2002 Schmidt et al.

9605

FLOW RECOMMENDATIONS FOR THE WHITE RIVER, UTAH-COLORADO

DRAFT REPORT

Prepared for:

Upper Colorado River Basin
Recovery Implementation Program
Project No. 5D

Geomorphic analysis in support of a channel maintenance flow recommendation for the White River near Watson, Utah

John C. Schmidt and K. Lynn Orchard
Department of Earth Sciences
Utah State University
Logan, Utah

and

Base flow recommendations for endangered fishes in the White River, Colorado and Utah, 1995-1996

Dave Irving, Bruce Haines, and Tim Modde
U.S. Fish and Wildlife Service
Vernal, Utah

August 2002

SYNOPSIS

Study Background:

The hydrology of the White River is characterized by high spring flows caused by runoff from snow melt, followed by recession to low, relatively stable, base flows between August and February. The average annual discharge of the White River at the Colorado-Utah state line is about 7.34×10^8 m^3 (595,100 acre-feet); average annual depletions in the basin are approximately 3.75×10^8 m^3 (304,000 acre-feet). The principal water use is irrigation, followed by municipal. Taylor Draw Dam, a run-of-the-river project, was completed in 1984. Its storage capacity is 3% of the total annual discharge. It is located near Rangely, Colorado, 168 km (104.5 river miles) upstream from the confluence with the Green River. The White River is important to the recovery of the Colorado pikeminnow. The highest catch rates of this species in the upper Colorado River basin have been in the White River, and preliminary estimates suggest that the density of Colorado pikeminnow is two to three times the density in the Yampa River. Furthermore, the White River population of Colorado pikeminnow contributes spawners to both the Yampa River and lower Green River.

Endangered fish occupying the White River are limited primarily to the adult life stage of the Colorado pikeminnow. No humpback chub or bonytail populations have been identified in the river and only a few razorback sucker and juvenile Colorado pikeminnow have been collected, most in the extreme lower reach of the river. Although the current hydrograph is similar to the historic flow, approximately 30% of the upstream habitat available to Colorado pikeminnow has been eliminated by the mainchannel barrier, Taylor Draw Dam. Colorado pikeminnow use a variety of habitats throughout the year, including runs and pools for resting during the day and riffles for foraging at night.

The recovery program goal is to recovery endangered fishes while allowing existing and new water development to proceed in the upper basin. The Recovery Implementation Program's Recovery Action Plan has as one of its recovery elements to identify and protect instream flows. The purpose of this report is to develop year-round flow recommendations that maintain channel integrity, promote habitat diversity and complexity, and protect Colorado pikeminnow habitat under low flow conditions in the White River. The overall project goals were to:

1. Determine the relationship of river peak discharge to channel morphology in the White River,
2. Determine habitat available to adult Colorado pikeminnow in the White River at alternative low flow scenarios, and
3. Incorporate data from the above objectives to develop year-round flow recommendations for the White River that identify channel maintenance requirements, minimum low-flows for Colorado pikeminnow, and guidelines for releases at Taylor Draw Dam.

This task was approached through two independent studies, one to evaluate the peak flows needed to maintain channel stability and diversity, and the second to identify habitat available to Colorado pikeminnow during the base-flow period. The first study addressed Objective 1 and was conducted by Dr. John Schmidt and K. Lynn Orchard, Utah State University. The second study addressed Objective 2 and was conducted by Dave Irving, Bruce

Haines, and Tim Modde, U.S. Fish and Wildlife Service. The individual reports addressed separate objectives and are presented as individual, complete studies that stand alone.

Study findings:

An integrated flow recommendation was determined through these two independent stduies, one to evaluate the peak flows needed to maintain channel stability and diversity, and the second to identify a minimum base flow needed to maintain habitat for the Colorado pikeminnow population.

<u>Channel maintenance flow/high flow recommendations</u>: There are two approaches to determining the discharges necessary to maintain channel diversity. One is to directly measure channel bed movement measuring sediment transport and bed scour and fill in those parts of the channel that are critical habitat. A second is to determine those discharges at which habitats are maintained on typical alluvial streams. We pursued both in these studies.

Several lines of evidence indicated that a high-flow component of an instream flow should preserve most of the natural flow regime greater than approximately 40 m^3/s (~1,400 ft^3/s).

Historical discharge and depth records at our study site near the Watson, Utah U.S. Geological Survey gage showed that flows of this magnitude scoured the bed, and thus flows greater than this were capable of transporting fine bed sediment. We inferred that bedload movement occurred at 51 m^3/s (1,800 ft^3/s), because bedforms were detected on fathometer traces at those cross sections with fine-grained bed material at this discharge.

The White River is a sediment supply-limited stream, because much more suspended sediment is carried on the rising limb of the annual snowmelt hydrograph than on the falling limb. Thus, some low flows might not be necessary to maintain an equilibrium sediment mass balance wherein the entire load delivered to the stream is transported downstream. A rule of thumb used elsewhere has been to claim all flows greater than the discharge above which 70% of the long-term annual load is transported. At the study site, that flow was about 40 m^3/s. We assumed that sediment normally transported by lower discharges could be transported by flows greater than 40 m^3/s because of the supply-limited nature of the stream.

Flows higher than 40 m^3/s were capable of entraining gravel exposed on bars in the study reach. Entrainment occurred at many bars near bankfull discharge of 105 m^3/s (3,700 ft^3/s), which has a recurrence interval of about 3 years on the partial duration series for the period following completion of Taylor Draw Dam (1984-97). In this case, bankfull discharge was much greater than the effective discharge for suspended load, which we estimated to be between 48 and 82 m^3/s (1,000 – 2,900 ft^3/s).

Our study plan precluded determination of the effective discharge for bedload, but this discharge was likely larger than that for suspended load. The high volume of suspended load, however, and the larger proportion of the bed covered by fine sediment suggested that a habitat maintenance flow claim be based on ensuring that all suspendable sediment be transported through the study reach.

The White River underwent an annual cycle of scour and fill that changed the elevation of the bed by as much as 1 meter. The range of scour and fill defined the active layer of the bed that can be mobilized during flooding. These flows thus had the ability to reshape instream habitats. The changes in bed elevation during the spring flood suggested that much of the sediment transported in the White River was moved as a pulse of mobilized bedload material.

Whereas the bed scoured at higher discharges in most of the measured cross sections, aggradation occurred near the coarsest cobble bars. Aggradation of the bed in these regions could be due to finer material moving over the more stable coarse material, which suggested the occurrence of selective transport. Other studies found that transport of finer bed material occurred at discharges below bankfull stage in several coarse-bedded rivers. The channel of the White River within the study reach was made of both fine-grained and gravel deposits. While some of our evidence suggested that a threshold of equal mobility was reached near 41 m^3/s (1,450 ft^3/s), it was more likely that selective transport of the finer deposits occurred at this discharge. Both the aggradation of the bed at higher discharges in very coarse bedded areas of the stream, and a peak in the sediment transport curve at 14 m^3/s (500 ft^3/s), suggested that finer sediments were transported selectively at low discharges.

Base flow/low flow recommendation: The purpose of this study was to identify the base flow needs of endangered fish, i.e., adult Colorado pikeminnow, in the White River. Two approaches were used: 1) protection of Colorado pikeminnow habitat and 2) protection of riffle habitat to maintain biological productivity. Both methods used physical habitat simulations to estimate changes in macrohabitat (pool, run, eddy, and riffles) and microhabitat (depth, velocity, substrate, and cover) changes that resulted from changing flows. Curve break analysis was used to identify the flow below which the greatest rate of habitat change occurred.

Study results showed that most of the habitats in the White River consisted of riffles and runs, and pools and eddies were secondary components. Habitat proportions remained constant as discharge ranged from 4.2 to 17.0 m^3/s (150 - 600 ft^3/s) ; below 4.2 m^3/s (150 ft^3/s), riffles increased and eddies decreased.

Adult Colorado pikeminnow habitat was estimated for three sets of habitat suitability criteria and applied to the White River physical habitat simulation at discharges ranging from 0.028 to 17.0 m^3/s (1-600 ft^3/s). The first criterion used White River data from previous studies. It showed an almost linear increase in usable habitat as flows increased from 0.028 to 17.0 m^3/s. The second criterion used night foraging data from the Yampa River (1996 and 1997). It showed usable habitat area almost identical to that of the White River data, the result of similar suitability indices for depth and velocity. The third criterion was for daytime resting fish, also developed from Yampa River data. This showed low usable habitat score for all White River flows. This was the result of the Yampa River data showing daytime use of pools and runs > 1.2 m deep; however, these depths were rare in the White River. White River Colorado pikeminnow apparently found suitable daytime resting areas in other habitats < 1.2 m deep, e.g., undercut banks and within channel structure.

The riffle surface area-discharge relationship was nearly linear for all flows examined, and thus no curve break was identified. The wetted perimeter-discharge relationship, however, was non-linear and increased rapidly with discharge between 0.028 and 4.24 m^3/s (1 - 150 ft^3/s) and then gradually approached a plateau near 14.2 m^3/s (500 ft^3/s) before again increasing at 15.6 m^3/s (550 ft^3/s). Curve break analysis found that at discharges below of 4.2 m^3/s wetted perimeter decreased rapidly. Curve breaks were also calculated for width, depth, and velocity and yielded values similar to that of wetted perimeter.

Historical White River discharge during the base flow period (August-October) 1923 through 1997 dropped below 5.7 m^3/s (200 ft^3/s) less than 5% of the time and below 4.2 m^3/s less than 1% of the time.

We recommend that flows lower than 4.2 m^3/s (150 ft^3/s) not occur greater than the historical frequency (i.e., 1% of the time). This value is supported primarily by riffle wetted-perimeter curve break analysis and by similar curve breaks for other hydraulic parameters. Other important variables, like Colorado pikeminnow habitat and riffle area, show linear relationships with discharge and, therefore, are not helpful for determining minimum flow. At 4.2 m^3/s base flow, approximately 50% of the Colorado pikeminnow habitat and riffle surface area is preserved compared with that available at 17.0 m^3/s (600 ft^3/s), the highest potential base flow considered.

Integrated flow recommendation. We recommend that when spring runoff flows exceed 40 m^3/s (1,413 ft^3/s), all flows should remain in the channel for the purpose of channel maintenance. In addition, a base flow of 4.2 m^3/s (150 ft^3/s) should be maintained and that flows lower than 4.2 m^3/s (150 ft^3/s) not occur more often than 1% of the time, based on daily average flows at Watson, Utah. .

REPORT A

GEOMORPHIC ANALYSIS IN SUPPORT OF A CHANNEL-MAINTENANCE FLOW RECOMMENDATION FOR THE WHITE RIVER NEAR WATSON, UTAH

DRAFT REPORT

Prepared for

Upper Colorado River Basin
Recovery Implementation Program
Project No. 5D

John C. Schmidt
and
K. Lynn Orchard

Department of Geography and Earth Resources
Utah State University
Logan, Utah 84322-5240

August 2002

ACKNOWLEDGMENTS

This study was funded by the Recovery Implementation Program for Endangered Fish Species in the Upper Colorado River Basin. The recovery Program is a joint effort of the U.S. Fish and Wildlife Service, U.S. Bureau of Reclamation, Western Area Power Administration, states of Colorado, Utah, and Wyoming, Upper Basin water users, and environmental organizations.

Where trade names or commercial products are mentioned, the following disclaimer also should appear: "Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the authors, the Fish and Wildlife Service, U.S. Department of Interior, or members of the Recovery Implementation Program."

TABLE OF CONTENTS

LIST OF TABLES

Tables Page

LIST OF FIGURES

LIST OF KEY WORDS

White River, geomorphology, sediment transport, flow recommendation, channel maintenance flow, effective discharge, bankfull discharge

EXECUTIVE SUMMARY

Seventy percent of the long-term annual suspended load of the White River near Watson, Utah, is transported by discharges greater than 1,413 cfs. Flows greater than about 1,413 cfs are also capable of scouring the bed of fine sediment. The effective discharge of the stream is between 1,695 and 2,895 cfs. The White River is supply-limited because more sediment is transported on the rising limb of the annual snowmelt hydrograph than on the falling limb. Thus, higher flows are capable of transporting more suspended load than they do. A channel-maintenance flow regime that guaranteed no alteration to the natural flows greater than 1,413 cfs would prevent aggradation of fine sediment on the bed, entrain gravels when flows approach bankful flow of 3,708 cfs, and ensure the availability of in-stream habitats.

INTRODUCTION

High discharges are a necessary component of ecologically-based instream flows (Reiser et al. 1989; Hill et al. 1991; Jackson and Beschta 1992; Petts and Maddock 1996), because minimum streamflows are insufficient to transport sediment downstream. Kondolf and Wilcock (1996) stated that, "the importance of floods in maintaining the dynamic nature of riparian and aquatic ecosystems [is] now widely recognized." The purpose of this report is to provide the scientific basis for determining those high flows necessary to maintain the channel of the White River near Watson, Utah. The White River is known habitat for adult Colorado pikeminnow (*Pytchocheilus lucius*), which is a federally designated endangered species. A companion report (Chapter B) describes low-flow requirements for the Colorado pikeminnow in the White River. Together, these two studies could be used to develop an in-stream flow recommendation for the White River.

Background -- The Objectives of Habitat and Channel Maintenance

The general purposes of floods are to prevent the channel from aggrading and to maintain the distribution and abundance of habitats available to stream benthos and fish fauna. Specific ecological purposes of high flows include habitat and channel maintenance. One attribute of habitat maintenance is to protect the quality of riffle habitat by (1) preventing accumulation of surficial fine sediment, (2) preventing accumulation of interstitial fine sediments in gravels, and (3) maintaining gravel looseness. There are several ecological reasons why riffle habitat should be maintained.

Fine sediment on and within spawning gravels reduce egg suvival. Although there are no known Colorado pikeminnow spawning areas in the White River, some aquatic invertebrates use open interstices in cobbles and gravel, and accumulated fine sediment can eliminate this habitat characteristic. Another purpose of high flows is to restore or enhance pool habitat by preventing the accumulation of fine sediment in pools. Deep pools provide cover and adequately cool water which permit survival of some species during warm, low-flow months.

Another objective of including high flows as part of an in-stream flow recommendation is to maintain active channel width and topographic diversity of the channel. Ecological diversity and productivity of river channels and flood plains are directly related to the areal extent, complexity, and variety of available physical habitats. Hesse and Sheets (1993) pointed out that "we must be careful not to assume that the minimum flow necessary to move sediment is the correct flow to achieve a dynamic channel morphology." To accomplish this purpose of maintaining channel width and channel diversity, it is often necessary to prevent vegetation from encroaching on the active channel. This necessitates that seedlings of riparian plants be scoured at least biennially. Kondolf and Wilcock (1996) suggested that the 2 year flood accomplishes this objective.

Background -- Channel and habitat maintenance in Relation to the Geomorphic Concepts of Effective and Bankfull Discharge

There are two approaches to determining the discharges necessary to maintain the diversity of the channel. One approach is to directly measure habitat movement and reworking by measuring sediment transport and bed scour and fill in those parts of the channel that are important habitat. A second approach is to determine those discharges at which habitat maintenance is known to occur, on average, in typical alluvial streams. We pursued both approaches in this study.

The most widely accepted surrogates for establishing discharges necessary to transport significant amounts of sediment and, thereby, maintain the channel are the concepts of bankfull and effective discharges. Frequently occurring floods of moderate magnitude transport the greatest amount of sediment and are believed to accomplish the greatest amount of geomorphic work in alluvial rivers (Wolman and Miller 1960). While extremely high discharges can carry huge amounts of sediment, large floods are rare, and the majority of sediment is typically transported by more frequently occurring moderate floods. The discharge that accomplishes the most geomorphic work is known as the effective discharge. Andrews and Nankervis (1995) calculated effective discharge in 17 gravel-bedded streams, and found that effective discharge typically fell in the range of 0.8 and 1.6 times the bankfull discharge. Andrews (1980) found that the range of effective discharges had a recurrence interval of between 1.2 and 3.3 years in the Yampa River basin. The bankfull flood, because of this association with effective discharge, is often used as an indicator of the moderate flood which typically creates the form of the channel (Andrews and Nankervis 1995).

Background -- Geomorphic Research about the White River and Its relationship to the Requirements of Endangered Fish

Although streamflows have been gaged in the White River basin since 1904, there has been only limited research about sediment transport and the geomorphic characteristics of this river system. Increased attention was focused on the hydrology and geomorphology of the White River in the mid-1970s due to oil shale exploration in the region. Between 1974 and 1980, the U.S. Geological Survey (USGS) established baseline discharge and water quality data in anticipation of widespread oil shale extraction in the region (Lindskov and Kimbal1984). Suspended sediment transport measurements at the Watson gage were made on a daily basis for most of water year 1975, and these data are used in this study. Bedload transport was estimated from observed changes in mean channel depth during high flows at a gage temporarily located near the mouth of the White River (station 09306900) (Seiler and Tooley 1982). During a flood of 4,100 cfs, the bed scoured roughly 1 m at this site. They estimated that approximately 1.3 x 10^6 m^3 of bed material was scoured and filled in 18 rm upstream from the gage during this flood. Jurado and Fields (1978) used airphotos taken as early as 1936 to document long-term changes in channel position throughout the White River. They found that the White River is prone to channel migrations, and that the degree of channel migration is dependent on specific reach characteristics such as slope and degree of bedrock confinement. During the past century, the channel has migrated less in reaches of high slope and narrow bedrock confinement.

The listing of four endemic fishes as endangered species, including the Colorado pikeminnow, has also increased attention on the hydrology and geomorphology of the White River. Changing hydraulic and geomorphic conditions influence physical habitat features such as the size and frequency of eddies (Orchard and Schmidt 1998), and the amount of fine-grained sediment located in the interstitial spaces in gravel bars (Kondolf et al. 1987). To aid in the recovery of these fishes, the U.S. Fish and Wildlife Service (USFWS), in 1987, initiated the Upper Colorado Recovery Implementation Program (RIP). The program calls for the management of habitat using "...instream flows at certain times, locations, and in certain quantities..." (USFWS 1987) which promote the recovery of these species. As a part of this program, the Utah Department of Wildlife Resources (UDWR) began work to assess flow requirements for the Colorado pikeminnow in the White River, and identify those existing conditions which may impede the recovery of the species (Lentsch et al. 2000). Much of the work conducted by UDWR focused on the impact of Taylor Draw Dam, which was completed in 1984. Lentsch et al. (2000) identified several probable changes in the annual hydrograph of the White River that occurred after the completion of Taylor Draw Dam. They divided the available period of gaging records for the White River near Watson, Utah (station 09306500), into three time periods representing various degrees of human usage of the White River. The divisions were the early development period (1923 -- 1945), the middle development period (1946 -- 1978), and the post-Taylor Draw Dam period (1985 -- 1993). However, due to the short record after the completion of the dam (9 years), and the failure to consider discharges between 1979 and 1984 when the Watson gage was not active, the results about the post-dam period were inconclusive. Previous studies on the White River have observed that higher discharges modify habitat more so than baseflow discharges (Chart 1987), and that habitat diversity differs by reach (Miller et al. 1982), but specific flows that maintain or improve habitat were not identified.

Our objective in this paper is to augment previous studies of the White River by addressing the question of what discharges are necessary to maintain channel form and habitat diversity. Specifically, we wanted to 1) determine what discharges are necessary to mobilize the bed and, thereby, remove fine-grained sediments from gravel deposits and maintain gravel looseness, and 2) identify what discharges transport the majority of the sediment load and are responsible for maintaining channel form.

