SAN JUAN RIVER BASIN
RECOVERY IMPLEMENTATION PROGRAM

HYDROLOGY, GEOMORPHOLOGY AND HABITAT STUDIES

FINAL REPORT

prepared by

Ron Bliesner
Keller-Bliesner Engineering
78 East Center
Logan, Utah
(801) 753-5651

and

Vince Lamarra
Ecosystems Research Institute
975 South Highway 89-91
Logan, Utah
(801) 752-2580

February 25, 2000

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EXECUTIVE SUMMARY

INTRODUCTION

The studies reported here were completed in support of Objective 4.2 of the San Juan River Basin Recovery Implementation Plan (SJRIP) long range plan to "Identify, Protect, and Restore Habitats" for the endangered Colorado pikeminnow and razorback sucker. Field work was completed between 1992 and 1998. These studies also form a portion of the foundation for flow recommendations for the San Juan River in New Mexico, Colorado and Utah, a major milestone of the SJRIP long range plan.

The portion of the San Juan River addressed by these studies lies between Navajo Dam (River Mile (RM) 224) and the inflow to Lake Powell (RM 0). Hydrology, geomorphology and aquatic habitat were assessed.

HYDROLOGY

Prior to control by Navajo Dam in 1962, the San Juan River was relatively unregulated, although substantial diversion of water for irrigation and other uses has taken place since about 1870. The hydrology from 1929 to 1962 was relatively natural in shape, although depleted in volume, particularly in the summer. The river was characteristic of other large southwestern U.S. rivers, exhibiting a large spring runoff, associated with low base flow. Late summer and fall flows were strongly influenced by runoff associated with high intensity, short duration storm events from poorly vegetated lower river drainage basins, causing large increases in flow and sediment for short periods of time.

Subsequent to 1962, the hydrograph of the San Juan River was drastically changed as a result of conservation and flood control operation of Navajo dam. The dam was operated with the objective to conserve water and stabilize downstream flow, resulting in reduced spring discharge and elevated summer, fall and winter flow.

The test flow period clearly demonstrated the ability to operate Navajo dam in a manner that would mimic a natural hydrograph and ameliorate some of the impact of the dam on hydrology. This is especially true for the present level of depletions, but applies for additional levels of depletion as well. Much of the pre-dam hydrograph can be restored in terms of general shape, although magnitude is somewhat reduced. The test flows better matched pre-dam spring flows than winter base flows. A minimum release of 500 cfs from Navajo dam kept the winter flows elevated above pre-dam conditions.

While, on average, it appears that the potential exists for adequate mimicry, there are extreme conditions that cannot be met. With the present release capacity of Navajo Dam at 5,000 cfs, the ability to produce large spring floods below Farmington has been diminished. Further, historic minimum summer through winter base flows would likely not be matched, both as a result of restrictions on minimum releases and a desire to maintain more flow in the river to benefit the fish during these times.

Not only were flows impacted, but the temperature regime in the river was altered. The post-dam water temperatures in the summer at Shiprock are now cooler than pre-dam at Archuleta. With re-operation and increased releases during spring runoff, the depressed temperatures will extend further down river. The net result is a further loss in range for temperature critical activities of over 140 km. While the program has the goal of expanding range, the opportunity may be limited by temperature suppression. Further studies are needed to determine if this temperature suppression is limiting range in otherwise suitable habitat and the options available to correct it if it is found to be a problem.

Summer and autumn storm events markedly impact habitat quality in the San Juan by depositing fine sediment over cobble substrate and in backwaters. In the lower portion of the river, below Four Corners the storm influence is sufficient to require flushing flows to clean habitats 50% of the time on average. In the upper portions of the river below Farmington the frequency falls to about 1 year in 10 on average, suggesting that habitat is more easily maintained in the upper reaches of the river.

