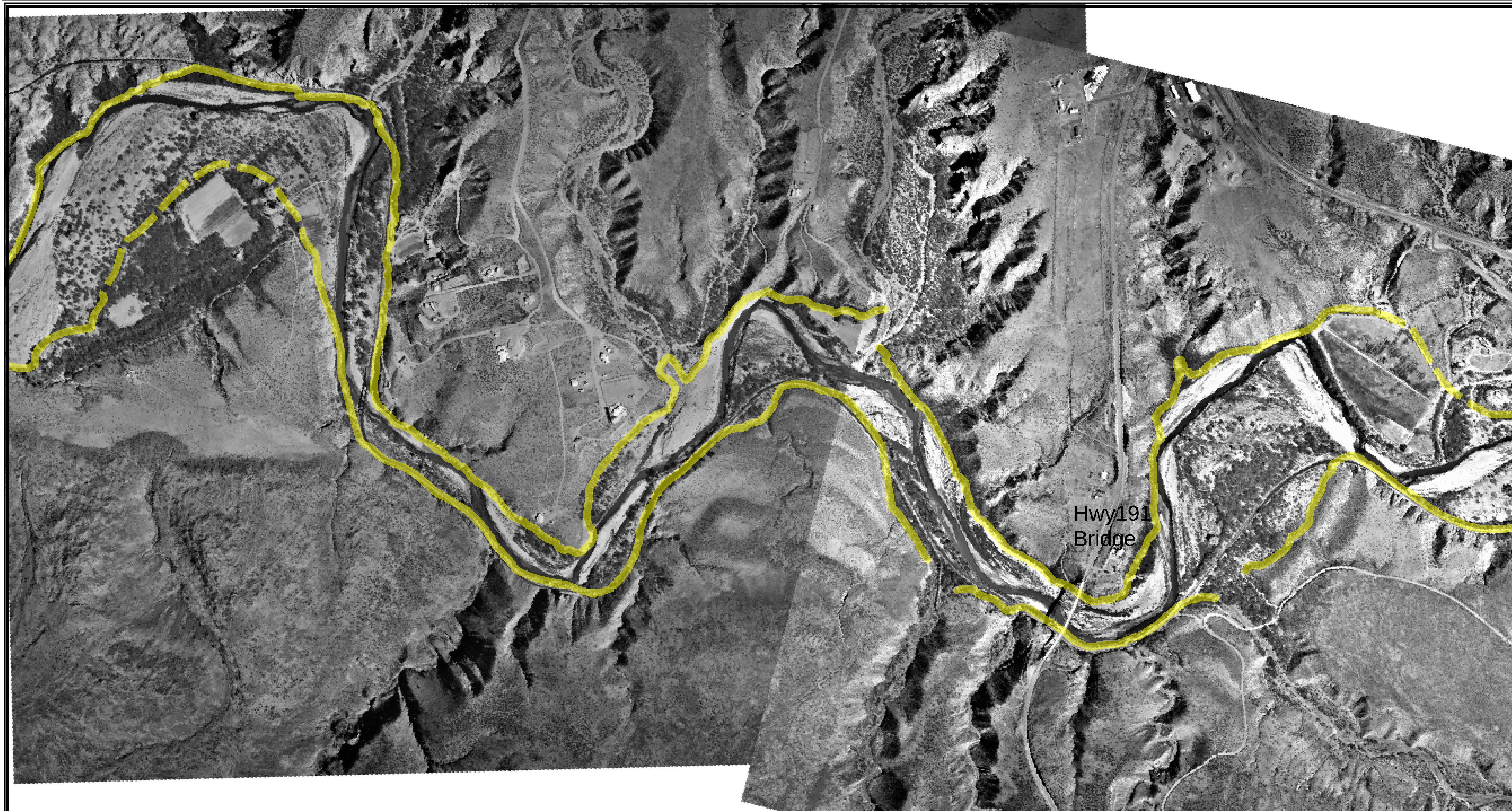
Legend:

- Property Loss
- Geomorphic Limit
- Geomorphic Limit +/- 200ft
- Pima Soil Boundary
- Pima Soil Boundary +/- 200ft
- Diversion Dam
- 1953 Levee
- 1967 Levee
- 1978 Levee
- 1981 Levee
- 1992 Levee

Maps Produced by the Bureau of Reclamation Technical Service Center
Orthophoto images created with 40m DEM and 1:10,000 scale aerial photography
Photography dated February 2000 - Arizona State Plane East Zone NAD 83
Report Title: Geomorphic Map, Arizona