Overview of the White River and Description of the Study Site

The White River basin is in northwest Colorado and northeast Utah (Figure A-1). The basin is south from the Yampa River basin, and north from the Colorado River. The White River originates in the Flat Top mountains of western Colorado at an elevation of approximately 3600 m. From its sources, the river flows westward for approximately 250 rm, and has incised shallow canyons through predominantly Tertiary sediments of the Unita and Green River formations. The river joins the Green River in the central Uinta Basin several miles downstream from the confluence of the Green and Duchesne Rivers. The channel has migrated across its valley, and oxbow lakes and the concentric patterns characteristic of migrating channels are present in many reaches (Figure A-2).

The principal water use in the White River basin is irrigation. Non-agricultural diversions are made by the towns of Rangely and Meeker. Combined agricultural and non-agricultural water depletions in the White River basin are approximately 304,000 acre-feet. Average annual streamflow in the White River at the Colorado-Utah state line is about 595,100 acre-feet.

Taylor Draw Dam (Figure A-3) was completed in 1984, and is located in northwestern Colorado at approximately rm 104, as measured upstream from the confluence with the Green River. Taylor Draw Reservoir has a storage volume of 13,800 acre-feet, which is less than 3% of the total volume of the average annual streamflow. The dam is primarily operated as a run-of-the-river project where discharges released from the dam equal the inflow to the reservoir. The reservoir is used primarily for recreation and supplies little to no water for irrigation.

Just downstream from the dam, the White River enters a broad alluvial valley. For the next 15 miles, the river flows through a valley where bedrock outcrops on opposite valley sides are between 0.9 and 1.2 rm apart. The river's slope is 0.0014 (Figure A-4) as it cuts a meandering course between outcrops of the Cretaceous Mancos Shale on the north, and the Tertiary Unita formation on the south. Several oxbow lakes occur on the flood plain in the upstream and downstream portions of this reach, and mid-channel islands are spaced at approximately 0.6 rm intervals. The town of Rangely, Colorado is located at approximately the center of this reach.

At approximately rm 81, 15 rm downstream from Taylor Draw Dam, the river cuts through the southwest flank of the Rangely anticline. The valley width narrows to between 0.25 and 0.5 rm and the channel's increased gradient is 0.0030, which is maintained for the next 3 rm.

Between rm 72 and 36, the river passes through a canyon cut into the Green River formation. Valley widths range from 0.1 to 0.4 rm, and the overall slope is 0.0013. River gradient within this canyon is steepest between the Colorado state line and the confluence with Evacuation Creek at rkm 97. The river slope is 0.0022 and the channel crosses the Mahogany Ledge oil shale member of the Green River formation.

Our detailed study site (Figure A5) lies just downstream from this steep subreach. The study site extends 0.5 rm upstream and 0.1 rm downstream from the U.S. Geological

Survey's gaging station located near Watson at rm 56. The Watson gage (station 09306500) is located 107 m downstream from the bridge on Utah State Highway 45 and is at an elevation of 1508 m above mean sea level. It is 1 rm downstream from Evacuation Creek, and 7 rm north from Watson. The drainage area upstream from the gage is 10,412 km^2. The gage was in operation from April 1904 to October 1906 (no winter records), May to November 1918, andApril 1923 to September 1979. The gage was deactivated in 1979 and relocated near the Colorado State line in anticipation of a proposed water storage project. The project was abandoned, and the gage was reactivated at its previous location in October 1985. Mean daily discharge values and all peak floods above 1,000 cfs for these time intervals are published and available from the USGS. The stage-discharge relationships at the gage that have been developed by the USGS have been based on repeated measurements. The notes from these measurements contain information on the width and depth of the channel. We analyzed data collected since 1968; earlier records are not available. Meandering reaches occur upstream and downstream from the study reach; the channel is predominantly straight and more narrowly confined where we collected data. Bedrock canyon walls are on average between 0.2 and 0.3 rm apart. The reach contains several pool-riffle sequences, and has an overall slope of 0.0012.

The White River through its lower course is a meandering stream. The river's alluvial valley, is inset into a shallow canyon within the Green River formation (Figure A-6). The channel has typically migrated across a broad alluvial valley which is confined by broadly spaced bedrock walls. However, the river is incised into entrenched meanders in several reaches in the lower course of the river. The river channel itself is inset within a series of alluvial terraces overgrown by dense stands of tamarisk *(Tamarix sp.*), Russian olive (*Elaeagnus anustifolia*), and a few cottonwoods (*Populus* sp.). Although the banks and flood plains are predominantly made up of fine-grained alluvium, the bed of the river is predominantly gravel.

Approximately 21 rm downstream from the study reach, the exposed bedrock at river level changes from the Green River formation to the Uinta formation. From Taylor Draw Dam to the mouth, river, has its steepest slope of 0.0044 for the 2 rm across the transition. Downstream from this point the river flows for 12 rm through entrenched meanders eroded into the Unita formation. The distance between canyon walls increases, and in the last 19 rm of its course, the river flows across a 1.2 mile wide alluvial valley. The slope nearing the confluence is 0.0005.

METHODS

Flood Frequency Analysis

Seventy-seven years of annual peak floods measured at the Watson gage were used to calculate the mean annual flood, and the return period of other annual peak discharges. Peak flood values are available at the Watson gage for 1904 and 1905, 1923 to 1979, and 1985 to 1997. Data from the Stateline gage (station 09306395) were used for the period when the Watson gage was inactive, between 1979 and 1985. The plotting position for each annual flood was determined using the formula:

$$RI = (n + 1)/M$$

where RI is the recurrence interval of the flood, n is the number of years of record, and M is the rank of the flood. A log Pearson Type III distribution was calculated for these data.

To determine whether peak flood magnitudes have changed over time we calculated partial-duration series for three shorter time intervals: 1923--1964, 1965--1983, and 1984--1997. Time intervals were chosen to coincide with apparent shifts in peak flood magnitudes, and with the installation of storage and diversion structures. The end of the first period was 1964, when there was a noticeable decrease in peak floods; a major irrigation diversion was constructed at this time, as well. The end of the second period was 1983, the last year the river was not regulated by Taylor Draw Dam, which was completed in 1984. All peaks above 1,000 cfs were used to calculate the partial duration series for the three time periods (Figure A-7). The calculation of recurrence interval using a partial-duration series is the same as above except n = number of peaks instead of number of years. A log Pearson Type III distribution was calculated for data from each of the three time periods (Figure A-8).

Topographic mapping

Topography of the study site was surveyed in April 1997, using a geodetic total station. Specific features which were surveyed included the river channel, thalweg elevation, and extent of flat-lying depositional surfaces that might be either the active flood plain or terraces. Coordinate data from the total station were downloaded to a personal computer for analysis. A technician then used the coordinate data to hand plot a map of the study site at a 1:400 scale. The hand drawn contour lines were then digitized into a geographic information system using a digitizing table and Arc/Info software (Trademark). Once digitized, control points in each map segment were assigned coordinate values in a local grid system. Each line segment (arc) and enclosed polygon was assigned attributes according to what each represents on the map.

Identifying bankfull discharge and the active flood plain

The active flood plain is defined as the flat depositional surface adjacent to the channel that is overtopped during times of flooding and is constructed by the present flow regime. The active flood plain is just overtopped at bankfull discharge. The recurrence interval of the bankfull discharge varies on different rivers.

We identified bankfull discharge in the study reach by surveying the elevation of each depositional surface at numerous locations throughout the reach and noting the vegetation on each surface. After plotting these points, a best-fit line was plotted through the surveyed elevations and projected through the gage. The discharge of the flood that inundates each surface was determined from the elevation of the line where it passes through the rating relationship at the gage. We identified three different flat surfaces adjacent to the channel within the study reach that might have been the active flood plain. The active flood plain was distinguished from low elevation terraces by choosing the lowest widespread depositional surface that is inundated by frequent low magnitude floods.

Cross Sections

Eleven channel cross sections were established in the study reach near the Watson gage in May 1995, and three additional cross sections were established in April 1997. Cross sections were used to characterize channel geometry; we also identified bed material at each side. Cross sections were spaced approximately one channel width apart, and were oriented perpendicular to the flow. Cross section endpoints were monumented with either rebar or fence posts pounded to depths such that about 10-cm were exposed above ground surface.

Transects were measured by attaching a length-calibrated Kevlar (Tradename) tag-line to the endpoints. A geodetic total station was used to measure ground-surface elevations under the tag line as well as to measure water-surface elevation and elevations of geomorphic surfaces near the channel. Elevation of cross section endpoints were all surveyed to a common reference datum. Elevation of the bed was measured either using the total station and a stadia rod placed on the bed at fixed intervals under the tagline, or was measured from a cataraft equipped with a paper-trace echo sounder and outboard motor. When measuring the bed from a raft, the boat operator maintained the boat carefully under the tag-line while slowly crossing the river. A second individual in the raft recorded depth using an echo sounder and position at marked locations along the tag-line. Measurements made from the raft were replicated at least four times. Where wading was feasible, bathymetric measurements made from the raft were also surveyed with the total station to verify the accuracy of the echo-sounder. Echo-sounder measurements concurred with total station measurements and rarely deviated more than a few centimeters. Coordinate data from the total station was reduced to distance and elevations relative to endpoints for purposes of plotting. Bathymetric traces of the bed were analyzed in the lab. Average depths below the water surface from the fourrepeated bathymetric surveys were converted to bed elevations by subtracting the depth of water from the surveyed elevation of the water surface. Transects were resurveyed in April

1997, and plots were overlain to visually compare changes in bed geometry.

Calculating Effective Discharge From Sediment Records

Effective discharge was determined by analyzing 847 suspended sediment measurements made at the Watson gage. Sediment transport measurements were made by the USGS between 1975 and 1990. A sediment rating relationship was developed by fitting a best-fit power function to a plot of the $\log_{10}$ of daily suspended sediment in kilograms/day vs. the $\log_{10}$ of discharge in cubic meters per second. For the reach near the Watson gage, this relationship was found to be:

$$Q_{sed} = 931.63Q^{2.205}$$

where Q_{sed} is sediment transport in kilograms/day, and Q is discharge in cubic meters per second. Using the sediment rating relation, the amount of sediment transported by given increments of discharge was determined. A flow duration curve developed from approximately 76 years of daily discharge values was then used to determine what percentage of time a given discharge occurred during that period. The percentage of time a given discharge occurred was multiplied by the sediment transported by that magnitude of discharge, and the resulting product was plotted against discharge. The peak in this curve represents the increment of discharge which transports the highest fraction of the annual sediment load of the stream, the "effective discharge", as defined by Andrews (1980).

Analysis of Discharge Records to Determine Threshold Discharges

We analyzed archived USGS discharge measurements for station 09306500 for the periods between September 15, 1967, and October 3, 1979, and between October 29, 1985, and September 30, 1997. Discharge measurement notes include channel depth and width, as well as the location of the measurement in relation to the gage. These records provide documentation of long-term changes in channel geometry and seasonal fluctuations in bed elevation. At low discharges, measurements typically were made with a wading rod within 75 meters up or downstream from the gage. At higher discharges, measurements were made with a sounding weight suspended from the cableway located at the gage. Actual discharge measurements were made approximately twice each month during the period of time while the gage was maintained, and were used to establish a stage-discharge rating relation. Measured discharges, cross-sectional area, mean depth, maximum channel depth, and distance of the measurement from the gage were transferred from the records into a spreadsheet and analyzed.

The bedelevation of the thalweg was calculated by subtracting the maximum depth during a discharge measurement from the stage elevation at the time of measurement. All elevations were adjusted to a common datum for comparison. The temporal sequence of thalweg elevation through time was compared to the record of mean daily discharge. We analyzed the response of the bed to changes in discharge, and we attempted to determine the discharge that caused scour and fill of the bed. Depth was only recorded during direct discharge measurements, so the resolution of bed elevation data was relatively low (approximately two per month) compared with published daily gage measurements of stage elevation. Because of this low resolution, it was not possible to determine precisely at what discharge the bed began to scour in each year directly from the records. However, a decrease in thalweg elevation between two discharge measurements indicates that at some time between the measurements the discharge was sufficient to scour the bed. Mean daily discharges between measurements where the bed elevation changed more than 0.25 m were determined and compared with discharges during periods where bed elevation remained constant. We used a two-tailed t-test and assumed equal variance to determine if the maximum discharges during periods of scour were drawn from statistically different populations than the maximum discharges when the bed elevation remained constant. We created histograms of the mean daily discharges for periods of bed stability and periods of scour to facilitate comparisons.

We also used the discharge records to look for long-term changes in channel width. The distance between right and left edges of water was recorded at the time of each discharge measurement. This measurement represented the top width of the inundated portion of the channel at the given discharge, but did not define the boundaries of the channel. To determine if the width of the channel had changed, we analyzed discharge measurements made between 10% greater than and 25% less than what we earlier had determined to be the bankfull discharge of 105 m^3/s (3700 ft^3/s). Because the location of discharge measurements varied, we limited the analysis to measurements made within a 60 m reach extending upstream from the cable.

Determination of D_{50} Particle Sizes

The D_{50}, or median bed particle size, was determined by performing pebble counts on representative exposed gravel deposits within the study reach. Six pebble counts were performed on three exposed or slightly submerged cobble bars during April

1997. For each pebble count, the intermediate axis of approximately 100 random particles was measured and recorded. Pebble counts were conducted on a straight line which crossed the cobble bar perpendicular to the direction of flow.

Calculation of Average Boundary and Critical Shear Stresses

The stage elevations and discharges necessary to inundate the three distinct geomorphic surfaces identified adjacent to the channel were used to calculate the average boundary shear stress at 12 of the 14 established cross sections. We then compared the average shear stresses applied by these discharges, with the critical shear stress necessary to entrain the D_{50} particle sizes from pebble count locations in the reach. Discharges where boundary shear stresses exceeded the critical shear stress were considered sufficient to mobilize sediment.

We used the Duboys equation to calculate the average shear stresses applied to the boundaries of the channel. Average boundary shear stress is calculated as:

$$t_o = gRS$$

where t_o is the average boundary shear stress in N/m^2, g is the specific weight of water at 10° C (9797 kg/m^2s^2), R is the hydraulic radius of the channel at the indicated stage, and S is the water surface slope at the indicated stage. When channel width is much greater than depth, mean depth is a good approximation of hydraulic radius. All of the cross sections measured in the study reach fit this criteria, and we approximated the hydraulic radius with mean depth, calculated as the cross-sectional area divided by the top-width of the channel. The slope of the water surface at the desired stages was not directly measured because we did not observe high discharges during our field work. We used a reach average slope of 0.0014, which is the average slope of the line connecting surveyed elevations of the high-water marks, and of the flood plain and terrace surfaces.

We used the Shields relation, as discussed by Andrews (1983), to calculate the critical shear stress necessary to entrain the D_{50} or median particle size. Andrews (1983) showed that in a naturally sorted gravel-bedded stream, a range of particle sizes is mobilized at nearly the same discharge. Assuming "equal mobility" of a range of particle sizes allows the use of a "reference" particle in the Shields relation and provides a means to calculate the critical shear stress necessary to entrain a range of bed material sizes. The Shields relation is calculated as:

$$t_{cr} = t^*_{50}\,(g_s - g_w)D_{50}$$

where t_{cr} is the critical shear stress necessary to entrain a particle, in N/m^2, t^*_{50} is the critical dimensionless shear stress, which for most gravel-bedded streams is between 0.033 and 0.086 (Andrews 1983; Buffington and Montgomery 1997), g_s is the specific weight of the particle, which is assumed to be 2650 kg/m^{2}s^2, and g_w is the specific weight of the fluid. Shields (1936) assumed t^*_{50} values of 0.06, and this determination has been widely used (Andrews 1983). However, recent findings by Buffington and Montgomery (1997) concluded that a universal t^*_{50} for gravel-bedded rivers does not exist. In this study we used 0.034 and 0.06 as the values for t^*_{50} for consistency with similar analyses (Smelser 1997; Andrews 1983; and Wilcock et al. 1996). When t_o is greater than or equal to t_{cr}, the discharge is sufficient to entrain the particle.

RESULTS

Flood Frequency Analysis

The magnitude of flooding on the White River has decreased significantly since the mid-1960s (Figure A-7). The average peak flood at the Watson gage between 1923 and 1965 was 4,300 cfs. The average peak flood magnitude between 1965 and the construction of Taylor Draw Dam in 1984 was 3,470 cfs. After the completion of the dam, peak floods have changed little. The average peak flood for the period between completion of dam in 1984 and 1997 was 3,437 cfs. Peak floods from these three time periods were compared using a series of t-tests. Test results (Table A-1) show that at a 95% confidence interval, the average peak flows between 1923 and 1964 are significantly different from peaks both before (1965 and 1983) and after the completion of Taylor Draw Dam (1984 and 1997). The average peak flows for the two time periods since 1965 are not significantly different. Thus, the decreased peak flow magnitudes which have occurred since the mid-1960s were not due to the construction of Taylor Draw Dam because the decrease occurred before the dam was built. Regional climate changes may be responsible for this shift.

Partial-duration series analyses for these same three time periods yields a slightly different perspective about the differences among these periods. The magnitude of high recurrence floods (1.25 - 2 year recurrence interval) has decreased in the post-Taylor Draw Dam period, while the magnitude of larger floods (5 - 10 year recurrence interval) may have increased (Figure A-8) (Table A-2). This may be due to the small storage capacity of Kenney Reservoir, and also to climatic changes during the period after completion of the dam. The small reservoir can store a portion of the inflow of small floods, but cannot control larger magnitude floods.

The distribution of mean monthly discharges has not changed substantially since the completion of Taylor Draw Dam. Hydrographs representing three time periods show that the monthly mean daily discharge has not changed appreciably since the completion of the dam (Figure A-9). Baseflow discharges after the dam (1984 – 1997) are slightly higher than the two decades directly preceding the dam (1965 –1983), but do not differ from the period between 1923 and 1964.

Identification of the Modern Flood Plain and Bankfull Discharge

Bankfull discharge is defined as the discharge at which the active flood plain begins to be inundated. In the detailed study site, the lowest elevation depositional surface that is longitudinally correlative begins to be inundated at a discharge of approximately 3,700 cfs, which has a recurrence of 1.7 years on the long-term annual series (Figure A-10) and about three years for the partial duration series for the period between in 1984 and 1997. This surface is characterized as a flat low-elevation surface comprised of predominantly fine-grained alluvium that overlies cobbles and gravels. The surface has been colonized by young vegetation such as horsetail grasses, and young tamarisk. This surface lacks mature woody vegetation such as large tamarisk or Russian olive (Figure A-11).

At least two other distinct flood plain-like surfaces exist adjacent to the White River within the detailed study site (Figure A-12). Figure A-13 shows the longitudinal profile of these surfaces, surveys of actual river conditions of known discharges, and thalweg elevations. The highest elevation surface identified in this study is a terrace approximately 1 m above the active flood plain. It is inundated at discharges of approximately 6,700 cfs, or the 12 year recurrence flood. The deposit is composed of fine-grained alluvium, and is overgrown by thick, mature stands of Russian olive, tamarisk and willow, with a cottonwood gallery forest. Some vegetation show signs of being buried in alluvium. These are characteristics similar to the cottonwood terrace identified elsewhere in the Green River Basin (Allred 1997, Grams 1997, Orchard and Schmidt 1998). The cottonwood terrace was abandoned in the Green River system in the late 1920s during a regional drought which caused a significant decrease in annual peak flood magnitudes (Orchard and Schmidt 1998). Discharge records do not exist for the White River during the period between 1906 and 1922, and it is unclear if the same decrease in flood magnitudes that occurred in the Green River system also occurred in the White River basin. However, because of similarity of the cottonwood terrace in the Green River system and the terrace described here in the White River basin, we hypothesize that the two surfaces are equivalent, and were abandoned around the same time in the late 1920s or early 1930s. This terrace was probably last inundated in 1965.