GEOMORPHOLOGY

History of Fluvial Morphology

The San Juan River has undergone a variety of changes over the last 100 years, for which we have documented evidence since the 1930's. The condition of the river in the 1930's is likely not the condition to which we would desire restoration. The lower portion of the river, including the canyon below Bluff, Utah, was heavily sediment laden. There was no stability to the channel and most of the cobble was probably buried in 0.3 to 2.0 meters of sand. By the early 1950's suspended sediment load dropped by nearly 50%, allowing the channel to scour the sand from the system and form a more defined channel and the invasion of tamarask had begun, with substantial establishment by this period. The smaller, stabler channel was quite different than the 1930's channel with larger, more stable islands and secondary channels. By the time Navajo dam was constructed in the early 1960's, the channel had stabilized even more, although the mean bankfull channel width was about the same as a decade earlier. With stabilization came a loss of channel complexity with fewer and smaller islands. Between the early 1960's and 1988, the channel became much smaller, but in the process, gained significant island area and island count. Since the bankfull channel area lost is almost equal to the island area gained, it appears that previous sand and cobble bars became vegetated during this period of reduced spring peak flows. The channel is much more stable and is now heavily armored with Russian Olive along most of its course. The loss of bankfull channel

capacity, estimated at between 15% and 30%, now requires less flow for channel maintenance and out-of-bank conditions occur at reduced flows.

Geomorphological Reach Description

To assist interpretation of research results in such a long reach of river, eight geomorphological reaches were identified. Following is a brief description of each reach:

Reach 1 (RM 0 to 16, Lake Powell confluence to near Slickhorn Canyon) is a low gradient, sand-bottomed reach created by backwater from Lake Powell.

Reach 2 (RM 17 to 67, near Slickhorn Canyon to confluence with Chinle Creek) is canyon bound but is located above the influence of Lake Powell, with a higher gradient, dominated by riffle-type habitat.

Reach 3 (RM 68 to 105, Chinle Creek to Aneth, Utah) is characterized by higher sinuosity and lower gradient (second lowest) than the other reaches, a broad floodplain, multiple channels, high island count, and high percentage of sand substrate. Backwaters are more abundant, but are easily perturbated by summer storm flows.

Reach 4 (RM 107 to 130, Aneth, Utah, to below "the Mixer") is a transitional reach between the upper cobble-dominated reaches and the lower sand-dominated reaches with relatively low abundance of backwaters and little clean cobble.

Reach 5 (RM 131 to 154, the Mixer to just below Hogback Diversion) is predominantly multi-channeled. Backwaters and spawning bars in this reach are much less subject to perturbation during summer and fall storm events than the lower reaches.

Reach 6 (RM 155 to 180, below Hogback Diversion to confluence with the Animas River) is predominately a single channel. Cobble and gravel substrates dominate, and cobble bars with clean interstitial space are more abundant in this reach than in any other. Four diversion dams limit upstream movement of fish.

Reach 7 (RM 181 to 213, Animas River confluence to between Blanco and Archuleta, New Mexico) is similar to Reach 6 in terms of channel morphology. The river channel is very stable, consisting primarily of embedded cobble substrate as a result of controlled releases from Navajo Dam and much of the river bank has been stabilized and/or diked.

Reach 8 (RM 213 to 224, between Blanco and Archuleta and Navajo Dam) is the most directly influenced by Navajo Dam, which is situated at its uppermost end (RM 224). This reach is predominantly a single channel with cobble substrate and clean, cold water as a result of Navajo Dam. These cool, clear water conditions have allowed development of an intensively managed blue-ribbon trout fishery to the exclusion of the native species in the uppermost portion of the reach.

Channel Geometry

During the course of the seven-year research study, the channel has shown a general trend of scour, resulting in an increase of mean cross-sectional area of 7 - 10%. The scour was most pronounced in the earlier years, with a trend towards a stability. This short term change is well within the range of changes seen at USGS gages over the last 50 years. The increased scour was accompanied by an increase in the portion of cobble substrate as a result of removing sand from the system.