Scale: 0, 500, 1,000, 2,000, 3,000, 4,000 Feet; 0, 0.125, 0.25, 0.5, 0.75 Miles

N



Geomorphic Map of the Upper Gila River, AZ

Upper Gila River Fluvial Geomorphology Study

Map 21

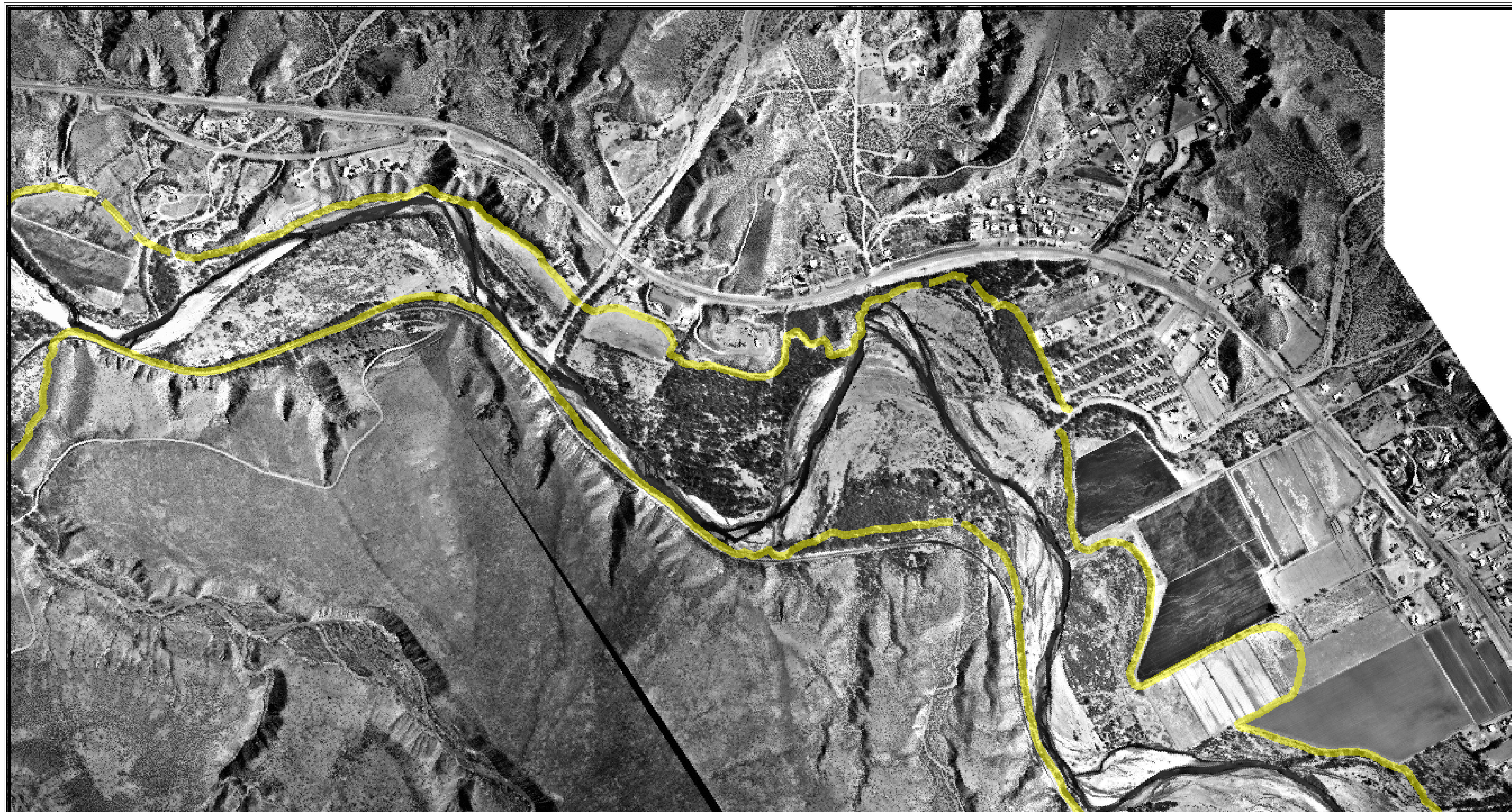
Legend:

- Property Loss
- Geomorphic Limit
- Geomorphic Limit +/- 200ft
- Pima Soil Boundary
- Pima Soil Boundary +/- 200ft
- Diversion Dam
- 1953 Levee
- 1967 Levee
- 1978 Levee
- 1981 Levee
- 1992 Levee

Maps Produced by the Bureau of Reclamation Technical Service Center
Orthophoto images created with 40m DEM and 1:10,000 scale aerial photography
Photography dated February 2000 - Arizona State Plane East Zone NAD 83
Report Title: Geomorphic Map, Arizona

Scale: 0, 500, 1,000, 2,000, 3,000, 4,000 Feet
0, 0.125, 0.25, 0.5, 0.75 Miles

N



Geomorphic Map of the Upper Gila River, AZ

Upper Gila River Fluvial Geomorphology Study

Map 22

Legend:

- Property Loss
- Geomorphic Limit
- Geomorphic Limit +/- 200ft
- Pima Soil Boundary
- Pima Soil Boundary +/- 200ft
- Diversion Dam
- 1953 Levee
- 1967 Levee
- 1978 Levee
- 1981 Levee
- 1992 Levee

Maps Produced by the Bureau of Reclamation Technical Service Center
Orthophoto images created with 40m DEM and 1:10,000 scale aerial photography
Photography dated February 2000 - Arizona State Plane East Zone NAD 83
Report Title: Geomorphic Map, Arizona

Scale: 0, 500, 1,000, 2,000, 3,000, 4,000 Feet
0, 0.125, 0.25, 0.5, 0.75 Miles

N

Geomorphic Map of the Upper Gila River, AZ

Upper Gila River Fluvial Geomorphology Study

Map 23

Legend:

- Property Loss
- Geomorphic Limit
- Geomorphic Limit +/- 200ft
- Pima Soil Boundary
- Pima Soil Boundary +/- 200ft
- Diversion Dam
- 1953 Levee
- 1967 Levee
- 1978 Levee
- 1981 Levee
- 1992 Levee