We termed the intermediate surface as the low terrace. The low terrace is just above the elevation of the active flood plain and is lower in elevation than the cottonwood terrace. This surface begins to be inundated at approximately 5,700 cfs, or by the seven year recurrence flood. We believe that the abandonment of this surface coincided with the significant decrease in flood magnitudes which occurred in the mid-1960s in the White River Basin. Unlike the active flood plain, the low terrace contains mature woody riparian species such as tamarisk, Russian olive and willow (Figure A-14). This terrace is underlain by horizontally bedded, fine-grained alluvium well stabilized by thick, abundant riparian vegetation. This surface typically terminates abruptly at a 0.5 m high scarp, which drops to the lower flood plain. Natural levees may also be present.

Average Boundary And Critical Shear Stress:

Average boundary shear stress in the detailed study site was calculated for discharges of 3,700 and 5,700 cfs, which are the discharges which just inundate the flood plain and low terrace, respectively, at twelve of the measured cross-sections. At 3,700 cfs, the average shear stress exerted on the bed ranges from 5.5 to 21.6 N/m^2 (Table A=3) At 160 m^3/s (5700 ft^3/s), average boundary shear stresses range from 13.1 to 27.3 N/m^2. For these high discharges, we assumed that the slope of the water's surface was 0.0014 at each cross section. Thus, mean depth (i.e., hydraulic radius, R) is the only variable that is different in the calculations, and shear stresses are highest where mean depth was greatest.

The critical shear stress necessary to entrain the median particle size was calculated for the six pebble counts made at three gravel bars in the channel within the study reach (Table A-4). Median particle size (D_{50}) ranged from 20 to 90 mm. Particle sizes were coarsest in a small riffle located at the extreme downstream end of the reach, and were finest near the center of the reach (Figure A-15) Average boundary shear stress generated by the bankfull discharge of 3,700 cfs was sufficient to mobilize sediment similar to the sizes of particles found on three of the six representative pebble count locations in the study site when assuming $t^*_{50} = 0.034$ (Figure A-16). The mobilized sites are located on a cobble bar in the riffle near cross sections 5 and 6, and had D_{50} values of 20, 24, and 32 mm. The location with the D_{50} of 32 mm was predicted to mobilize at discharges equal to bankfull, while the two sites with finer D_{50} would mobilize near 1,000 cfs, which is 27% of bankfull. The other three sites, which have D_{50} values of 66, 81, and 90 mm, were not predicted to be mobilized at a discharge of 5,700 cfs. When assuming $t^*_{50} = 0.060$, only one gravel bar was predicted to move at bankfull discharge. At 5,700 cfs only 2 of the 6 bars were predicted to mobilize.

Analysis of Sediment Records-Effective Discharge

Sediment transport on the White River was measured between 1975 and 1990. The strong correlation ($r^2 = 0.77$) of this relationship (Figure A-17) describes the increased ability of the river to transport sediment at increasingly higher discharges. We extrapolated this sediment transport rating relation to the entire available discharge record and found that the majority of sediment transported by the White River is carried by two different ranges of discharges; very low discharges of between 400 and 600 cfs, and moderate discharges around 2,100 cfs (Figure A-18). Discharges between 400 and 600 cfs are extremely common and were equaled or exceeded 30% of all days during the 77 years of record (Figure A-19). These low, frequent discharges create the first prominent peak in the sediment transport curve and carried 8% of the total sediment transported.

A second peak in the sediment transport curve occurs at about 2,100 cfs. At this discharge, 6.9×10^6 kg/day of sediment are transported past the Watson gage. This peak is less pronounced than the first peak, and sediment transport is high across a broad range of discharges somewhat more and less than 2,100 cfs, between 1,700 and 2,900 cfs). Discharges in this range carried 45% of the total sediment load during the period of record.

Analysis of Sediment Records-Evidence of Supply Limitation

Analysis of the sediment transport records, for 1988 and 1990 show that sediment transport is higher on the rising limb of each annual flood than on the receding limb (Figure A-20). For example, the spring runoff of 1988 peaked in late April, receded, then peaked again in mid-June. The initial peak in April carried more than four times the sediment as the peak of similar magnitude in June. Thus, the White River at the Watson gage is a supply-limited stream that could transport more sediment than it does, but these additional supplies are not available.

Analysis of Discharge Measurement Records

The analysis of discharge measurement records (Figure A-21) at the Watson gage shows that discharges on the White River follow an annual cycle of flooding and recession, with peak discharges arriving in early to late spring (Figure A-22). The bed near the gage responds to the seasonal flooding by scouring, or increasing the thalweg depth as each years flood rises (Figure A-23). Although significant scour or fill occurs during a wide range of discharges, all discharges greater than 1770 cfs scour the bed.

Bed elevation data were recorded on average twice each month between 1968 and 1979, and between 1985 and 1997. These measurements occurred relatively infrequently in relationship to changes in discharge. Accordingly, the precise discharges at which scour occurs could not be directly extracted from the discharge records. Therefore, we compared the largest discharges during periods when the bed changed less than 0.25 m with the largest discharges during periods when the bed scoured and filled more than 0.25 m. Results of a two-tailed t-test show that, with 95% certainty, the mean maximum discharge during periods of scour was larger than the mean maximum discharge during periods of bed stability (Table A-5). The highest discharge during a period of bed stability was 1,460 cfs, but in some cases the bed scoured at lower discharges. The lowest peak discharge during a scour event was 1,290 cfs. All discharges above 41 m^3/s caused scour. Figure A-24 shows the distribution from which these means were calculated. Discharge values during periods of bed stability are normally distributed. Discharges during periods of scour were skewed and bi-modal. Because we did not know which exact date scour began, some discharges which were not sufficient to move the bed were unavoidably included in the period of scour. The first mode probably represents these discharges. The second mode more accurately represents the discharges responsible for scouring the bed. The most common discharges in the second mode occur between 1,590 and 2650 cfs. Discharges during periods where the bed elevation did not change were most commonly between 400 to 500 cfs. The degree of scour in the thalweg varied by year and could be as much as 1 meter.

Discharge records also show that the width of the channel near the Watson gage has widened slightly since the late 1960s (Figure A-25). Adjustments in channel are likely a response to the large floods of 1983-84, which were the highest since the mid-1960s. The increases in channel widths took place between 1979 and 1985, and coincide with these flood events. No width data are available for dates earlier than 1968, when flood magnitudes typically were higher than during the period after 1968.

Cross Sectional Resurveys

Bed material at established cross sections is predominantly sand and gravel, but ranges in size from silt and clay to small, angular boulders. Banks and flood plain surfaces were predominantly comprised of fine-grained alluvium, while the bed was almost entirely comprised of coarse material. Changes in channel geometry that occurred between 1995 and 1997 were determined by resurveys of the cross sections. As expected, scour and fill is greatest where the bed material is finest, but bed elevation changes occurred over gravel and cobble beds as well. Channel cross sections with predominantly sand beds had the greatest change in bed elevation (Figure A-26) . Evidence of bedforms was detected at 1800 cfs at several crosssections, and is indicated by hummocky, uneven traces which did not exist at base-flow (Figure A-27). Slight aggradation of the bed in the cross sections with the coarsest substrate was evident at the higher discharge, which may indicate finer bedload moving over the top of less mobile coarse material (Figure A-28). Aggradation in the coarse bedded riffles occurred when adjacent pools scoured.

DISCUSSION

Channel Forming Flows

Several lines of evidence indicate that a high-flow component of an instream flow should preserve most of the natural flow regime greater than approximately 1,400 cfs. Flows of this magnitude are capable of scouring the bed near the cableway, because during our study the bed was never stable when the highest of two discharge measurements was more than about 1,400 cfs. Also, the bed never scoured when the highest of two discharge measurements was less than 1,300 cfs. Thus, flows greater than about 1,400 cfs are capable of transporting fine bed sediment. We inferred that bedload movement occurred at 1,800 cfs, because bedforms were detected at this discharge on fathometer traces at those cross sections with fine-grained bed material.

The White River is a supply-limited stream, because much more suspended sediment is carried on the rising limb of the annual snowmelt hydrograph than on the falling limb. Thus, some low flows might not be necessary to maintain an equilibrium sediment mass balance wherein the entire load delivered to the stream is transported downstream. A rule of thumb used in the federal reservation of in-stream flows for the purpose of channel maintenance in Idaho has been to claim all flows greater than the discharge above which 70% of the long-term annual load is transported. In the case of the White River near Watson, that flow is about 1,400 cfs. We assume that sediment normally transported by lower discharges could be transported by flows greater than1,400 cfs because of the supply-limited characteristic of the stream.

Flows higher than 1,400 cfs are capable of entraining gravel exposed on bars in the study reach, as estimated by Shield's relation. Entrainment occurs at many bars near bankfull discharge of about 3,700 cfs, which has a recurrence interval of about three years on the partial duration series for the period following completion of Taylor Draw Dam (1984 – 1997). In this case, bankfull discharge is much greater than the effective discharge for suspended load, which we estimate to between 1,700 and 2,900 cfs).

Our study plan precluded determination of the effective discharge for bedload, but this value is likely to be larger than that calculated for suspended load. The high volume of suspended load, however, and the larger proportion of the bed covered by fine sediment suggests that a habitat-maintenance flow claim be based on ensuring that all suspendable sediment be transported through the study reach.

The White River undergoes an annual cycle of scour and fill which can change the elevation of the bed by as much as 1 meter. The range of scour and fill defines the active layer of the bed which can mobilized during flooding. These flows thus have the ability to reshape instream habitats. The changes in bed elevation during the spring flood suggest that much of the sediment transported in the White River is moved as a pulse of mobilized bedload material.

While the bed scours at higher discharges in most of the measured cross-sections, aggradation of the bed occurs near the coarsest cobble bars. Aggradation of the bed in these regions could represent finer material moving over the more stable coarse material, and suggests the occurrence of selective transport. Lisle (1995) found that transport of finer bed material occurred at discharges below bankfull stage in several of the coarse-bedded rivers he studied. The channel of the White River within the study reach is made of both fine-grained and gravel deposits. While some of our evidence suggests that a threshold of equal mobility is reached near 1,460 cfs, it is more likely that selective transport of the finer deposits occurs at this discharge. Both the aggradation of the bed at higher discharges in very coarse-bedded areas of the stream, and a peak in the sediment transport curve at 500 cfs, suggests that finer sediments are being transported selectively at low discharges.

Flood magnitudes decreased significantly in the mid-1960s and have remained, on average, lower than during the earlier portion of the 20th century. While mean daily discharge values are available for most of the 20th century, the actual notes made by technicians conducting discharge measurements at the Watson gage only exist for dates between 1968 and present. These notes provide information on channel width and depth used for the analysis in this study. Thus, the analysis we conducted using these data only represent conditions during the past two or three decades where peak floods have been significantly lower than during than during the first half of the century.

CONCLUSIONS

1. Effective discharge, the discharge where the river accomplishes the most geomorphic work, occurs at discharges lower than bankfull. Discharges responsible for maintaining the form of the channel occur between 1,700 and 2,900 cfs.
2. The bed in the study reach undergoes an annual cycle of scour and fill. The depth of scour represents an active layer of sediment which is approximately 1 meter in depth near the Watson gaging station. This layer becomes mobile at discharges at least as low as1,450 cfs. Sediment transport at these low discharges is likely predominantly comprised of finer-grained sediments. Discharges greater than bankfull are required to mobilize gravel deposits with D_{50} diameters greater than 40 mm.
3. Sediment transport is higher during the rising limb of the annual spring flood than on the receding limb, suggesting that this reach of the White River system is supply-limited.
4. The channel was widened by the high flows of 1983 and 1984

REFERENCES

Allred, T. M.. 1997. Channel narrowing of the Green River near Green River, Utah: History, rates, and processes of narrowing. Masters Thesis, Utah State University, Logan.

Andrews, E. D. 1980. Effective and bankfull discharges of streams in the Yampa River basin, Colorado and Wyoming. Journal of Hydrology 46: 311-330.

Andrews, E. D. 1983. Entrainment of gravel from naturally sorted riverbed material: Geological Society of America Bulletin 94: 1225-1231.

Andrews, E. D., and J. N. Nankervis. 1995. Effective discharge and the design of channel maintenance flows for gravel-bed rivers Pages 151-164, *in* J. E. Costa, A. J. Miller, K. W. Potter, and P. R. Wilcock, editors. Natural and anthropogenic influences in fluvial geomorphology, Geophys. Monogr. Ser, Washington, D. C.

Buffington, J. M., and D. R. Montgomery. 1997. A systematic analysis of eight decades of incipient motion studies, with special reference to gravel-bedded rivers. Water Resources Research 33.

Chart, T. E. 1987. The initial effect of impoundment on the fish community of the White River, Colorado. Masters Thesis, Colorado State University, Fort Collins.

Grams, P. E. 1997. Geomorphology of the Green River in Dinosaur National Monument. Masters Thesis, Utah State University, Logan.

Hesse, L. W., and W. Sheets. 1993. The Missouri River hydro system. Fisheries 18: 5-13.

Hill, M. T., Platts, W. S., and Beschta, R. L. 1991. Ecological and geomorphological concepts for instream and out-of-channel flow requirements. Rivers 2:198-210.

Jackson, W. L., and R. L. Beschta. 1992. Instream flows for rivers: maintaining stream form and function as a basis for protecting dependent uses. Pages 524-535, *in* Jones, M. E., and A. Laenen, editors. Interdisciplinary approaches in hydrology and hydrogeology, American Institute of Hydrology.

Jurado, A., and F. K. Fields. 1978. Channel migration of the White River in the eastern Unita Basin, Utah and Colorado: U.S. Geological Survey Miscellaneous Investigations Map I-1087, scale 1:48,000.

Kondolf, G. M., G. F. Cada, and M. J. Sale. 1987. Assessing flushing-flow requirments for brown trout spawning gravels in steep streams. Water Resources Bulletin 23: 927-935.

Kondolf, G. M., and P. R. Wilcock. 1996. The flushing flow problem: defining and evaluating objectives. Water Resources Research 32: 2589-2599.

Lentsch, L.D., L.M. Lubomudrov, and B.G. Hoskins. 2000. The White River and endangered fish recovery: a hydrological, physical and biological synopsis. Final Report submitted to theUpper Colorado River Endangered Fish Recovery Program, Denver, Colorado, Project No. 21.

Lindskov, K. L., and B. A. Kimball. 1984. Water resources and potential hydrologic effects of oil-shale development in the southeastern Unita Basin, Utah and Colorado. Professional Paper 1307, U.S. Geological Survey.

Lisle, T. E. 1995. Particle size variations between bed load and bed material in natural gravel bed channels: Water Resources Research 31:1107-1118.

Miller, W. H., D. L. Archer, H. M. Tyus, and K. C. Harper. 1982, White River fishes study. Final Report. Colorado River Fishery Project, Fish and Wildlife Service Salt Lake City, Utah

Orchard, K. L., and J. C. Schmidt. 1998. A geomorphic assessment of the availability of potential humpback chub habitat in the Green River in Desolation and Gray Canyons, Utah. Final Report submitted to the Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado.

Petts, G. E., and I. Maddock. 1996. Flow allocation for in-river needs. Pages 60-79 *in* G. E. Petts, and P. Calow, editors. River restoration. Blackwell Science Ltd.

Pitlick, J., and M. M. Van Steeter. 1998. Geomorphology and endangered fish habitats of the upper Colorado River, 2; Linking sediment transport to habitat maintenance. Water Resources Research 34: 303-316.

Reiser, D. W., M. P. Ramey, and T. A. Wesche. 1989. Flushing flows. Pages 91-135 *in* J. A. Gore, and G. E. Petts, editors. Alternatives in regulated river management. CRC Press, Boca Raton.

Schmidt, J. C., and D. M. Rubin. 1995. Regulated streamflow, fine-grained deposits, and effective discharge in canyons with abundant debris fans. Page 77-195, *in* J. E. Costa, A. J. Miller, K. W. Potter, and P. R. Wilcock, editors. Natural and anthropogenic influences in fluvial geomorphology, American Geophysical Union.

Seiler, R. L., and J. E. Tooley. 1982. Erosion and sediment characteristics of the southeastern Unita Basin, Utah and Colorado. Water-Resources Investigations 82-428, U.S. Geological Survey.

Shields, A. 1936. Application of similarity principles and turbulence research to bed-load movement. Mitt. Preuss. Verschsanst., Berlin, Wasserbau Schiffbau, Report 167, in Ott, W. P. a. U., J. C. (translators), ed., Pasadena, California, California Institute of Technology.

Smelser, M. G. 1997. Geomorphic adjustability of streams draining the Unita Mountains of Utah. Masters Thesis, Utah State University, Logan, Utah.

U.S.Fish and Wildlife Service. 1987. Recovery implementation program for endangered fish species in the Upper Colorado River Basin, Denver, Colorado, U.S. Fish and Wildlife Service.

Van Steeter, M. M., and J. Pitlick. 1998. Geomorphology and endangered fish habitats of the upper Colorado River, 1, Historic changes in streamflow, sediment load, and channel morphology. Water Resources Research 34: 287-303.

Wilcock, P. R., A. F. Barta, C. C. Shea, G. M. Kondolf, W. V. G. Matthews,, and J. Pitlick. 1996. Observations of flow and sediment entrainment on a large gravel-bed river. Water Resources Research 32: 2897-2909.

Wolman, M. G., and J. C. Miller. 1960. Magnitude and frequency of forces in geomorphic processes. Journal of Geology 68: 54-74.

Table A-1. Three t-tests comparing peak discharge from different time periods. There is a significant difference between the 2 sample means if the absolute value of the t-statistic is greater than the t-critical value. These tests show that the peak floods from the early part of the century are statistically different from the two later time periods. Peak floods for the decades directly before (1965-1983) and after Taylor Draw Dam (1984-1997) are not significantly different.

Time periods	1923-1965	1965-1983	1923-1965	1984-1996	1965-1983	1984-1996
Mean Peak Discharge (cfs)	4344	3461	4344	3426	3461	3426
Variance (10^6)	2.231	0.989	2.206	1.872	0.919	1.872
Observations	59	27	59	17	27	17
Pooled Variance (10^6)	1.806		2.134		1.280	
Hypothesized Mean Difference	0		0		0	
df	84		74		42	
t Stat	2.83		2.30		0.12	
P(T<=) two-tail	0.006		0.024		0.903	
t Critical two_tail	1.99		1.99		2.02	
Difference between periods	significant diff		significant diff		significant diff	

Table A-2. Discharge (cfs) of specific return periods for 3 time periods.

		Recurrence interval (years)			
	Time period	1.25	2	5	10
Partial-duration	1923-1964	3108	4061	5368	6251
	1965-1983	2684	3602	4520	4979
	1984-1996	2260	3249	4520	5333
Annual series	1923-1997	2190	3849	5297	6180

Table A-3. Average boundary shear stress (Neutons/m^2) at 2 discharges at cross-sections.