Continued channel scour can lead to channel simplification if the main channel degrades and secondary channels are isolated. Studying the trend in island count at low flow over the research period indicated a slight trend to simplification when peak flows were near bankfull or less. Channel complexity increased when flows exceeded 10,000 cfs for more than 5 days.

The scour that has occurred has resulted in an increase in bankfull channel capacity of about 12% over the research period to an average flow of about 8,000 cfs. Since the bankfull channel area is still much less than during pre-dam conditions, the historic bankfull capacity was likely greater than 8,000 cfs, although now measurements have been made to quantify the historic bankfull discharge.

Cobble Bar Characterization

Characterization of cobble bars in the San Juan River indicates that there are multiple locations that have characteristics suggesting that they are suitable for spawning as well. Cobble with substantial depth of clean open interstitial space is more abundant above RM 131 than below, corresponding to the other studies that indicate an increase in sand substrate with distance down river.

Flows to Support Cobble Transport

Based on the results of the studies conducted to date, it is concluded that sufficient local cobble movement exists to provide some clean cobble for spawning with flows of 2,500 cfs or higher for a duration of at least 10 days prior to spawning.

The bankfull flow of 8,000 cfs was selected as the flow required for cobble transport and bar building based on model results of four research reaches and flow calculations at the RT cross-sections. Examination of the cobble movement data suggests an 8-day duration as appropriate for the minimum duration necessary for bar-building cobble transport. An average recurrence frequency of 1 year in 3 years (33%) will provide the frequency of conditions necessary for maintenance of channel capacity. Therefore, 8,000 cfs for 8 days with an average recurrence frequency of 1 year in 3 years are the conditions recommended for cobble bar construction and channel maintenance. From a sediment-transport and channel-maintenance standpoint, the full range of flows from 2,500 cfs through 10,000 cfs plays an important role. Mimicking a natural hydrograph that includes flows in this range is necessary. Just providing the conditions required at 8,000 cfs would be inadequate and could lead to channel simplification and armoring over time. Because of the short period of study, monitoring should continue to verify these relationships.

Flows above 10,000 cfs are recommended periodically for maintaining channel complexity and floodplain integrity. The response of islands to flows indicates that flows less than 10,000 cfs (1992 to 1994) may result in channel simplification with time unless combined with higher flows that develop new secondary channels and islands through overbank flow (1995). High flows are the most-altered portion of the natural hydrograph in the San Juan River. Historically, these flows have played a major role in floodplain development. While all the mechanisms of importance have not been identified and quantified during the research period, the general paradigm of natural flow mimicry would not be met without restoration of these higher flows to some degree. Therefore, a conservative threshold requirement of 5 days at or above 10,000 cfs is recommended for purposes of natural flow mimicry and maintenance of channel complexity.

The cobble bar maintenance flow (2,500 cfs) should occur at a frequency sufficient to ensure long-term reproductive success of the species of interest. The cobble bar construction flow (8,000 cfs) is needed less frequently if bars are maintained (cleaned and reworked) on a regular interval. Data suggest that the bars can be reworked to provide clean cobble for several years without the necessity of reconstruction or replacement. Channel maintenance requirements indicate an average recurrence of 1 year in 3 years for flows above 8,000 cfs. The 10,000-cfs flow condition is not required as frequently. Historically, it had been 8 years between the occurrence of these conditions (1987 and 1995). Looking at the potential for channel complexity deterioration indicated in Figure 3.29, the required average recurrence frequency for maintenance of channel complexity and floodplain integrity was determined to be 5 years. During the pre-dam period, the 10,000-cfs flow conditions were met 39% of the time (4 years in 10, vs. 2 years in 10 in this recommendation). The reduction in channel capacity that has occurred since the closure of Navajo Dam allows a lower frequency of achieving these conditions. Given the short duration of the studies upon which these recommendations are based, future refinement of the recommendations will likely be necessary, thus requiring an adaptive management approach.