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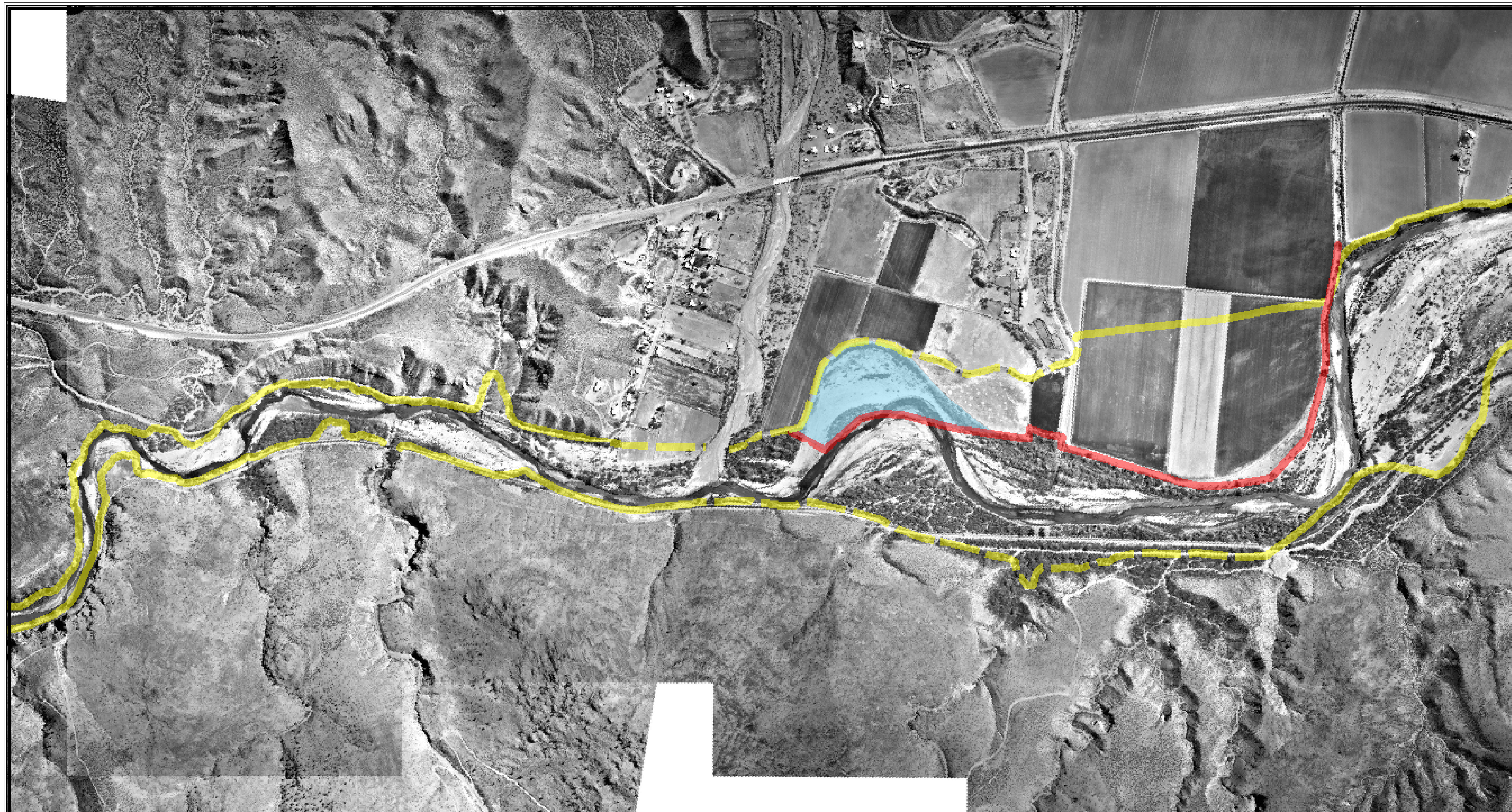
Report Title: Geomorphic Map, Arizona