	Average boundary shear stress (Neutons/m^2)											
Cross-sections	XS2a	XS2	XS3	XS4	XS5	XS6	XS7	XS8	XS9	cable	XS10	XS11
Distance from an arbitrary datum (m)	830	1000	1058	1121	1188	1236	1297	1346	1398	1481	1545	1595
Discharge which inundates the:												
Floodplain (3708 cfs)	5.54	16.98	16.27	17.96	17.31	20.45	17.97	19.96	20.40	21.62	20.46	19.31
Low Terrace (5650 cfs)	13.11	21.38	17.54	17.37	22.28	22.39	23.79	25.53	26.33	27.26	26.42	24.56

Table A-4. Critical shear stress (Neutons/m^2) at cross-sections.

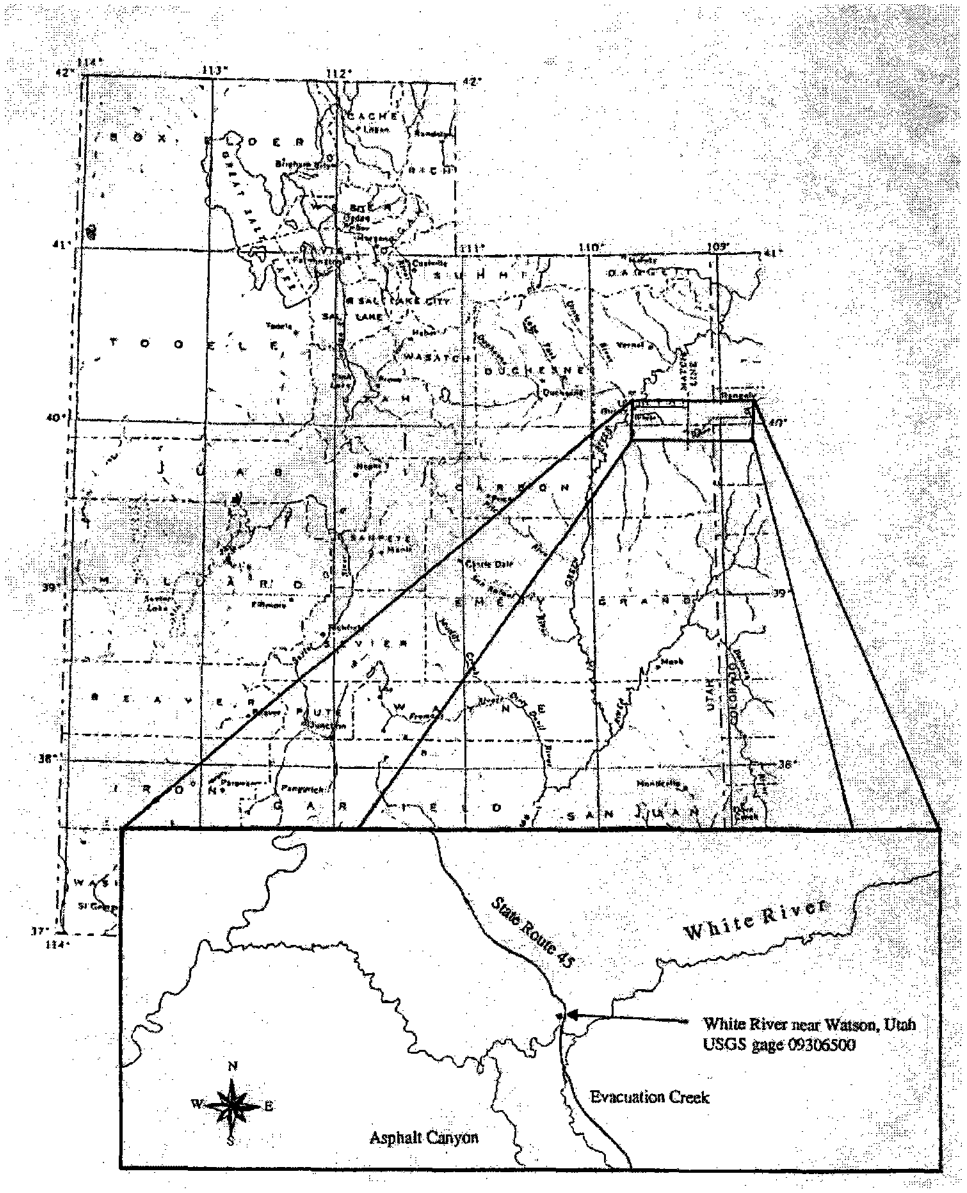
	Cross-section (Distance from an arbitrary datum)					
	840	1195	1212	1230	1580	1595
D_{50}[1]	0.07	0.03	0.02	0.02	0.09	0.08
$\tau_{cr\,0.034}$[2]	36.3	17.6	13.2	11.0	49.5	44.5
$\tau_{cr\,0.060}$[3]	64.0	31.1	23.3	19.4	87.3	78.6

[1] Median particle size (mm)
[2] Critical shear stress calculated when τ^*_{50} value assumed to be 0.034 (see text).
[3] Critical shear stress calculated when τ^*_{50} value assumed to be 0.060 (see text).

Table A-5. T-test comparing maximum discharge during periods of scour and periods of no scour. There is a significant difference between the two sample means if the absolute value of the t-statistic is greater than the t-critical value. In this case a significant difference between the two groups exists.

	No scour	Scour
Mean maximum discharge during period (cfs)	883	2648
Variance (10^4)	6.61	110
Observations	14	22
Pooled variance (10^5)	7.10	
Hypothesized mean difference	0	
df	34	
t stat	-6.16	
P(T<=t) two-tail	0.000	
t Critical two-tail	2.03	

Figure A-1. Map showing the study area.



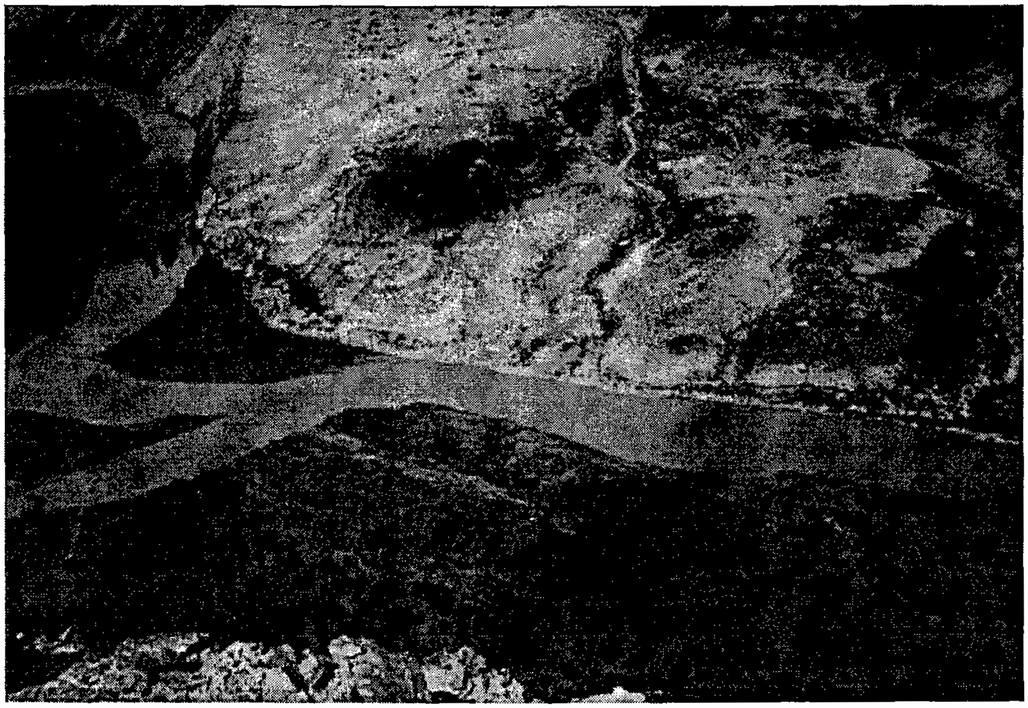


Figure A-2. Photograph showing the White River immediately upstream from the study reach. Parallel bands of vegetation on the point bar in the center of the photo are evidence of channel migration.

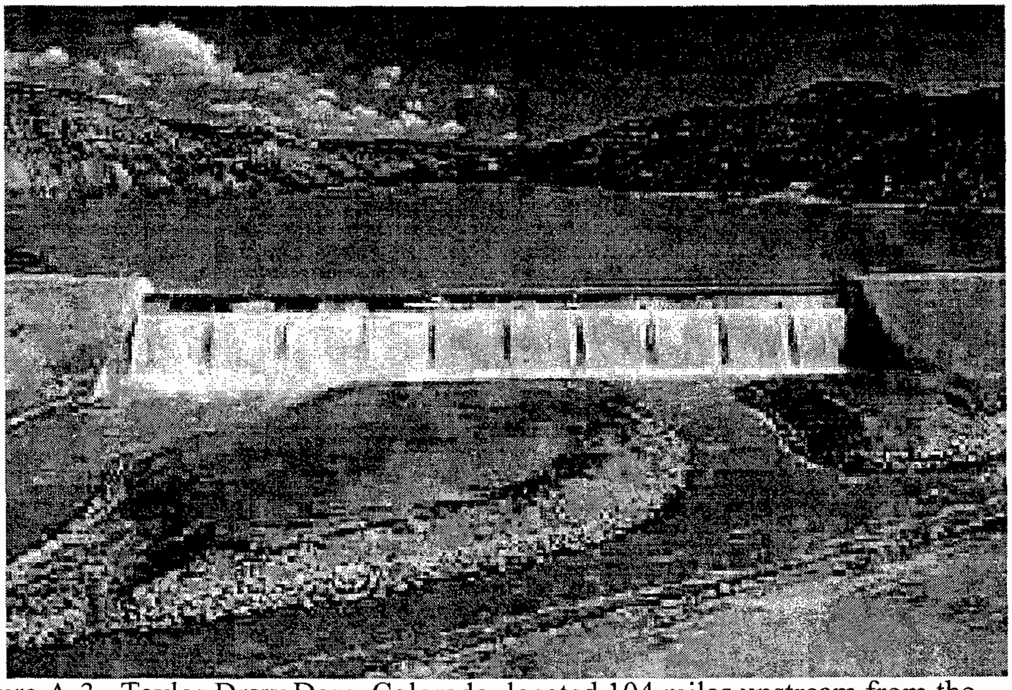


Figure A-3. Taylor Draw Dam, Colorado, located 104 miles upstream from the confluence with the Green River.. The dam was completed in 1984 and has a storage capacity of 1.7 x10^7 cubic meters (13, 800 acre-feet). It is used primarily for recreation and supplies little to no water for irrigation. The storage capacity is less than 3% of the total volume of annual streamflow.

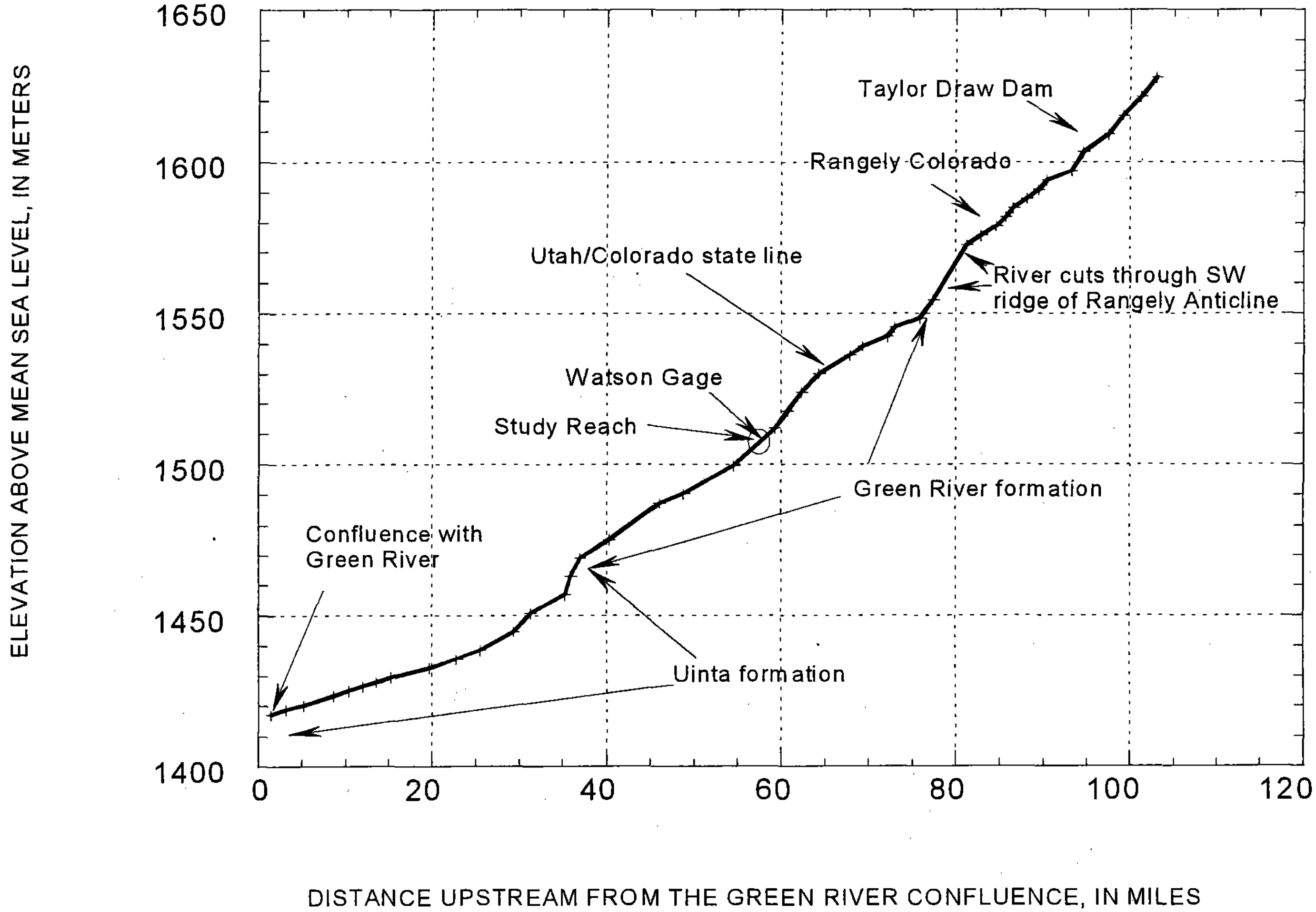


Figure A-4. Longitudinal profile of the White River.

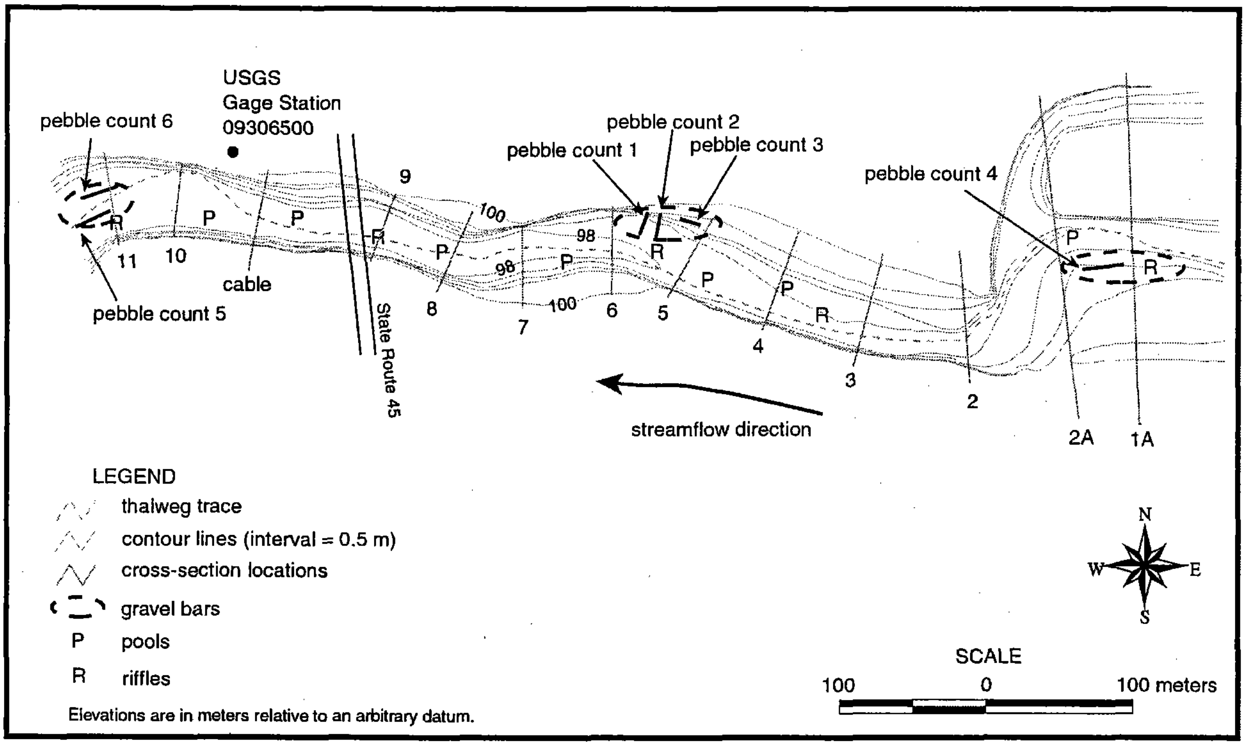


Figure A-5. Map showing the study site.

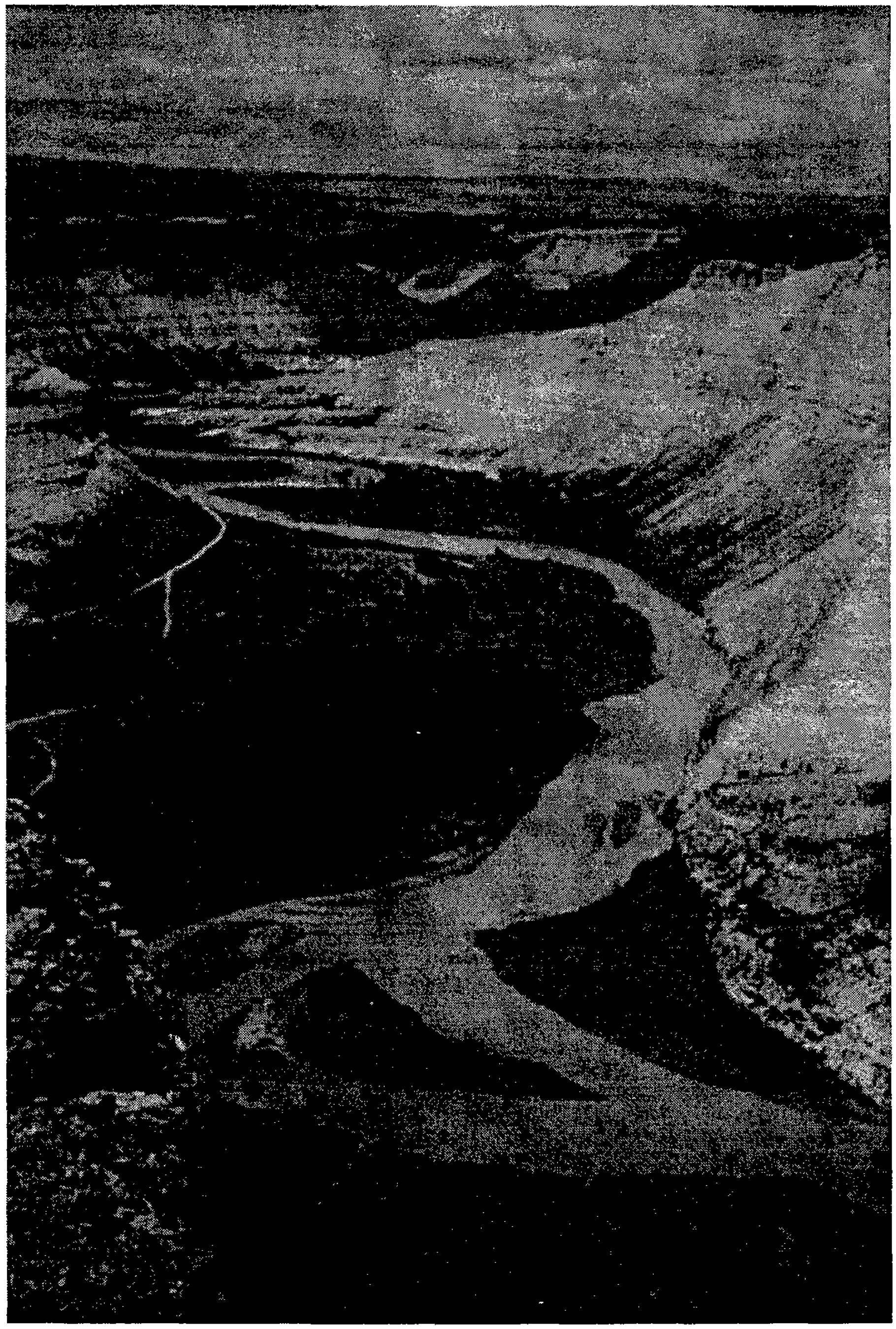


Figure A-6. Photograph showing a typical reach of the White River. This reach is immediately upstream from the detailed study site. The view is upstream and shows the channel meandering across a broad alluvial valley confined by shallow canyon walls.