LOW VELOCITY HABITAT MAINTENANCE

During the course of the research period, no relationship could be found between spring runoff conditions and bedform structural change influencing backwater formation. Studies of bar change did not indicate a relationship between bar height and peak runoff magnitude or volume for the range of flows tested, likely because most peak flows were at or above bankfull where stage and shear stress change little with change in flow. Further, a large percentage of backwaters are associated with secondary channel or tributary mouths. Therefore, the structural studies concentrated on backwater cleaning processes.

Detailed monitoring and modeling of fine sediment transport in two secondary channel associated backwaters indicated flows must be in the 4,000 - 5,000 cfs range to initiate cleaning. Further, flushing is improved by longer durations and higher magnitudes of spring flows. Both backwaters begin to refill with sediment on the descending limb of the hydrograph. Modeling indicated that steeper descending limbs tended to limit the amount of deposition. Summer storm events can fill in these backwaters during heavily perturbating (multiple sediment laden storm events in one

season) years. Modeling is very sensitive to sediment concentration and grain size distribution, making it difficult to accurately predict performance in a non-calibration year. So far, each year analyzed has required a separate calibration, with low accuracy of predicted capability. For modeling to be effective, more intense sediment concentration data would be needed in conjunction with a more robust model that would address the geometry of the bedform and the mechanisms of transport more precisely than the one dimensional model used.

Combining the results of the backwater cleaning measurements and modeling with the results of overall scour in the cross-sections, a threshold flow of 5,000 cfs has been identified as necessary for backwater cleaning, with a duration of 21 days and an average frequency of 50%.

SUSPENDED SEDIMENT ANALYSIS

In any study of fluvial morphology it is desirable to be able to measure sediment inflow and outflow to determine the sediment balance. While this is possible for non-storm influenced periods in the San Juan, it is not practical to measure all the inflows required in the San Juan River due to the numerous inflows. The sediment data collected did indicate that the concentrations measured fall within the range of historic sampling, although averages were on the low side of the historic mean This could represent a shift to lower sediment concentrations, or indicate a sampling bias as the non-runoff period was not sampled.

Sufficient analyses have been completed to know that the system is heavily perturbated by summer and fall storm runoff events, where measured tributary inflow concentrations of total suspended solids (tss) have been as great as 130,000 ppm (13%). These heavy sediment contributions lead to reduced backwater habitat quality and require more frequent flushing to maintain system health.

HABITAT

The quantity and quality of aquatic habitat in the San Juan River was determined in a number of different investigations. The surface areas of a wide variety of habitat types in the San Juan River were mapped thirteen separate times with flows ranging from 525 to 8,000 cfs. At times, the mapping occurred over the entire 225 miles of river from Navajo Dam to the confluence with Lake Powell. Some habitat types (runs, eddies, inundated vegetation and shoal) displayed strong relationships with mapping flows while other habitats (slackwaters) displayed high variability with no relationship to flow. Backwater habitats, although variable, demonstrated a systematic pattern related to the inundation of the mouths of secondary channels and the subsequent loss via flow through these channels at higher flows. Backwater habitat areas were also found to be diminished due to summer silt-laden storm events.

The habitats mapped through airborne videography and field studies were determined by visual inspection of surface features (eddy lines, riffle lines, etc. In order to verify that these habitats are physically different, an investigation was undertaken to quantify the physical conditions of these habitats. During this study it was found that the eight habitat types selected, significantly differed

in most cases with respect to mean velocity, depth, and depth to embedded layer (DTE). Substrate composition also differed between some habitats with generally finer substrates being more abundant in lower velocity types and coarser substrates in higher velocity types. DTE tended to be higher in most habitats in the most upstream reach below Navajo Dam, indicating less embedded substrate in those areas. Highly reduced sediment loads in the upper reach was a likely explanation for that finding.