0 500 1,000 2,000 3,000 4,000 Feet

0 0.125 0.25 0.5 0.75 Miles

N

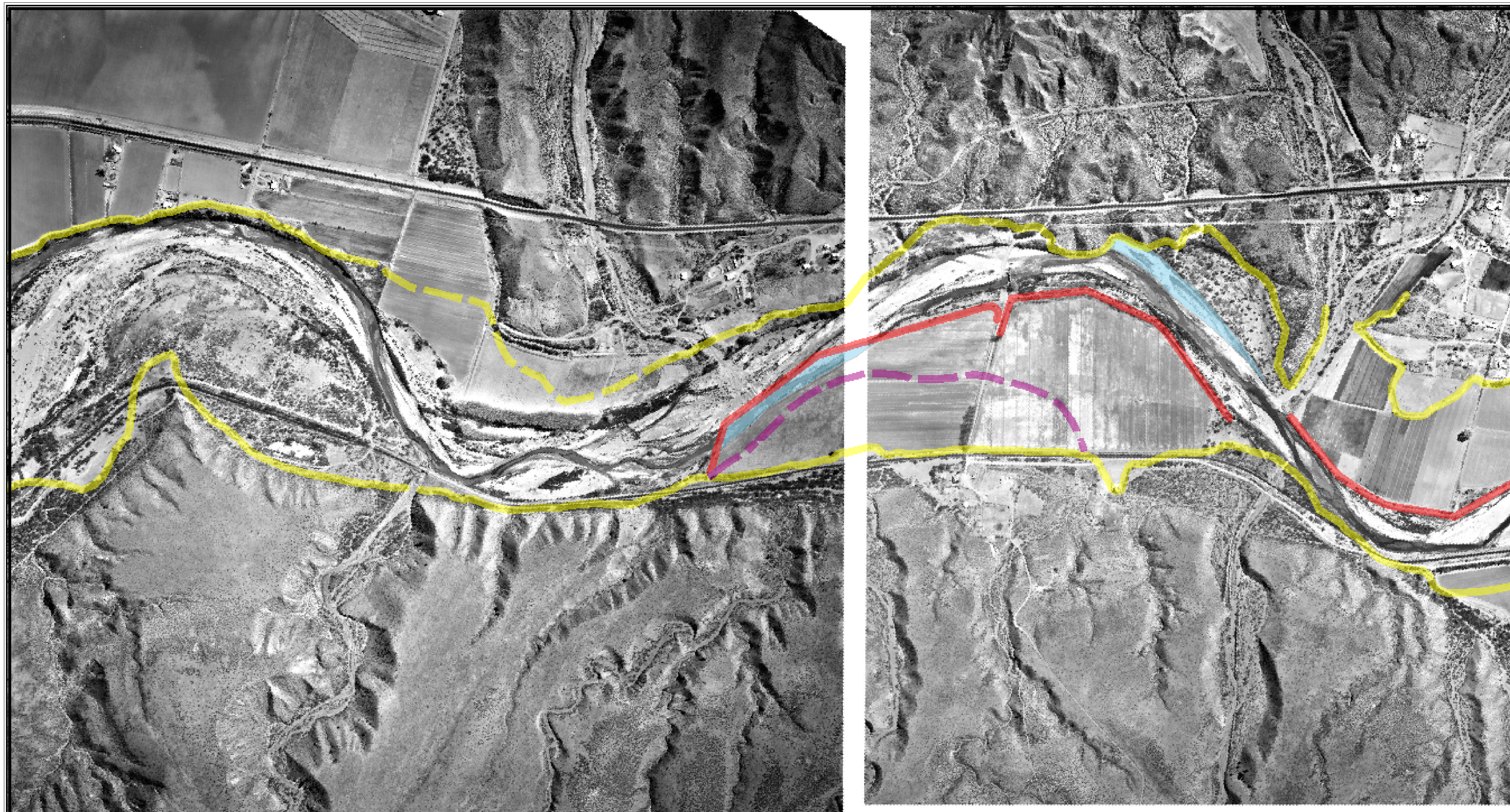


Geomorphic Map of the Upper Gila River, AZ

Upper Gila River Fluvial Geomorphology Study

Maps Produced by the Bureau of Reclamation Technical Service Center
Orthophoto images created with 40m DEM and 1:10,000 scale aerial photography
Photography dated February 2000 - Arizona State Plane East Zone NAD 83
Report Title: Geomorphic Map, Arizona

Map 24



Geomorphic Map of the Upper Gila River, AZ

Upper Gila River Fluvial Geomorphology Study

Map 25

Legend:

- Property Loss
- Geomorphic Limit
- Geomorphic Limit +/- 200ft
- Pima Soil Boundary
- Pima Soil Boundary +/- 200ft
- Diversion Dam
- 1953 Levee
- 1967 Levee
- 1978 Levee
- 1981 Levee
- 1992 Levee