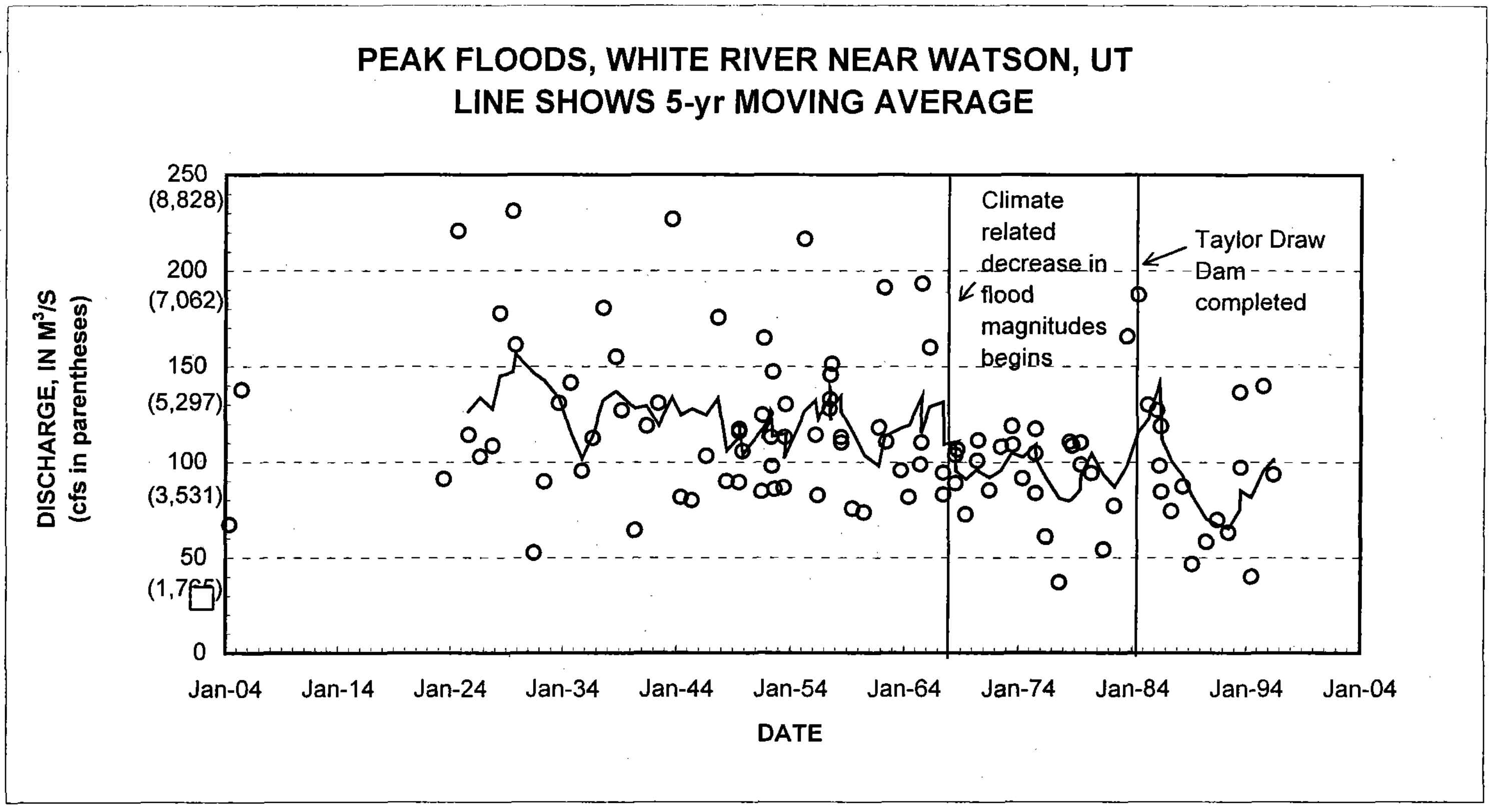


Figure A-7. Graph showing all peak floods above 990 cfs on the White River at station 09306500. The solid line is a 5-point moving average and shows an overall decrease in the average peak flood over the entire time period. A climate related decrease in flood magnitudes occured in the mid-1960s and lasted until the floods of the mid-1980s.

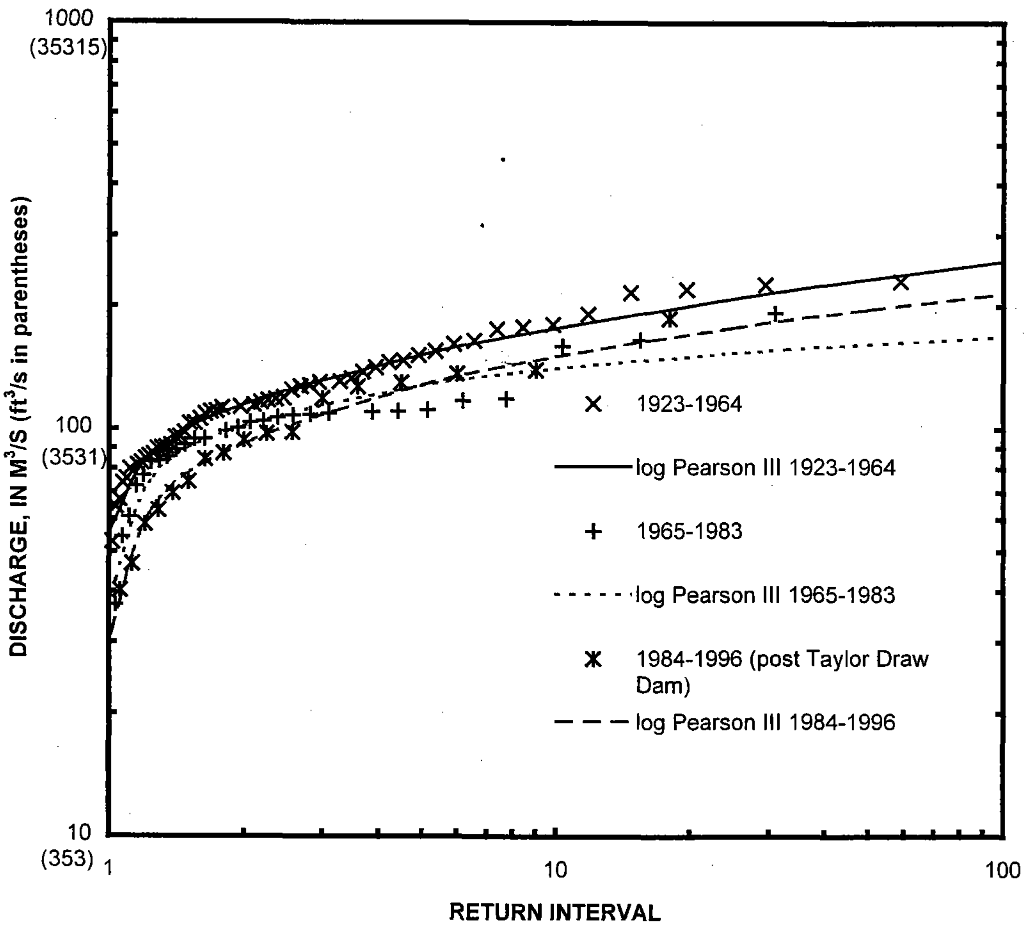


Figure A-8. Return intervals for three time periods based on partial-duration series using all floods greater than 990 cfs. Plotting positions for best-fit lines were based on a log Pearson type III calculation. The magnitude of floods with return intervals less than 3 yrs is lower for the period following the completion of Taylor Draw Dam than the two decades preceding the dam, while the magnitude of the 5 - 10 yr floods has increased.

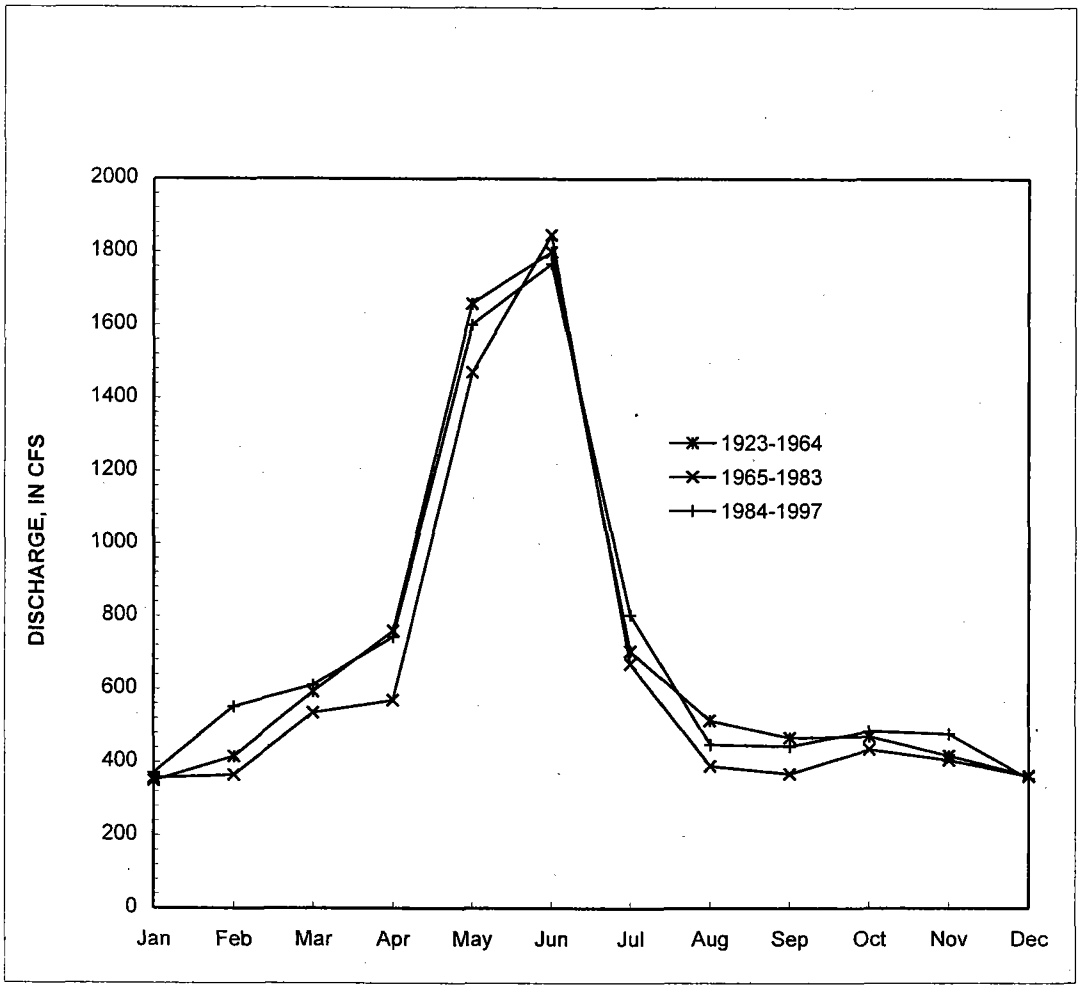


Figure A-9. Hydrographs representing the average mean daily discharge for the indicated month. Baseflow discharges are lowest during the drought period between 1965 and 1983. Baseflow discharges after the completion of Taylor Draw Dam in 1984 are higher than in the preceding 2 decades, but not substantially different from the 1923 to 1964 time period.

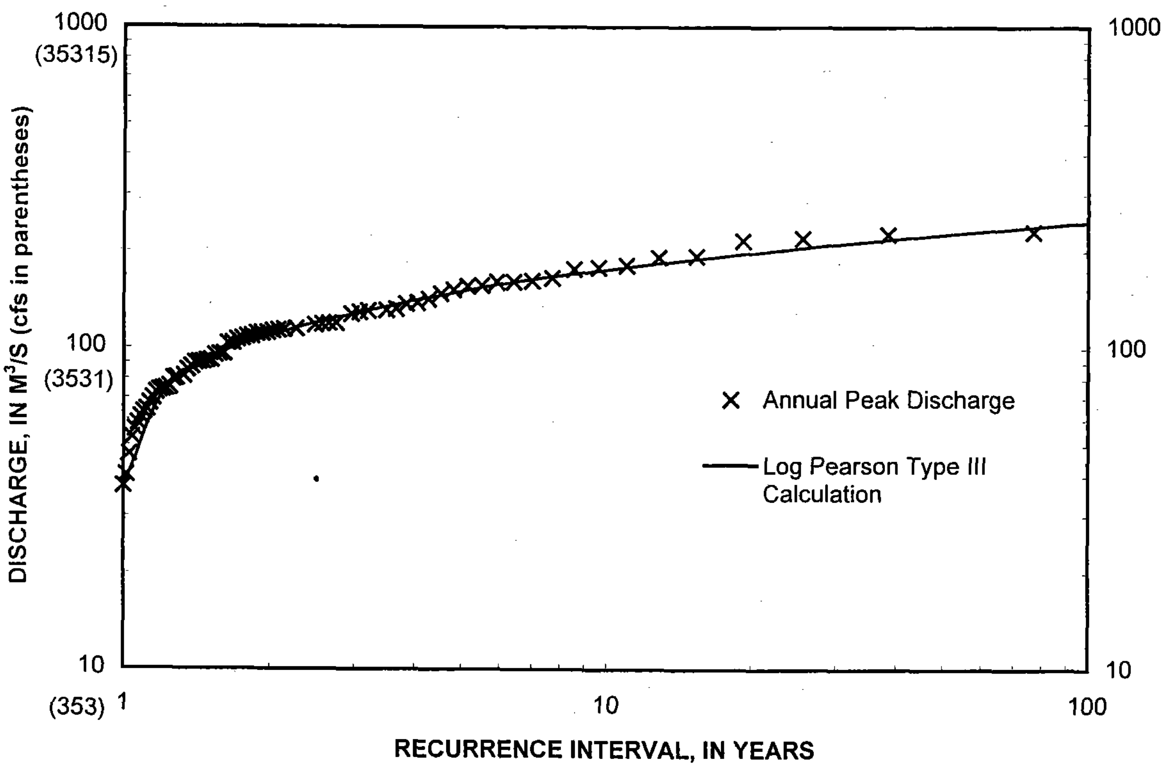


Figure A-10. Flood recurrence intervals for station 09306500, White River near Watson, UT 1904-5, 1923-53, 1955-1997. Recurrence intervals are calculated using a Log Pearson Type III regression fit to 77 years of annual peak flood data.

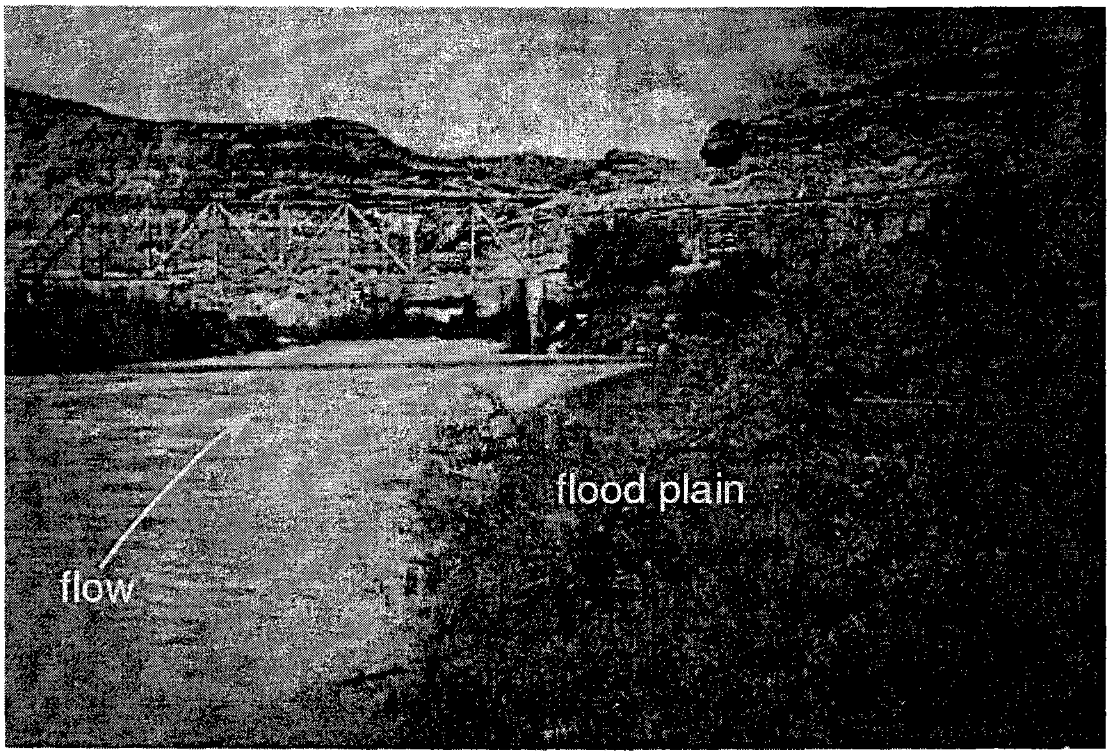


Figure A-11. Photograph showing the White River and its floodplain. The floodplain is inundated at about 3,700 cfs and is vegetated with grasses and seedling tamarisk. The thicker vegetation at the right of the photograph is predominately Russian olive and is growing on the slightly high "low terrace".