Storms were observed to increase the percentage of fines and/or decrease the DTE in every habitat described. Conversely, the cleansing action of high runoff was noted in nearly all habitats as well. This illustrated the necessity for considering the effect of hydrology on these particular attributes when describing specific habitats. For example, using DTE as a measure to distinguish between riffles and other relatively high velocity habitats following a large storm event might be counter-productive as riffle habitats would likely be similarly, highly embedded.

Because riffle and run habitat types were found to be physically different, they were sampled for abiotic and biotic parameters before and after spring runoff for the years 1994, 1995 and 1996 with the purpose of quantifying primary and secondary trophic structures. The physical parameters (depth to embedded layer, D_{50}, and percent surface area embedded) were significantly different between riffles and runs. Biological parameters (periphyton, detritus and invertebrates) were not different between habitat types. The comparison of sample locations (geomorphological reach) by habitat types for the abiotic and biotic parameters indicated significant longitudinal differences for periphyton, detritus and invertebrates with upper geomorphological reaches having higher densities (greater biomass) than lower reaches. The comparison between the lower 200 miles of the Colorado with the San Juan study area indicated similar characteristics in abiotic conditions and similar biomass levels for biological components.

Backwaters, which represented a critical habitat for native fishes were also quantified over a multiple year sequence. The results of this investigation indicated that storms reduced the biomass of phytoplankton, periphyton, and benthic invertebrates (chiefly chironomids) in San Juan River backwaters. In addition, periods of relative stability in discharge (i.e., reduction in frequency and/or intensity of storms) on the order of months during the fall-to-spring period resulted in increased production of phytoplankton, zooplankton, periphyton, benthic invertebrates, and detritus in San Juan River backwaters. However, storms also increased the abundance of zooplankton and detritus in some river reaches on certain occasions. Periphyton was the one parameter that displayed a clear longitudinal pattern following stable flows in the San Juan River, with biomass steadily declining downstream.

Backwater depth river-wide in the San Juan River was relatively high following the higher magnitude runoff in 1995, but declined to lower levels thereafter during a two-year period characterized by frequent storm events. The reductions in backwater depth in the San Juan River over the study period coincided with an increased amount of ultra-fine sized sediment accumulation in the backwaters. As a comparison, data from the Colorado River backwaters within the Moab to Potash reach tended to be deeper, less turbid, cooler, and more oxygenated than San Juan River backwaters over the same time period. Colorado River backwaters also contained higher levels of

periphyton over the same time period as the San Juan River backwaters river-wide, while other biological parameters were similar on average.

During the monsoon period in 1997 when storms were prevalent, the San Juan, Colorado, and Green River backwaters contained similarly low primary and secondary productivity, indicating physical disturbances to the backwaters throughout all three drainages.

CHAPTER 1: INTRODUCTION

Hydrology, geomorphology and habitat studies of the San Juan River began in 1992 as a part of the San Juan River Basin Recovery Implementation Program (SJRIP). The work reported here represents activities completed through 1998 as part of the seven-year research effort incorporated into the SJRIP.

The purpose of the SJRIP is to "protect and recover endangered fishes in the San Juan River basin while water development proceeds in compliance with all applicable federal and state laws" (SJRIP Program Document, February 1995). Objective 4.2 of the long range plan developed as part of this program document is to identify, protect and restore habitats, recognizing that recovery of endangered species is linked to the condition of their habitat. As a part of this objective a need for modeling the response of habitat to flow was identified. Further, the response of channel morphology to research flows is necessary to define the relationship between flow and habitat. The studies reported here were designed to meet this objective.

The hydrology for the basin during the study period is presented and discussed in terms of the historic setting and the frequency with which these conditions occurred under historic conditions. These flows are then related to geomorphological conditions and changes in the river in an analysis of river channel dynamics. The river channel dynamics studies include analysis of river cross-sections, response of cobble bars, movement of bed material and an analysis of suspended sediment data.