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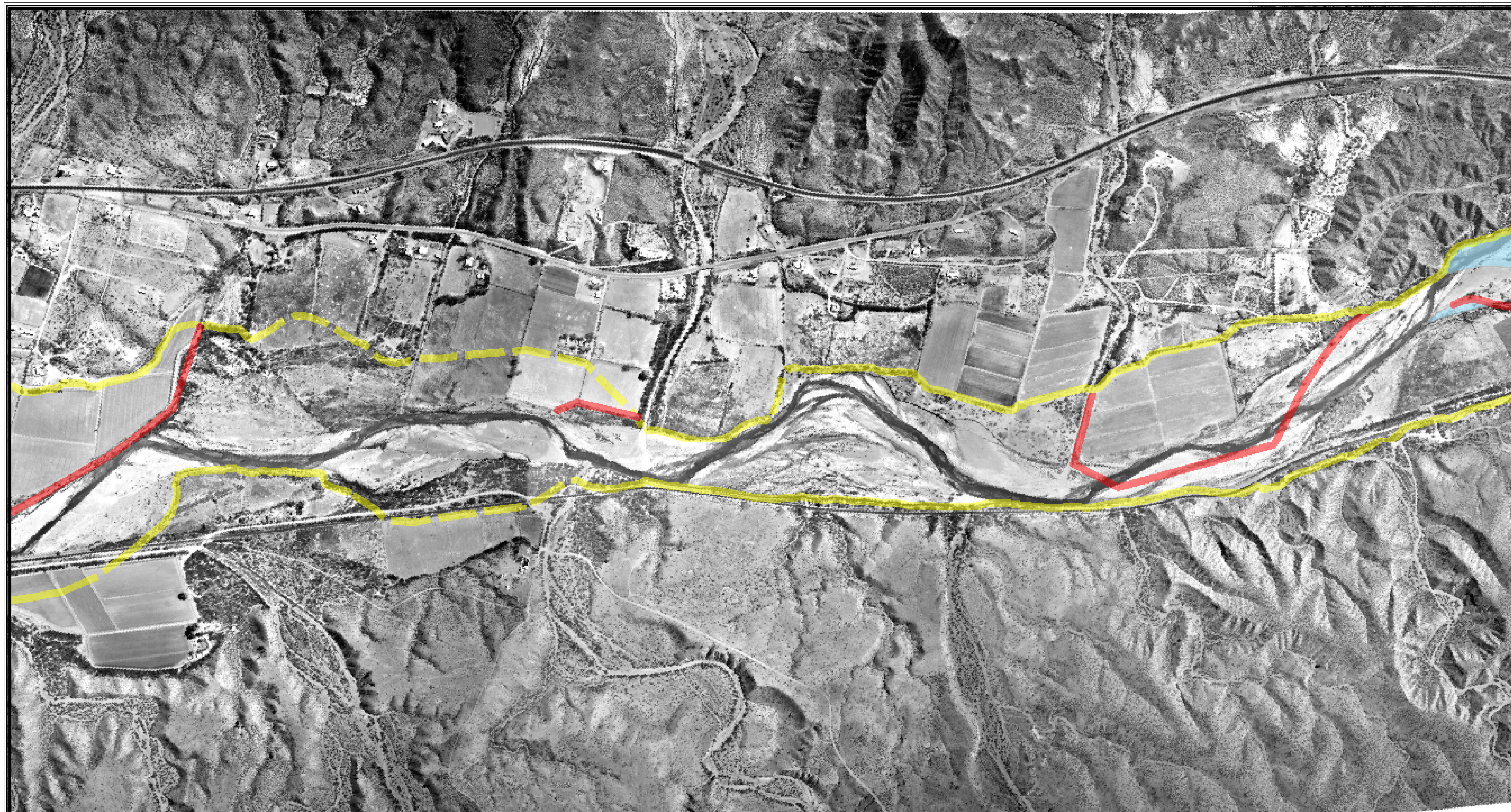
Report Title: Geomorphic Map, Arizona

Scale: 0 500 1,000 2,000 3,000 4,000 Feet; 0 0.125 0.25 0.5 0.75 Miles

N



Geomorphic Map of the Upper Gila River, AZ

Upper Gila River Fluvial Geomorphology Study

Map 26

Legend:

- Property Loss
- Geomorphic Limit
- Geomorphic Limit +/- 200ft
- Pima Soil Boundary
- Pima Soil Boundary +/- 200ft
- Diversion Dam
- 1953 Levee
- 1967 Levee
- 1978 Levee
- 1981 Levee
- 1992 Levee

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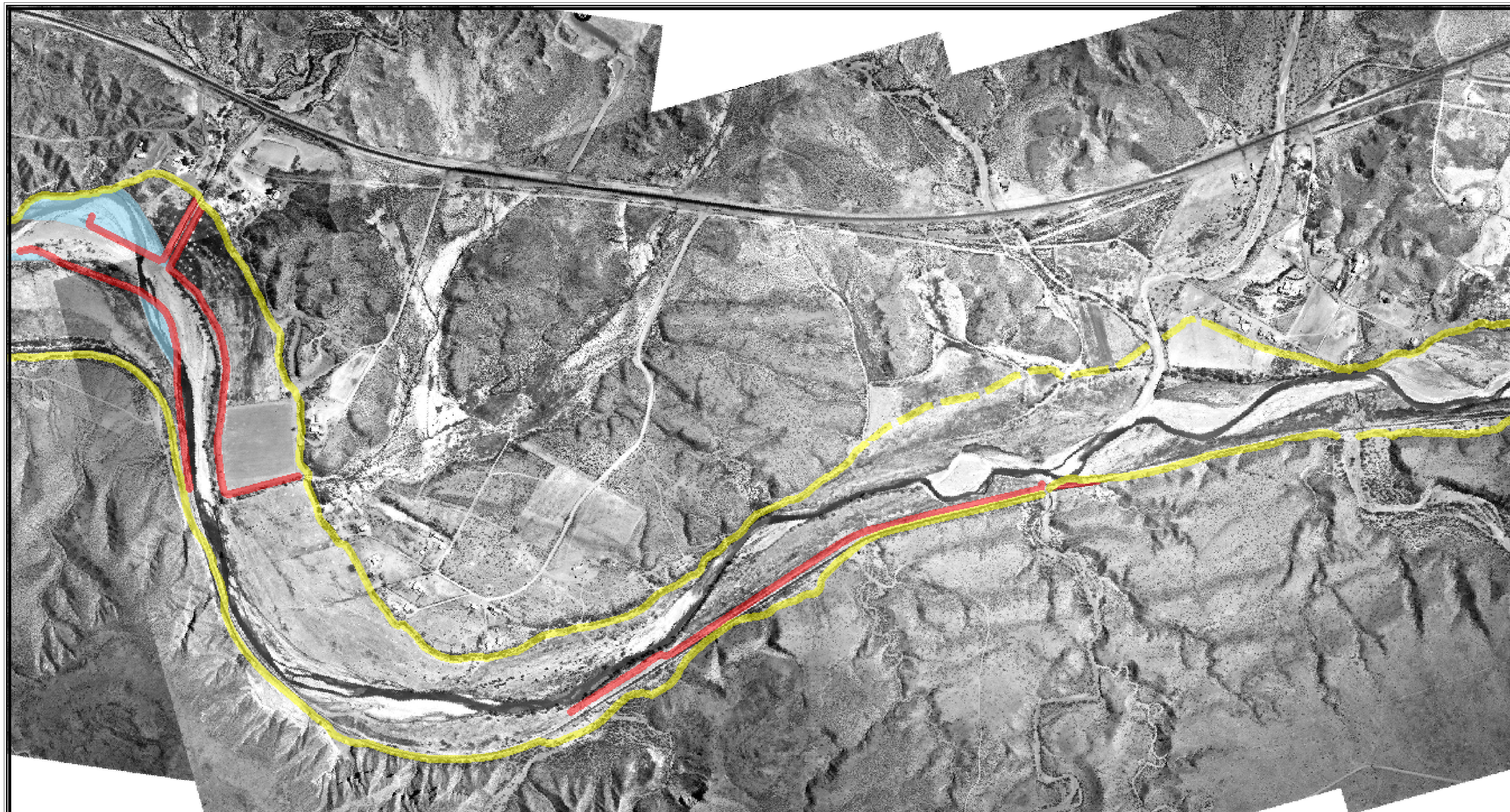
Report Title: Geomorphic Map, Arizona