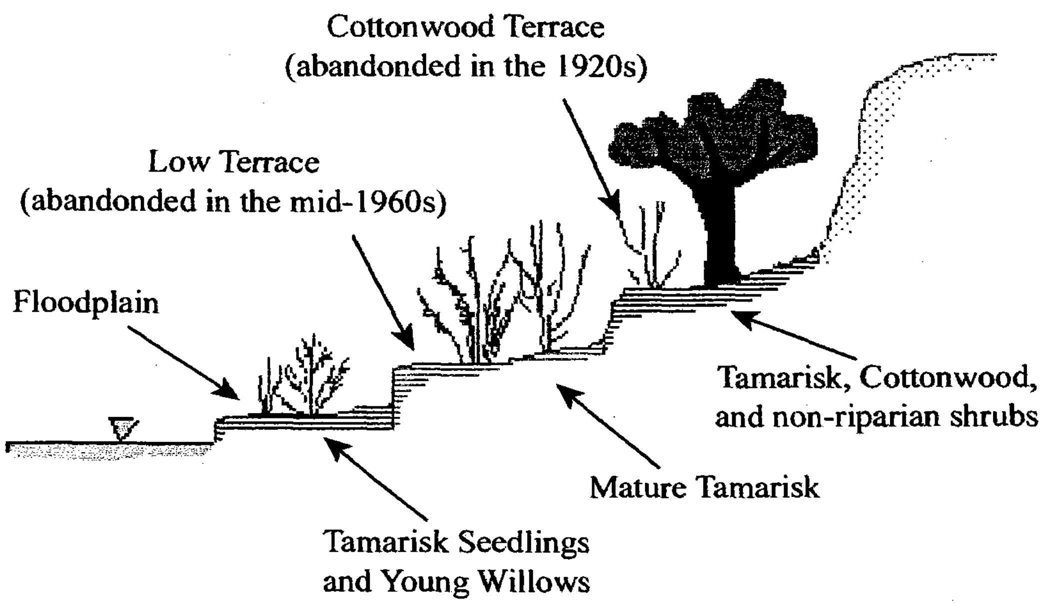


Figure A-12. Diagram showing a typical cross section of the White River alluvial valley. The floodplain is vegetated by tamarisk seedlings and sparse willows and is inundated at approximately 3,700 cfs. The low terrace is just inundated by floods of 5,700 cfs and is densely vegetated with mature tamarisk. The low terrace was likely abandoned during the mid-1960's due to a decrease in peak floods. The cottonwood terrace is characterized by mature cottonwood trees and abundant non-riparian shrubs such as sagebrush. It was likely abandoned in the late 1920's.

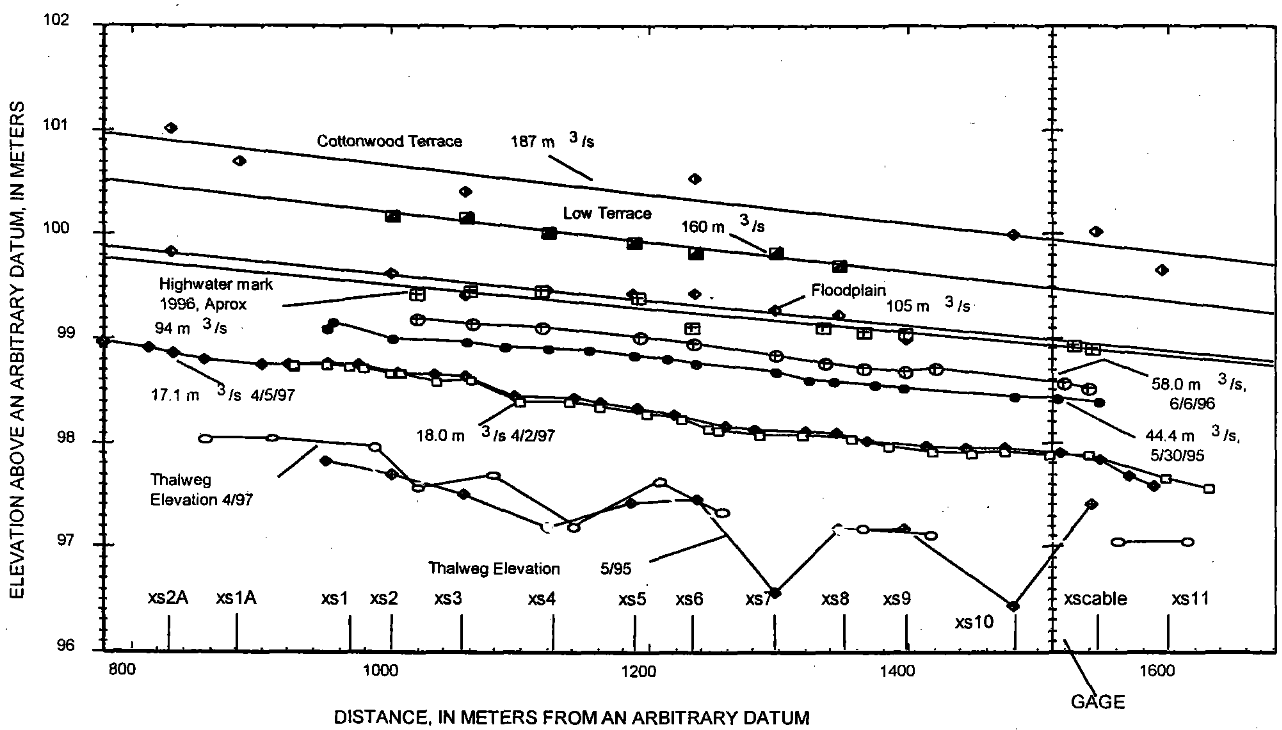


Figure A-13. Graph showing longitudinal profile of flood plain-like surfaces, surveys of acutal river conditions of known discharges, and thalweg elevations.

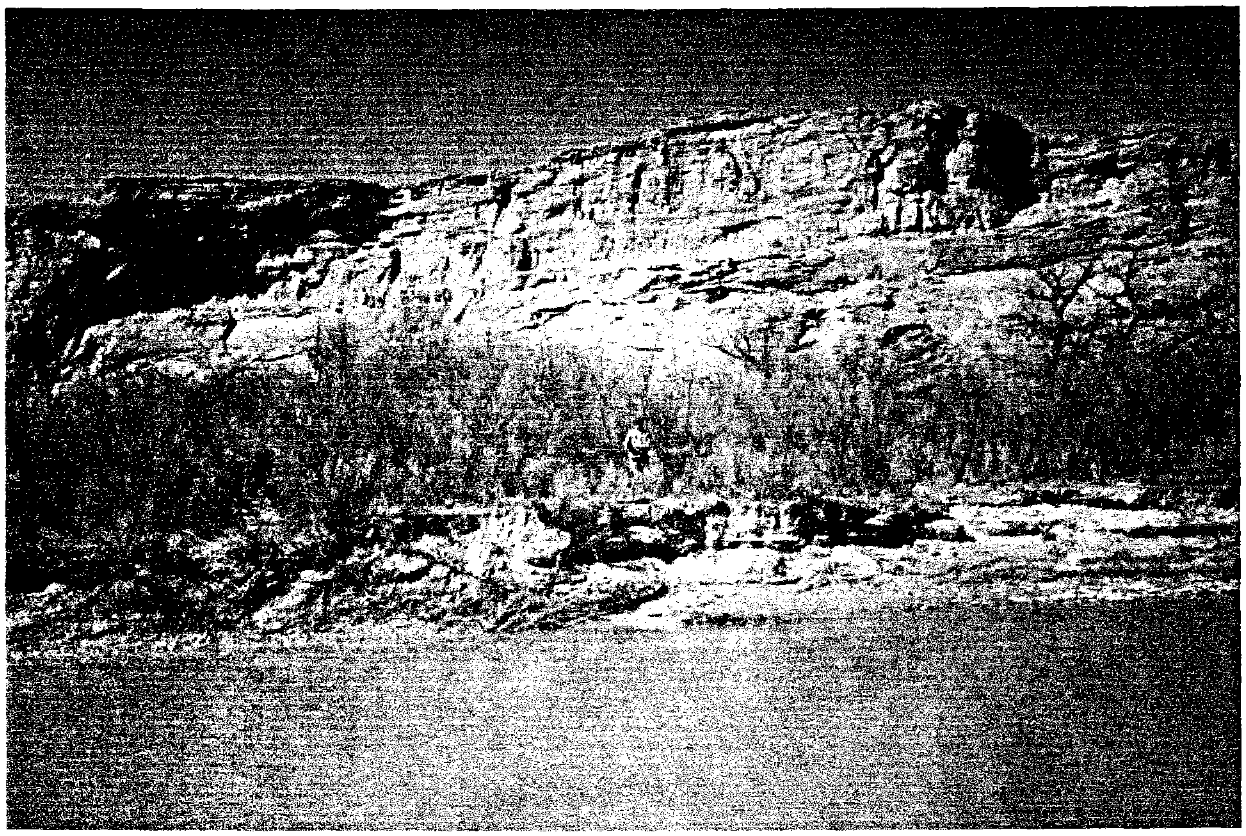


Figure A-14. Photograph showing person standing on the low terrace surface. This surface is inundated by discharges of approximately 5,700 cfs and is vegetated by mature saltcedar and Russian olive.

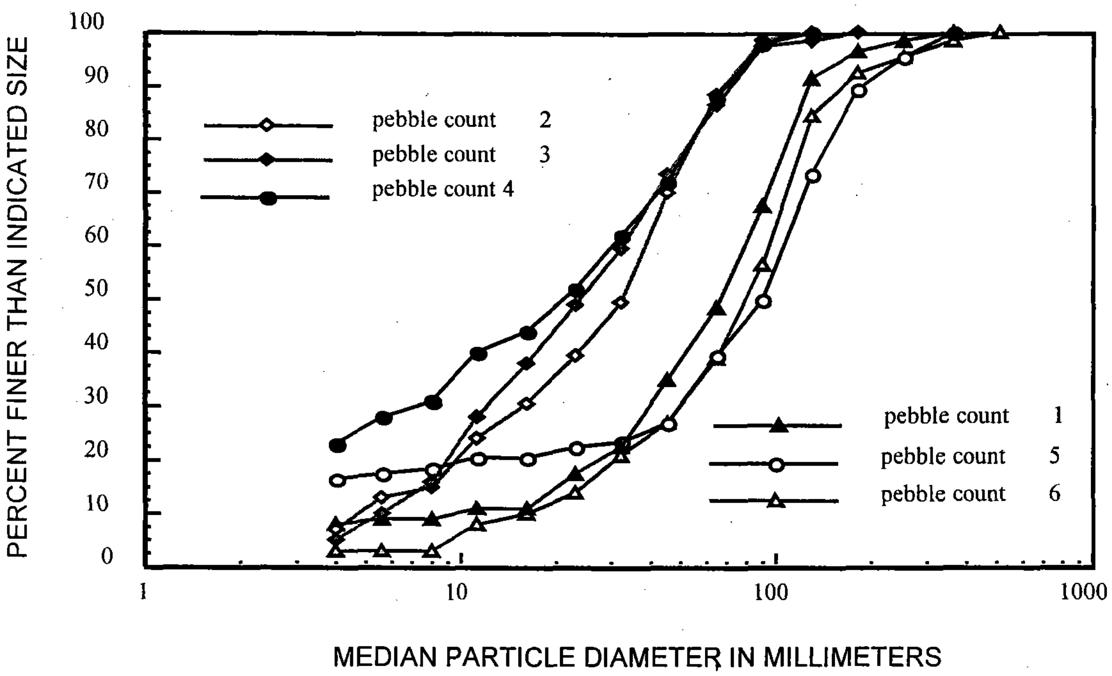


Figure A-15 . Graph showing particle size distribution from representative cobble bars in the study reach. Stress analysis predicted that gravelat pebble count locations 2, 3, and 4 would be transported by the backfull flood. Locations 1, 5, and 6 are near riffles. Location 2, 3, and 4 are bars adjacent to pools and runs.

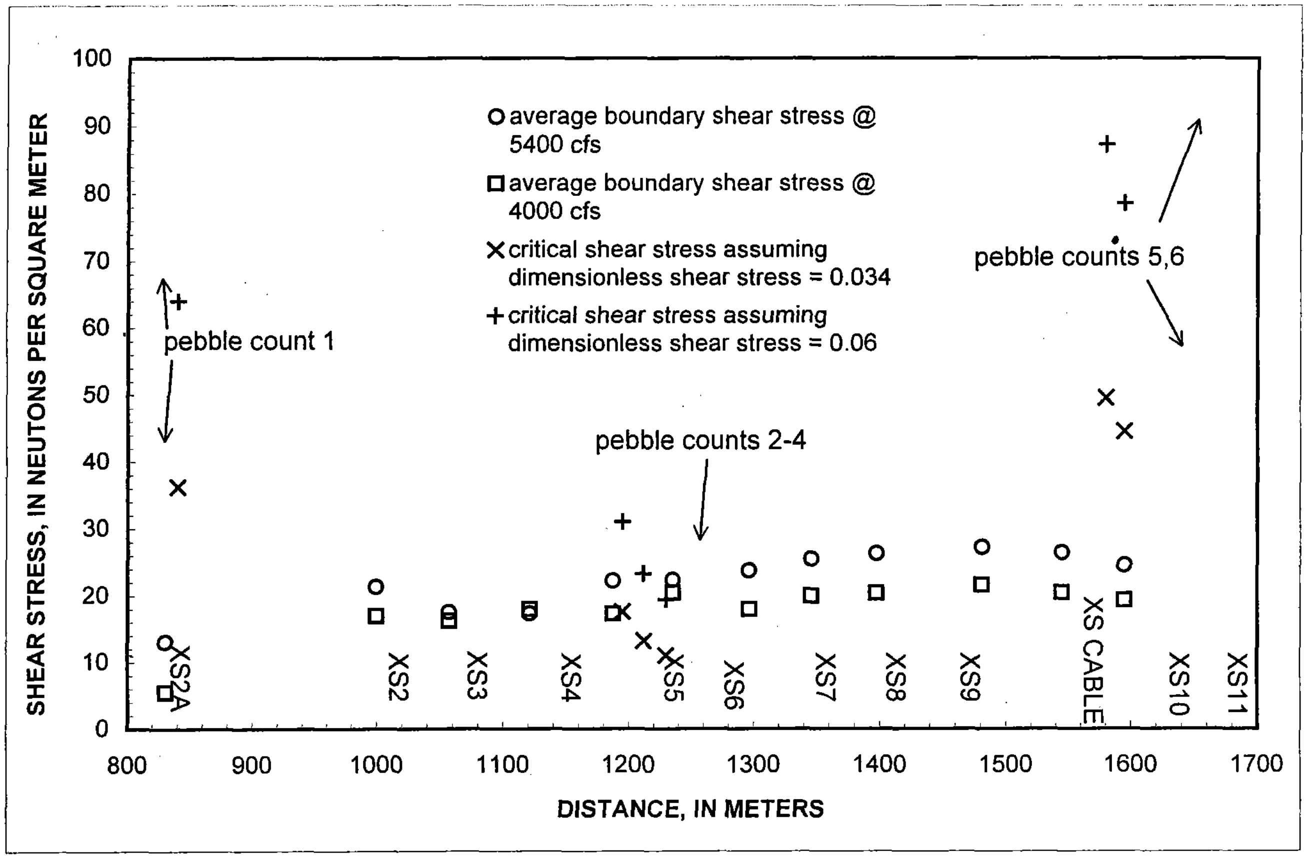


Figure A-16. Plot represents the average boundary shear stress generated at two high discharges at 12 of the measured cross-sections. The X data set represents the critical shear stress necessary to entrain the median particle size from 6 representative gravel/cobble deposits assuming critical dimensionless shear stress is 0.034. The + data set is the critical shear stress

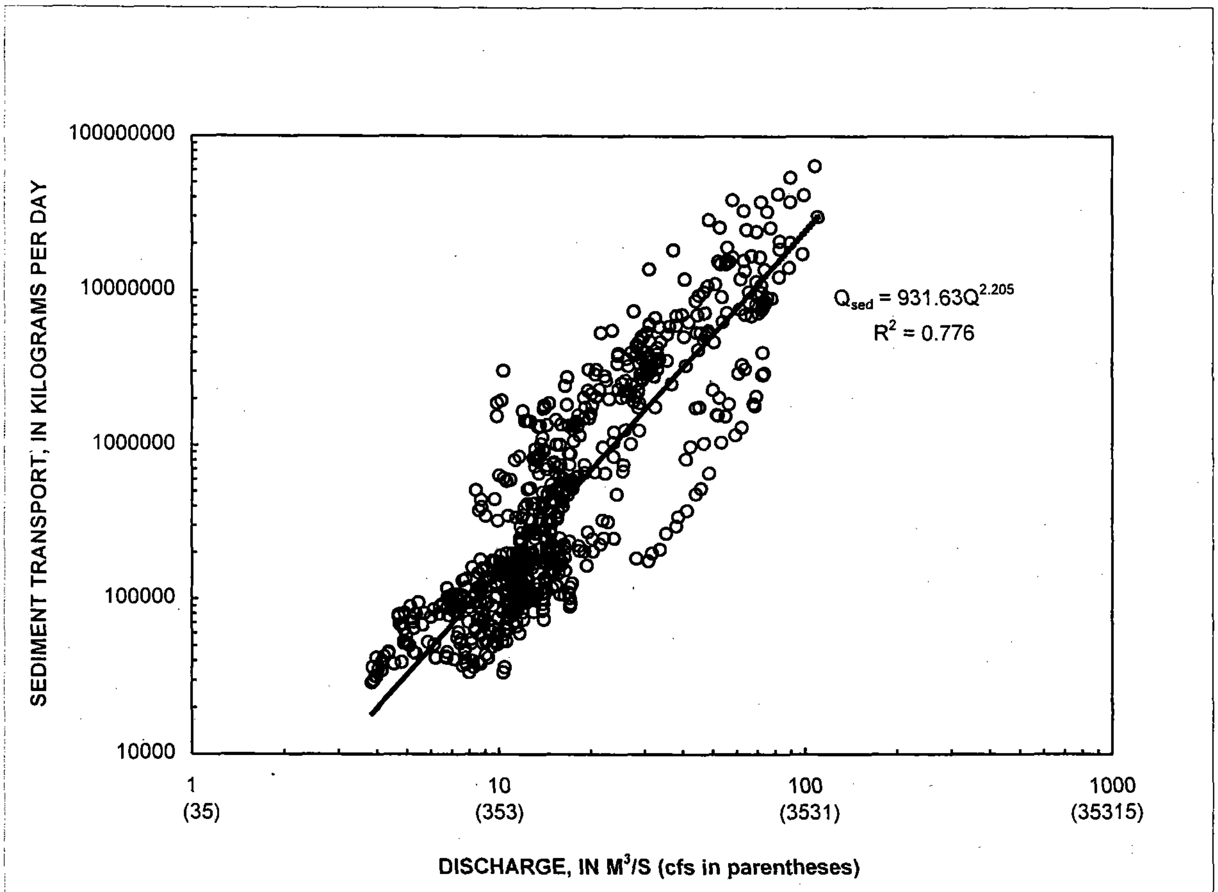


Figure A-17. Sediment transport rating relationship for White River near Watson (station 09306500). Relationship is based on 847 sediment transport measurements made between 1975 and 1990.

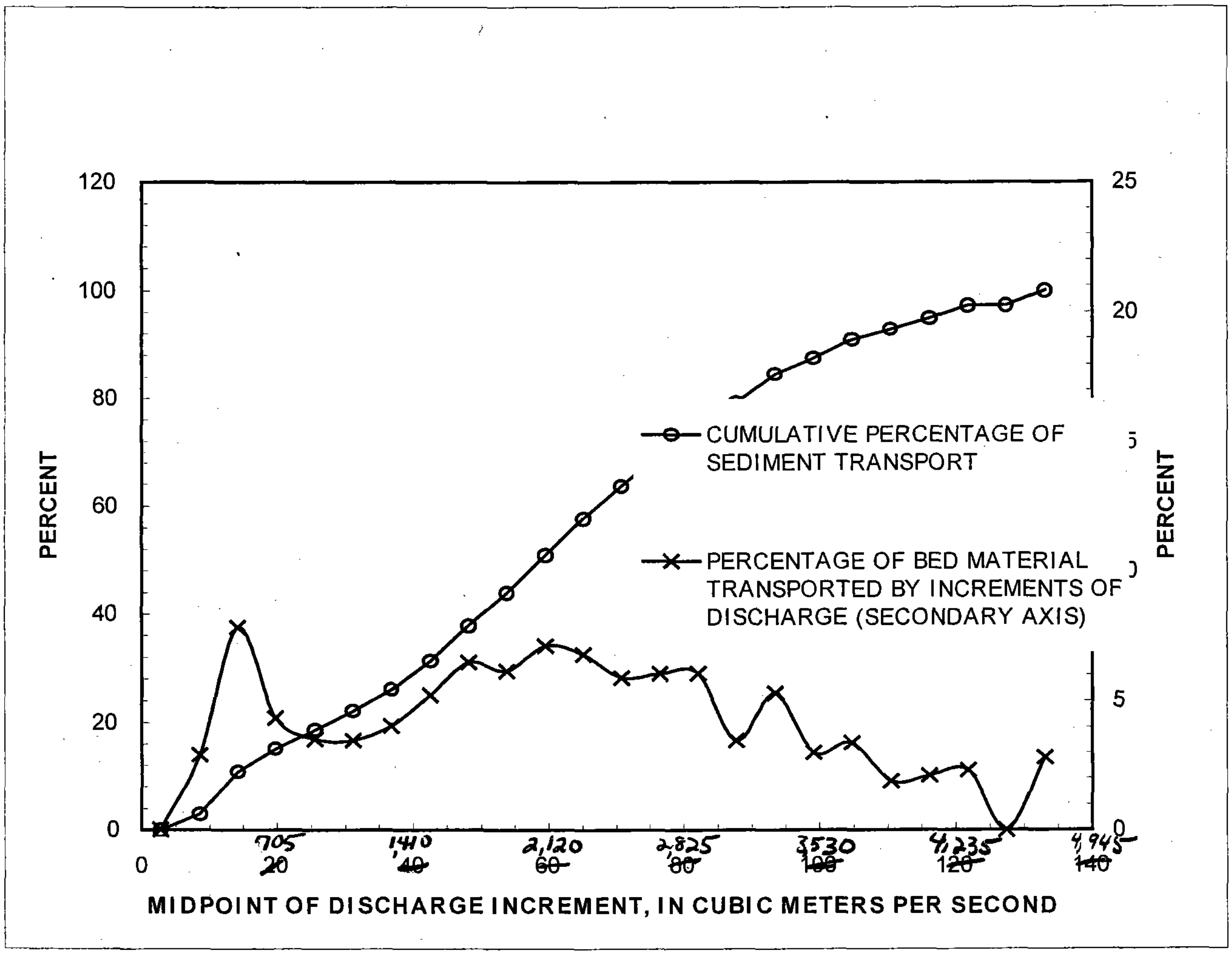


Figure A-18. Sediment transport curves as a function of discharge for station 09306500.

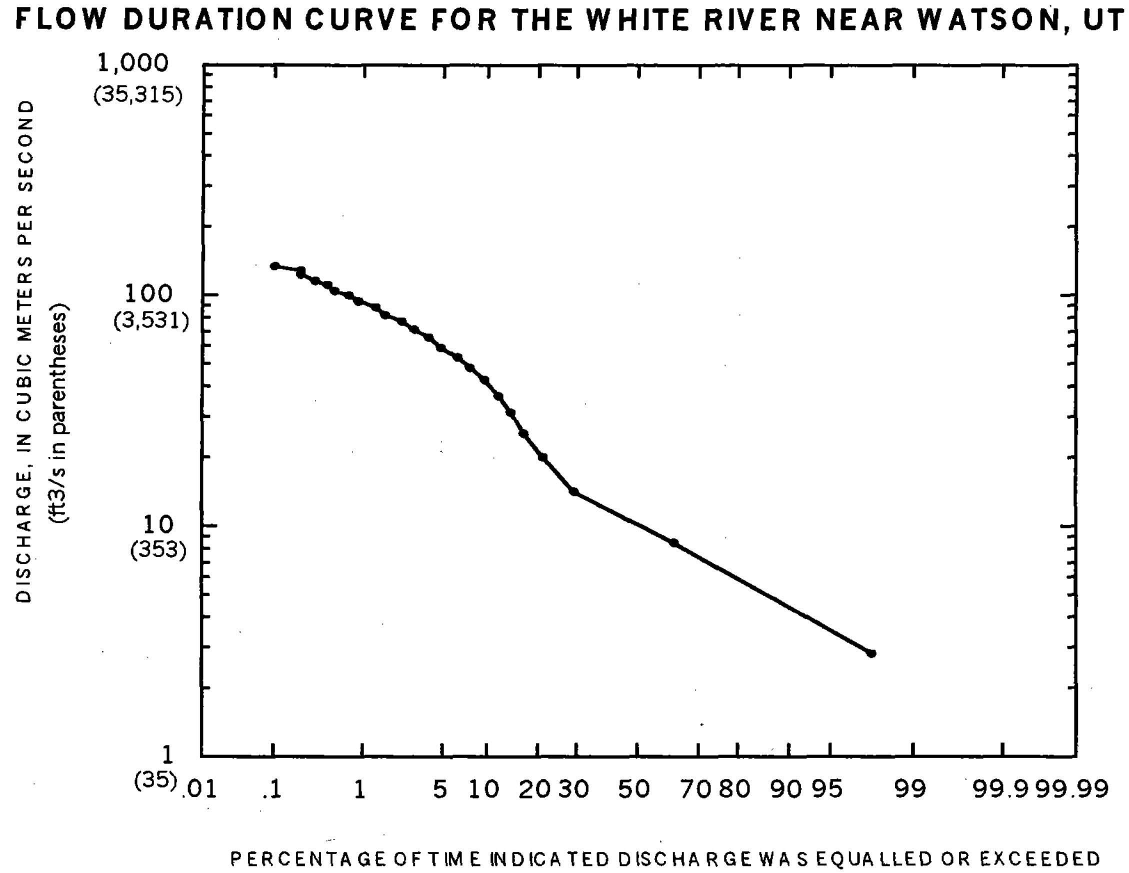


Figure A-19. Flow duration curve for station 09306500 based on mean daily discharge values for the periods 1904 to 1905, 1923 to 1979, and 1985 to 1997.

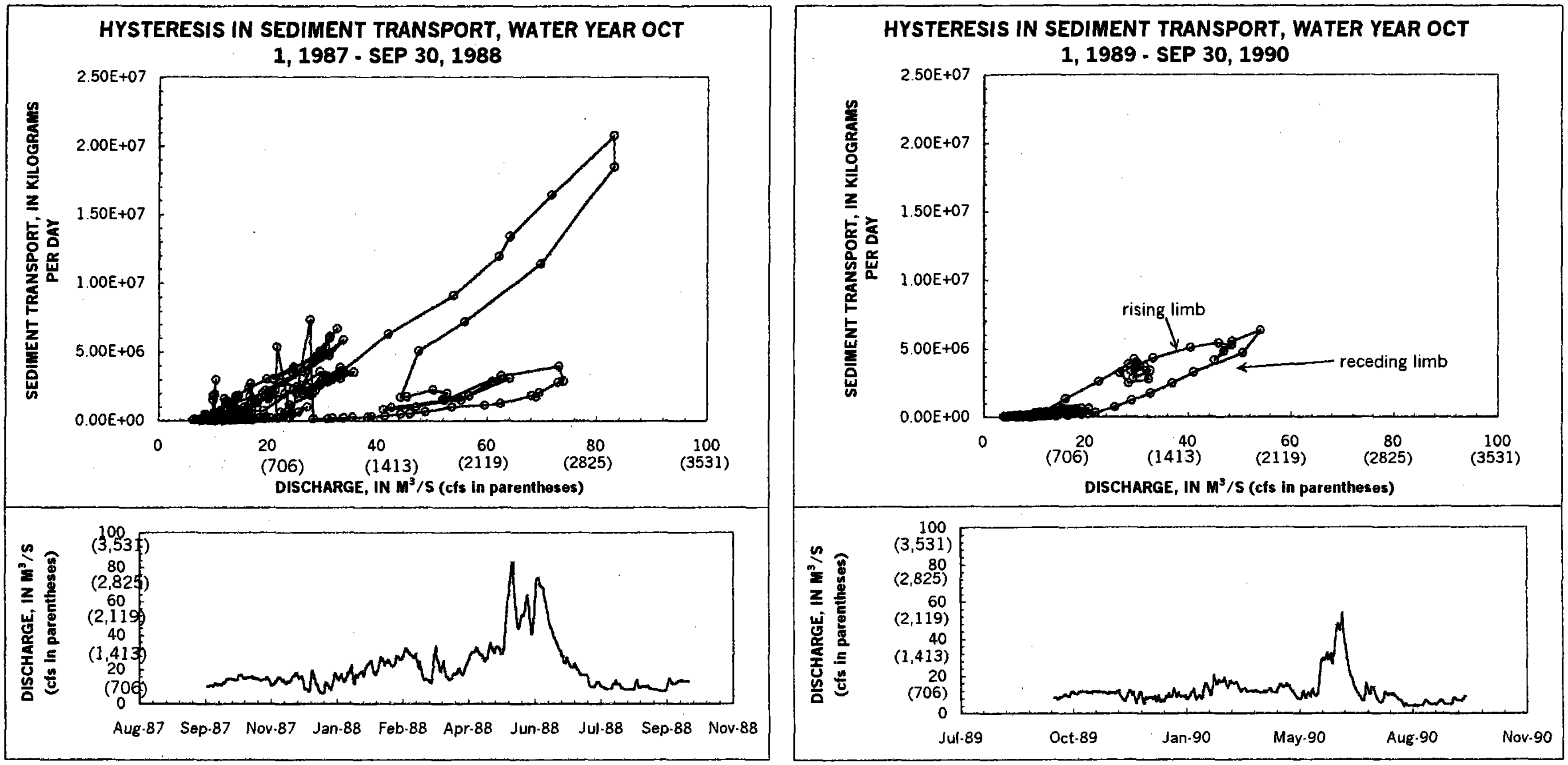


Figure A-20. Graphs showing hysterisis in sediment transport. The upper plots show daily sediment transport values plotted against their corresponding discharges. The lower plots show the hydrographs for the period of time represented in the upper plots.

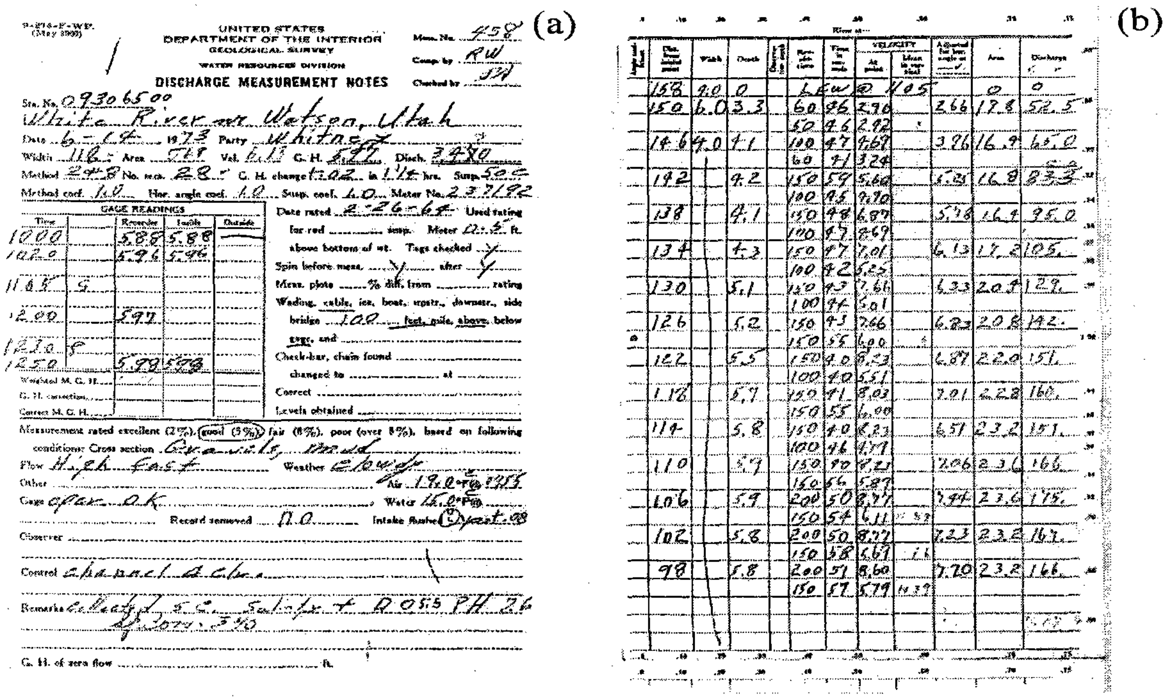


Figure A-21. Photograph of a US Geological Survey discharge measurement notes. These measurements were made on the White River near Watson, Utah (station number 09306500) on June 14, 1973. The first page (a) contains a data summary, notes concerning channel conditions, and the location of the measurement. The second page (b) contains the measured cross-section and the discharge calculations. A maximum depth of 5.9 ft was recorded at positions 106 feet and 110 feet from the initial point.

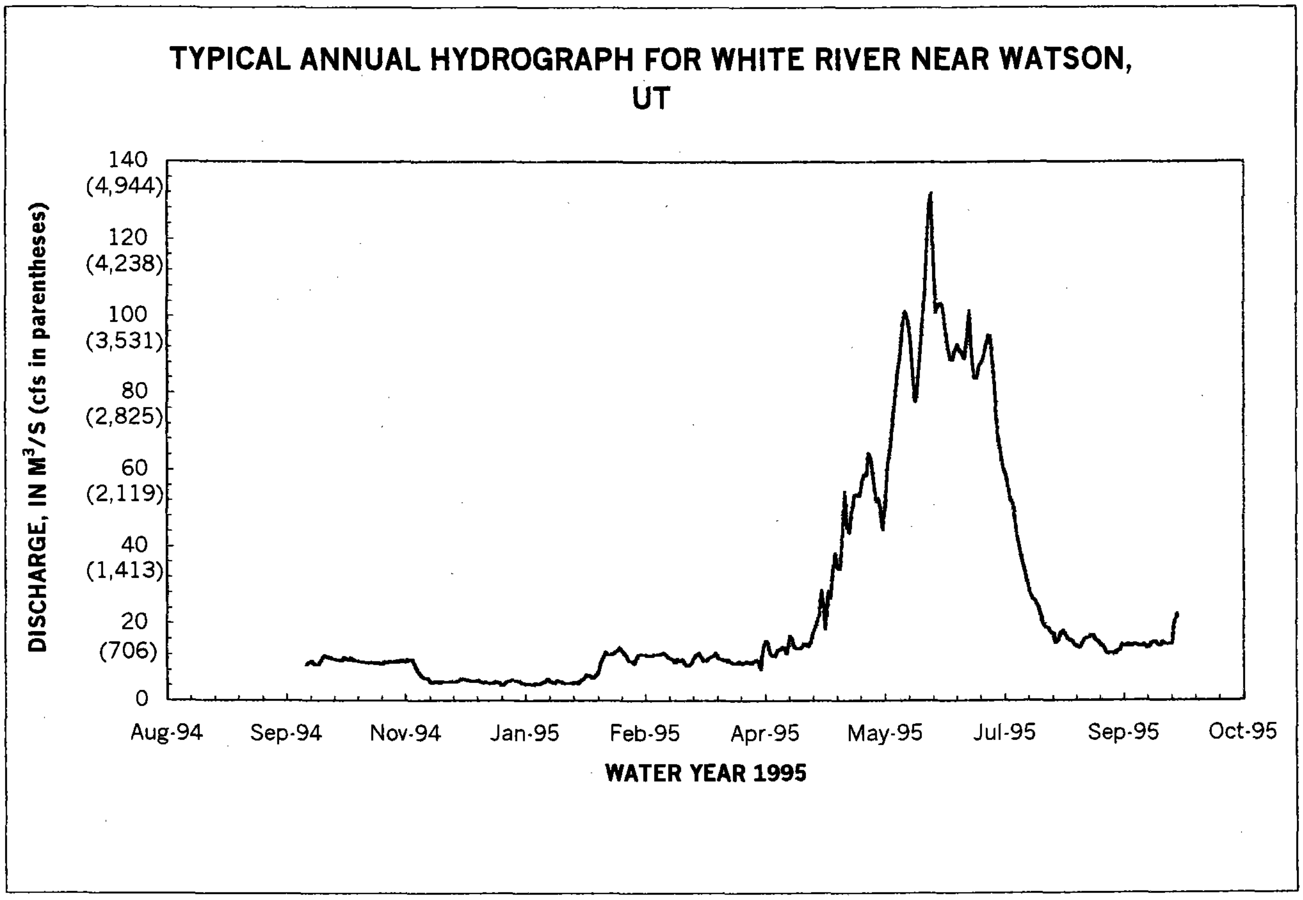


Figure A-22. Typical hydrograph for the White River near Watson, Utah. The river typically remains at baseflow until the spring when melting snow causes a sharp increase in discharge. Spring floods typically last from mid-April to late June.