Scale: 0, 500, 1,000, 2,000, 3,000, 4,000 Feet; 0, 0.125, 0.25, 0.5, 0.75 Miles



Geomorphic Map of the Upper Gila River, AZ

Upper Gila River Fluvial Geomorphology Study

Map 27

Legend:

- Property Loss
- Geomorphic Limit
- Geomorphic Limit +/- 200ft
- Pima Soil Boundary
- Pima Soil Boundary +/- 200ft
- Diversion Dam
- 1953 Levee
- 1967 Levee
- 1978 Levee
- 1981 Levee
- 1992 Levee

Maps Produced by the Bureau of Reclamation Technical Service Center
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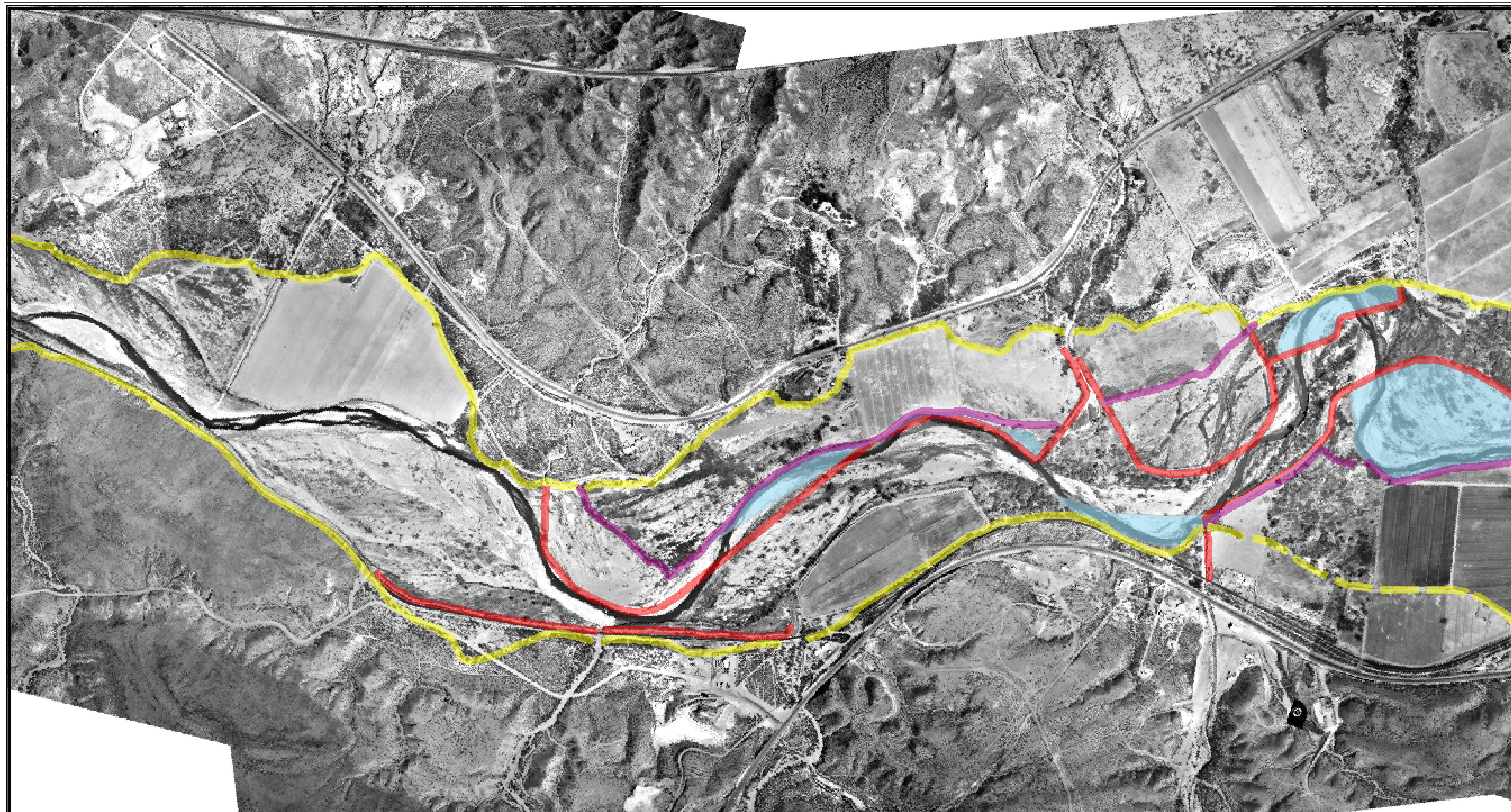
Photography dated February 2000 - Arizona State Plane East Zone NAD 83
Report Title: Geomorphic Map, Arizona