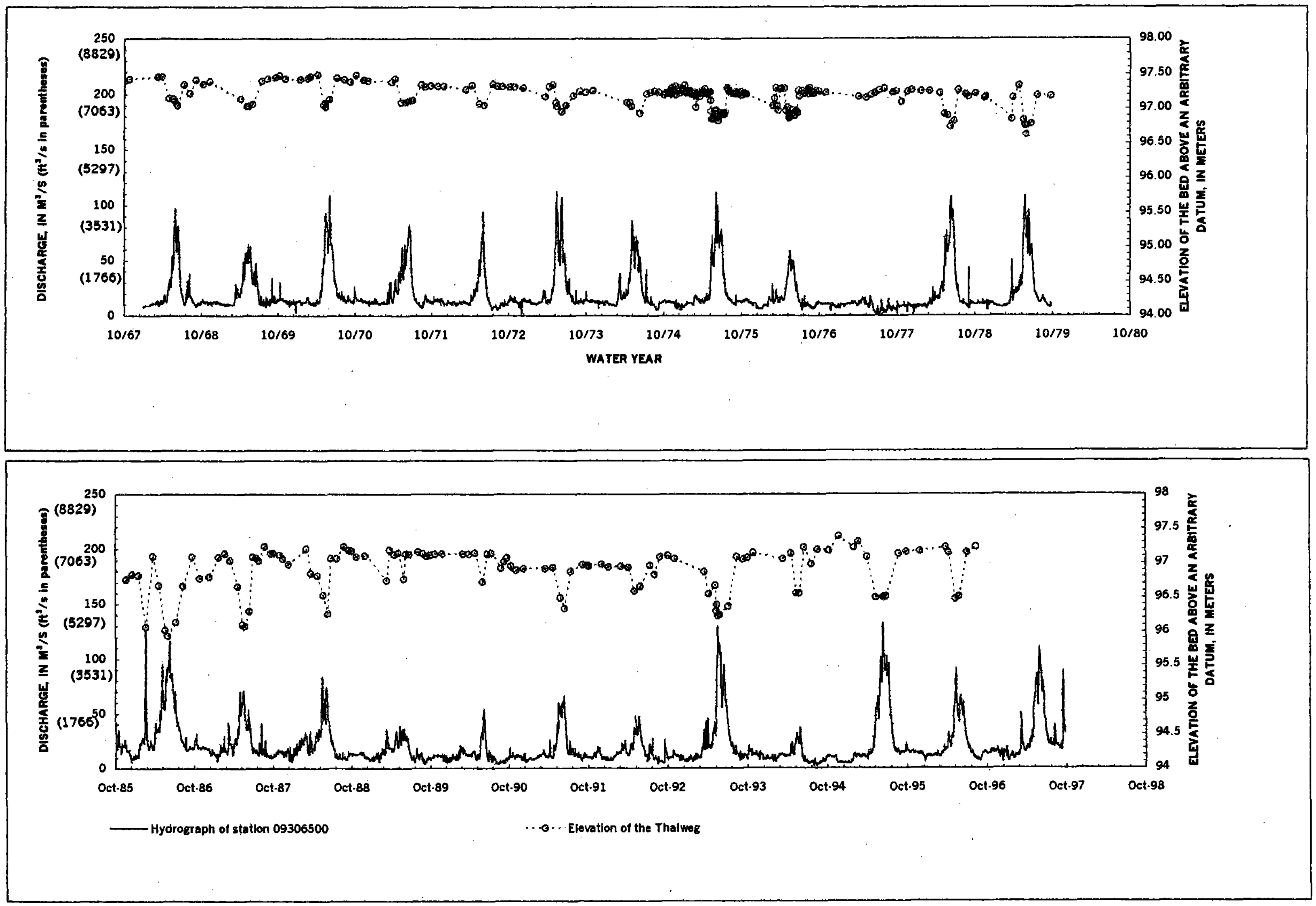


Figure A-23. Plots show mean daily discharges from station 09306500 (solid line) plotted with the corresponding bed elevations (dashed line). The annual rise in the hydrograph is accompanied with up to a meter decrease in bed elevation. After the flood peak passes, bed elevation increases to approximately the same elevation as prior to the flood . This scouring of the bed, and subsequent filling represents a pulse of sediment transport.

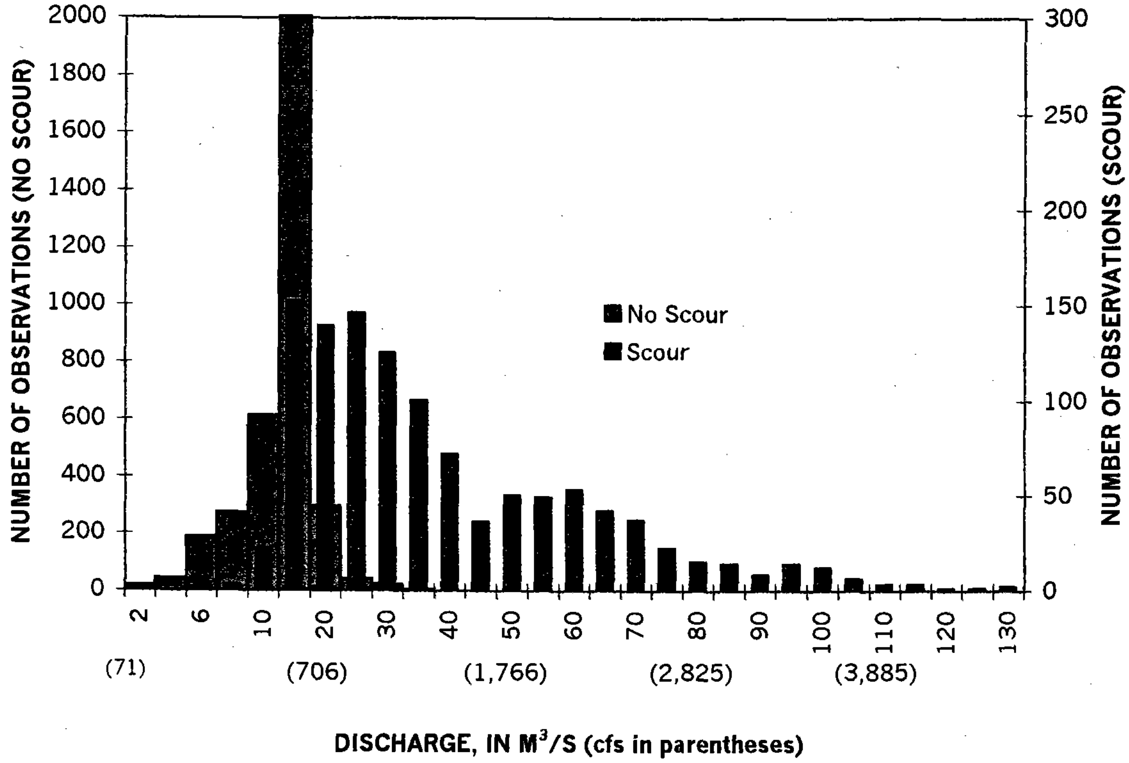


Figure A-24. Graph showing histograms for discharges during periods of stable bed elevation and periods of scour. Figure shows that the most common discharges during periods of scour are between 1,590 and 2,650 cfs. All discharges above 1,765 cfs are associated with a decrease in bed elevation.

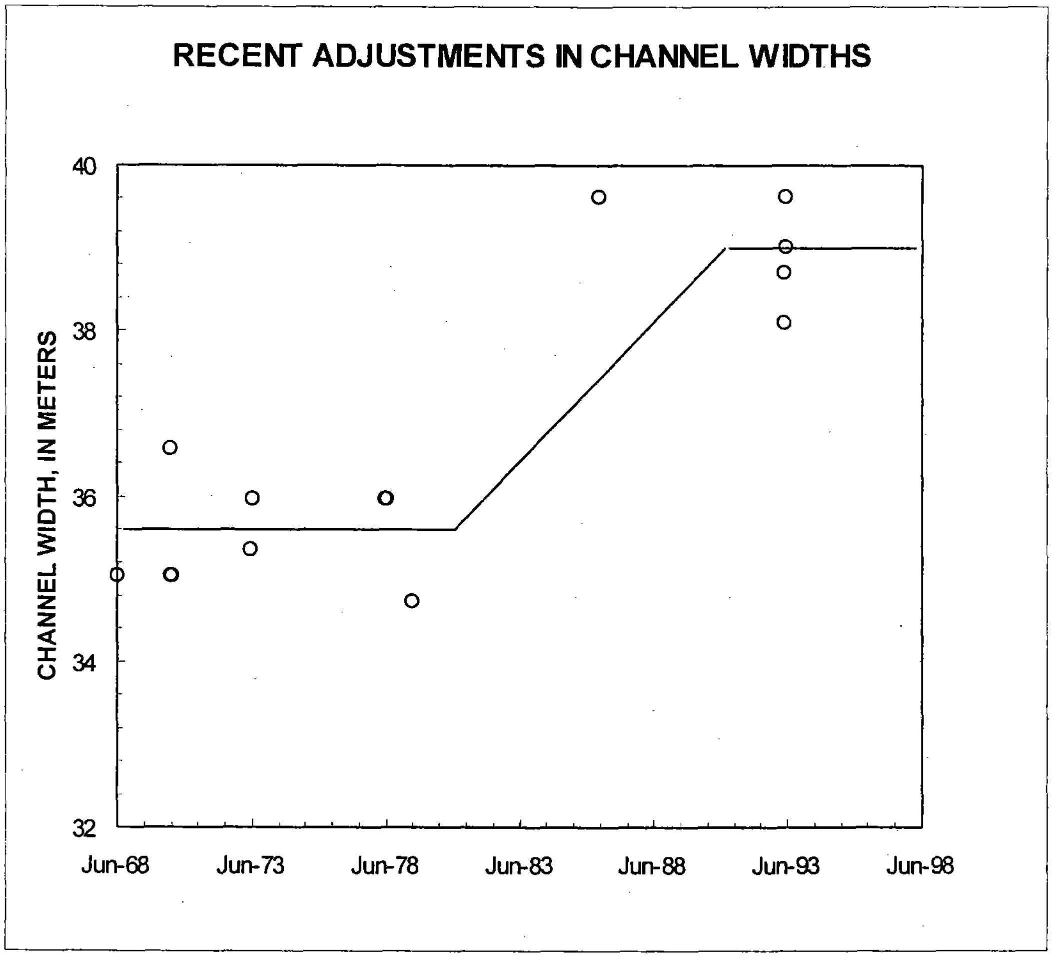


Figure A-25. Graph showing increased channel widths following the 1983-84 floods. Data points represent channel widths measured at similar locations during discharges 10% above and 25% below bankfull discharge.

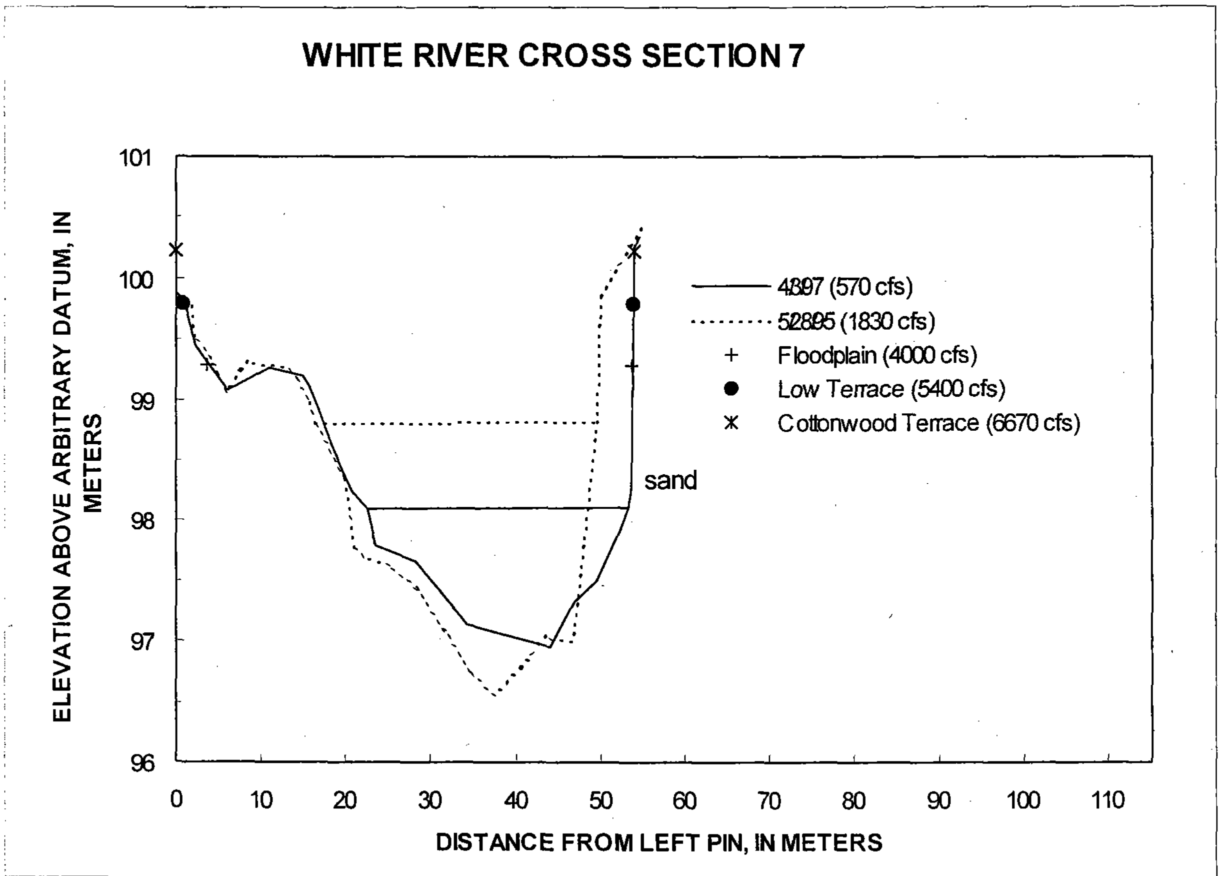


Figure A-26. Cross sections of channel at two discharges. In reaches where the bed was predominantly fine-grained alluvium, the bed elevation decreased at higher discharges.

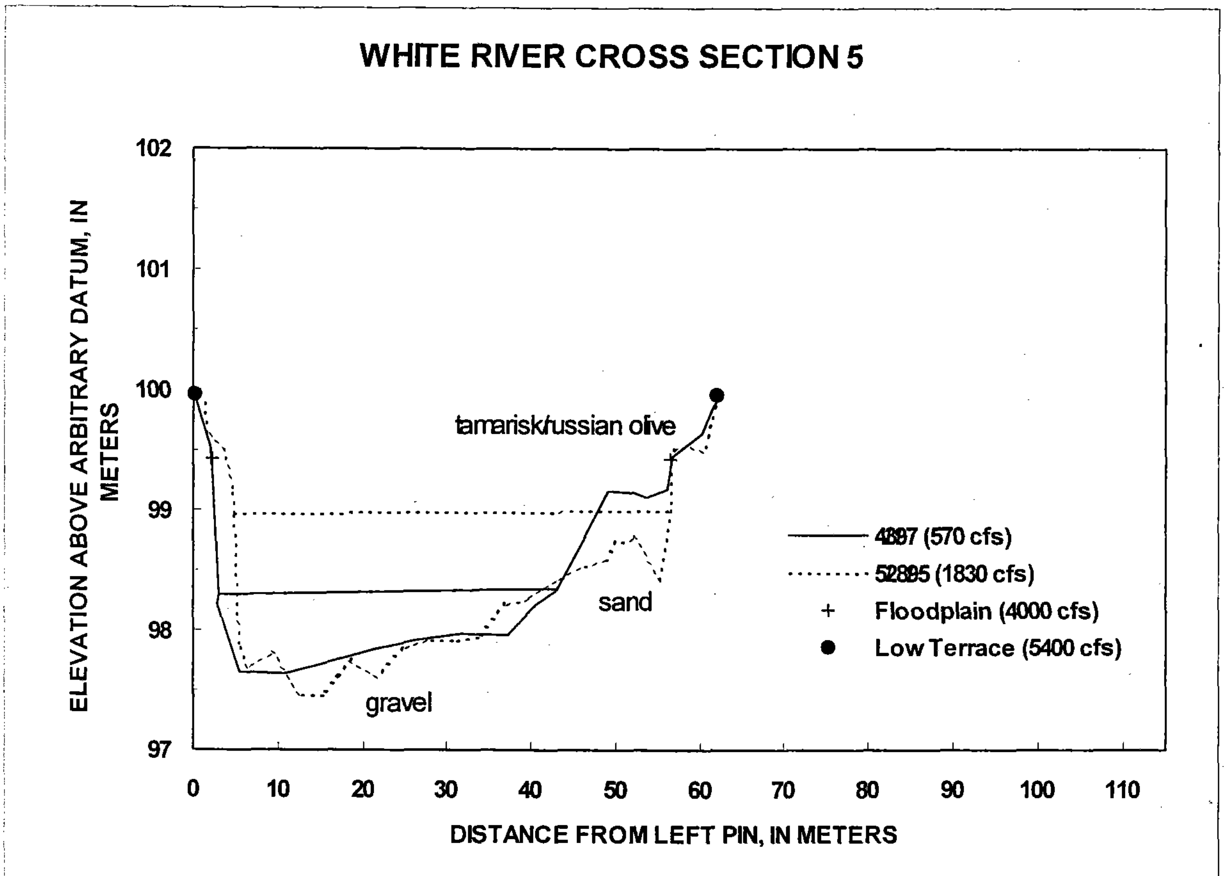


Figure A-27. Cross sections of channel at to discharges. Increased bed roughness was detected at several cross sections at higher discharges. The jagged dashed line in this figure indicates the presence of bedforms which were not present at the lower measured discharge.

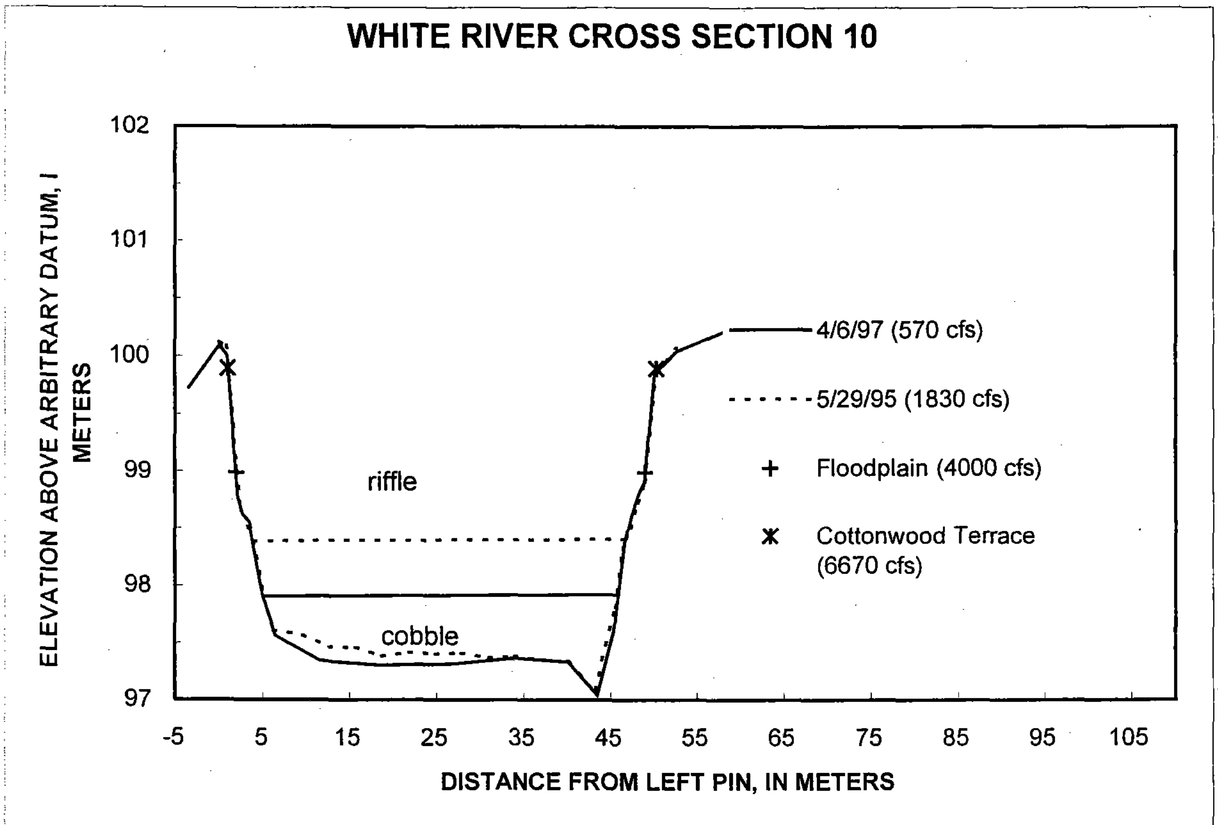


Figure A-28. Cross sections of channel at two discharges. Iincreased bed elevation was observed at higher flows at several cross sections where the bed was very coarse. The observed discharges were insufficient to scour these areas, and sediment, mobilized from upstream, moved over the coarse material and increased bed elevation.