Scale: 0, 500, 1,000, 2,000, 3,000, 4,000 Feet; 0, 0.125, 0.25, 0.5, 0.75 Miles

N



Geomorphic Map of the Upper Gila River, AZ

Upper Gila River Fluvial Geomorphology Study

Map 28

Legend:

- Property Loss
- Geomorphic Limit
- Geomorphic Limit +/- 200ft
- Pima Soil Boundary
- Pima Soil Boundary +/- 200ft
- Diversion Dam
- 1953 Levee
- 1967 Levee
- 1978 Levee
- 1981 Levee
- 1992 Levee

Maps Produced by the Bureau of Reclamation Technical Service Center
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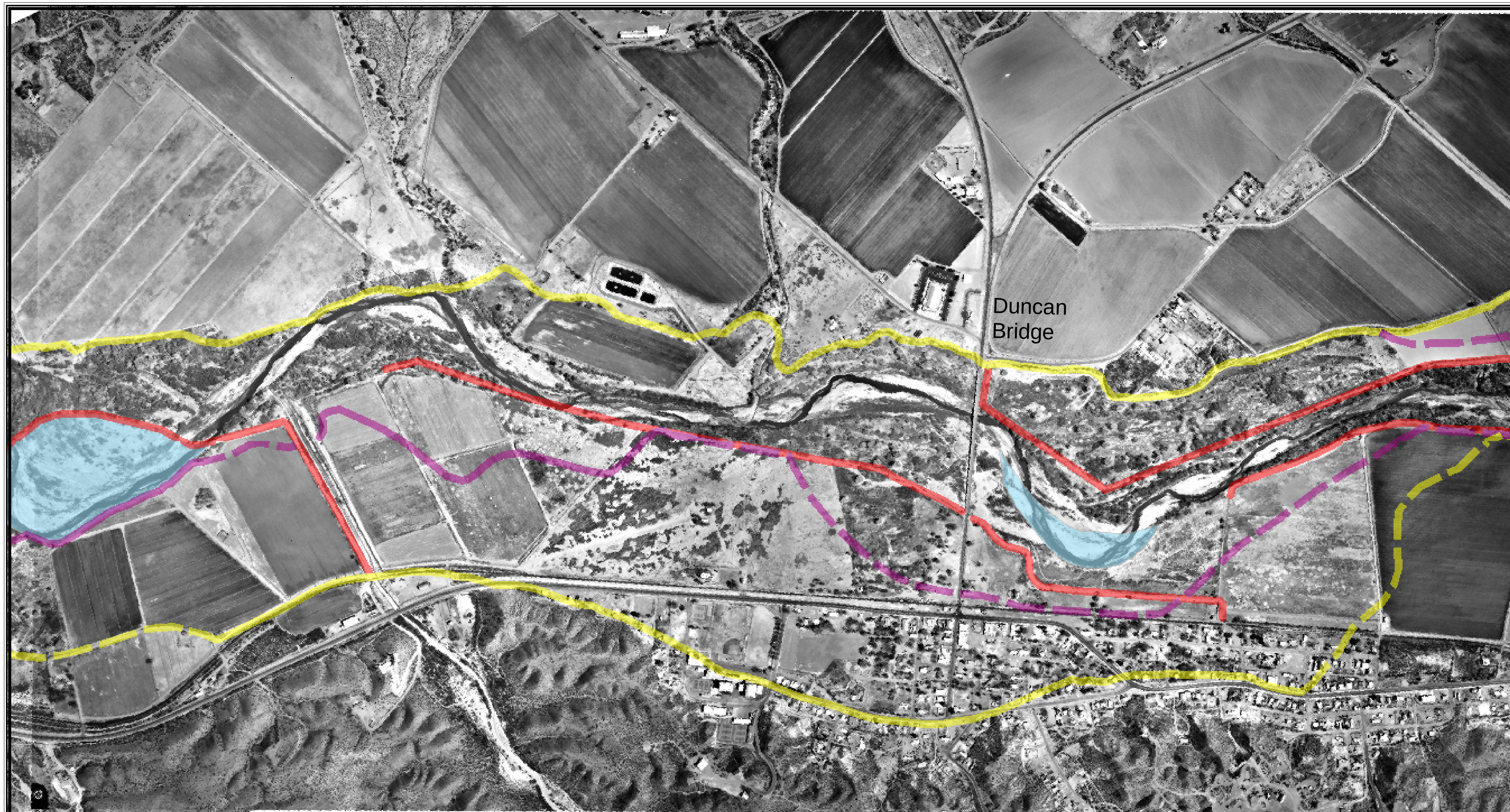
Report Title: Geomorphic Map, Arizona

Scale: 0, 500, 1,000, 2,000, 3,000, 4,000 Feet; 0, 0.125, 0.25, 0.5, 0.75 Miles



Geomorphic Map of the Upper Gila River, AZ

Upper Gila River Fluvial Geomorphology Study

Map 29

Legend:

- Property Loss
- Geomorphic Limit
- Geomorphic Limit +/- 200ft
- Pima Soil Boundary
- Pima Soil Boundary +/- 200ft
- Diversion Dam
- 1953 Levee
- 1967 Levee
- 1978 Levee
- 1981 Levee
- 1992 Levee

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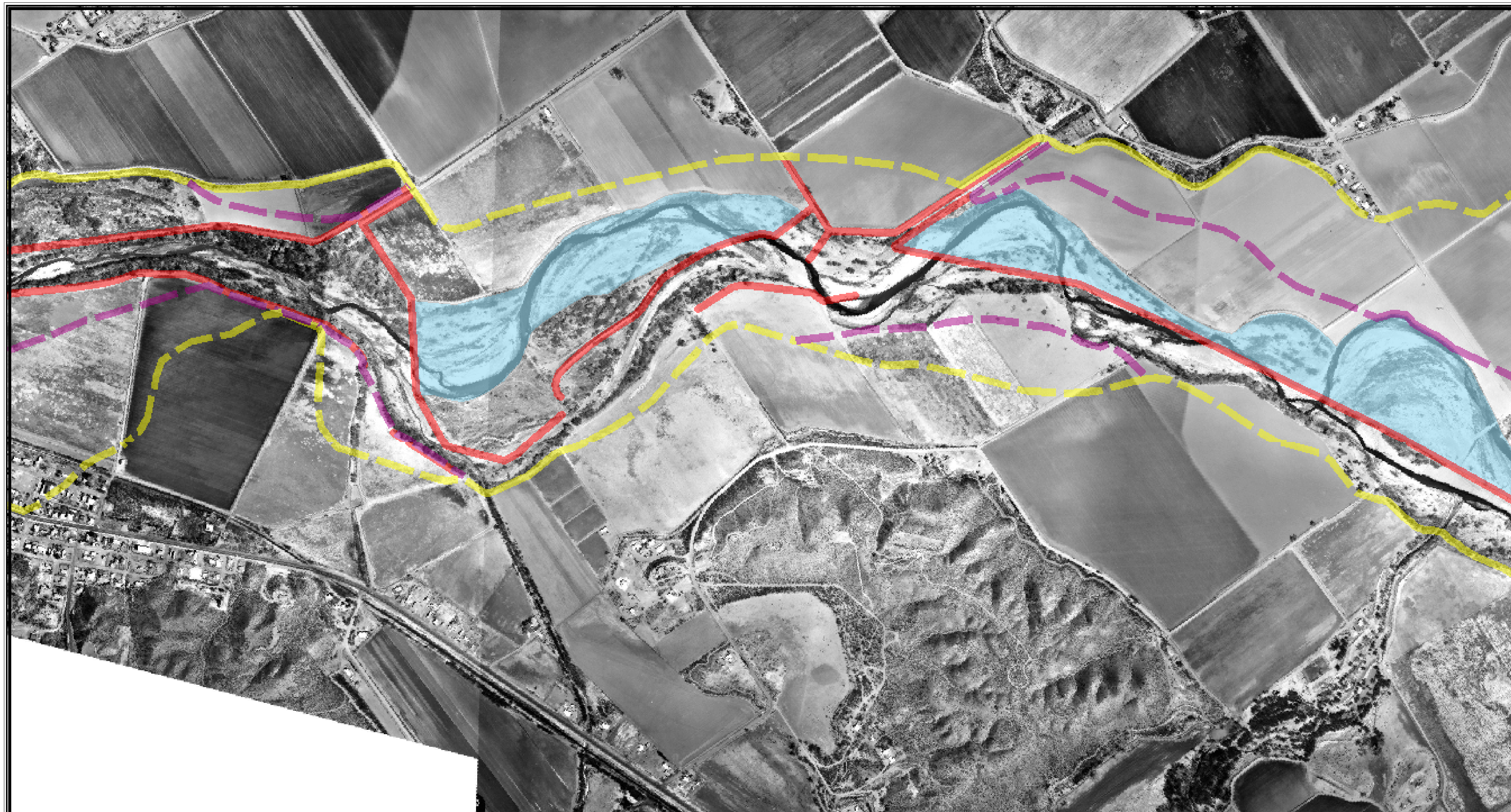
Report Title: Geomorphic Map, Arizona

Scale: 0, 500, 1,000, 2,000, 3,000, 4,000 Feet; 0, 0.125, 0.25, 0.5, 0.75 Miles

N



Geomorphic Map of the Upper Gila River, AZ

Upper Gila River Fluvial Geomorphology Study

Legend:

- Property Loss
- Geomorphic Limit
- Geomorphic Limit +/- 200ft
- Pima Soil Boundary
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Report Title: Geomorphic Map, Arizona

0 500 1,000 2,000 3,000 4,000 Feet

0 0.125 0.25 0.5 0.75 Miles

N

Map 30