Water temperature data collected at nine stations along the San Juan and Animas Rivers are reported and compared to historical data to aid the assessment of habitat quality.

The results of the geomorphic reach definition study completed in 1994 are reported here. The results of this study are used as a basis for analysis of the several data sets, with the objective of identifying similarities and differences in the response of these reaches to flows.

Physical habitat mapping that has been completed on the San Juan River from Navajo Dam (river mile (RM 224) to the confluence with Lake Powell (RM 0) from 1992 through 1997 is reported here (1998 data reduction is not complete).

Habitat quality studies were also conducted between 1994 and 1996 to identify the temporal and longitudinal distribution of physical and biological components of habitat quality in riffles, runs and backwaters.

SAN JUAN RIVER STUDY AREA DESCRIPTION

The San Juan River is a major tributary of the Colorado River and drains 99,200 km^2 in Colorado, Utah, Arizona, and New Mexico (Figure 1.1). From its origins in the San Juan Mountains of southwestern Colorado at elevations exceeding 4,250 m, the river flows westward for about 570 km to the Colorado River. The major perennial tributaries to the San Juan River are the Navajo, Piedra, Los Pinos, Animas, La Plata, and Mancos rivers, and McElmo Creek. In addition there are numerous ephemeral arroyos and washes contributing little total flow but large sediment loads.

Navajo Reservoir, completed in 1963, impounds the San Juan River, isolating the upper 124 km of river and partially regulating downstream flows. The completion of Glenn Canyon Dam and subsequent filling of Lake Powell in the early 1980's inundated the lower 87 km of the river, leaving about 359 km of river between the two bounding features.

From Navajo Dam to Lake Powell, the mean gradient of the San Juan River is 1.67 m/km. Locally, the gradient can be as high as 3.5 m/km, but taken in 30 km increments, the range is from 1.24 to 2.41 m/km. Between the confluence of the San Juan River with Lake Powell and the confluence with Chinle Creek about 20 km downstream of Bluff, UT, the river is canyon bound and restricted to a singled channel. Upstream of Chinle Creek the river is multi-channeled to varying degrees with the highest density of secondary channels between the Hogback Diversion about 13 km east of Shiprock and Bluff, Utah. The reach of river between Navajo Dam and Farmington, NM is relatively stable with predominantly embedded cobble substrate and few secondary channels. Below the confluence with the Animas River, the channel is less stable and more subject to floods from the unregulated Animas River. Between Farmington and Shiprock cobble substrate still dominates, although it is less embedded. Between Shiprock and Bluff the cobble substrate becomes mixed with sand to an increasing degree with distance downstream, resulting in decreasing channel stability.

Except in canyon-bound reaches, the river is bordered by nonnative salt cedar (*Tamanix chinensis*) and Russian olive (*Elaeagnus angustifolia*) and native cottonwood (*Populas fremonti*) and willow (*Salix* sp.). Nonnative woody plants are most abundant with cottonwood and willow accounting for less than 15% of the riparian vegetation.

Discharge of the San Juan River is typical of rivers in the American Southwest. The characteristic annual pattern is one of large flows during spring snowmelt, followed by low summer, autumn, and winter base flows. Base flows are frequently punctuated by convective storm-induced flow spikes during summer and early autumn. Prior to closure of Navajo Dam about 73% of the total annual discharge (based on USGS Bluff, Utah gage) of the drainage occurred during spring runoff (1 March through 31 July). The median daily peak discharge during spring runoff was 10,400 cfs (range = 3,810 to 33,800 cfs). Although flows resulting from summer and autumn storms contributed a comparatively small volume to total annual discharge in the basin, the magnitude of storm-induced flows exceeded the peak snowmelt discharge about 30% of the years, occasionally exceeding 40,000 cfs (mean daily discharge). Both magnitude and frequency of these storm induced flow spikes are greater than those seen in the Green or Colorado rivers.

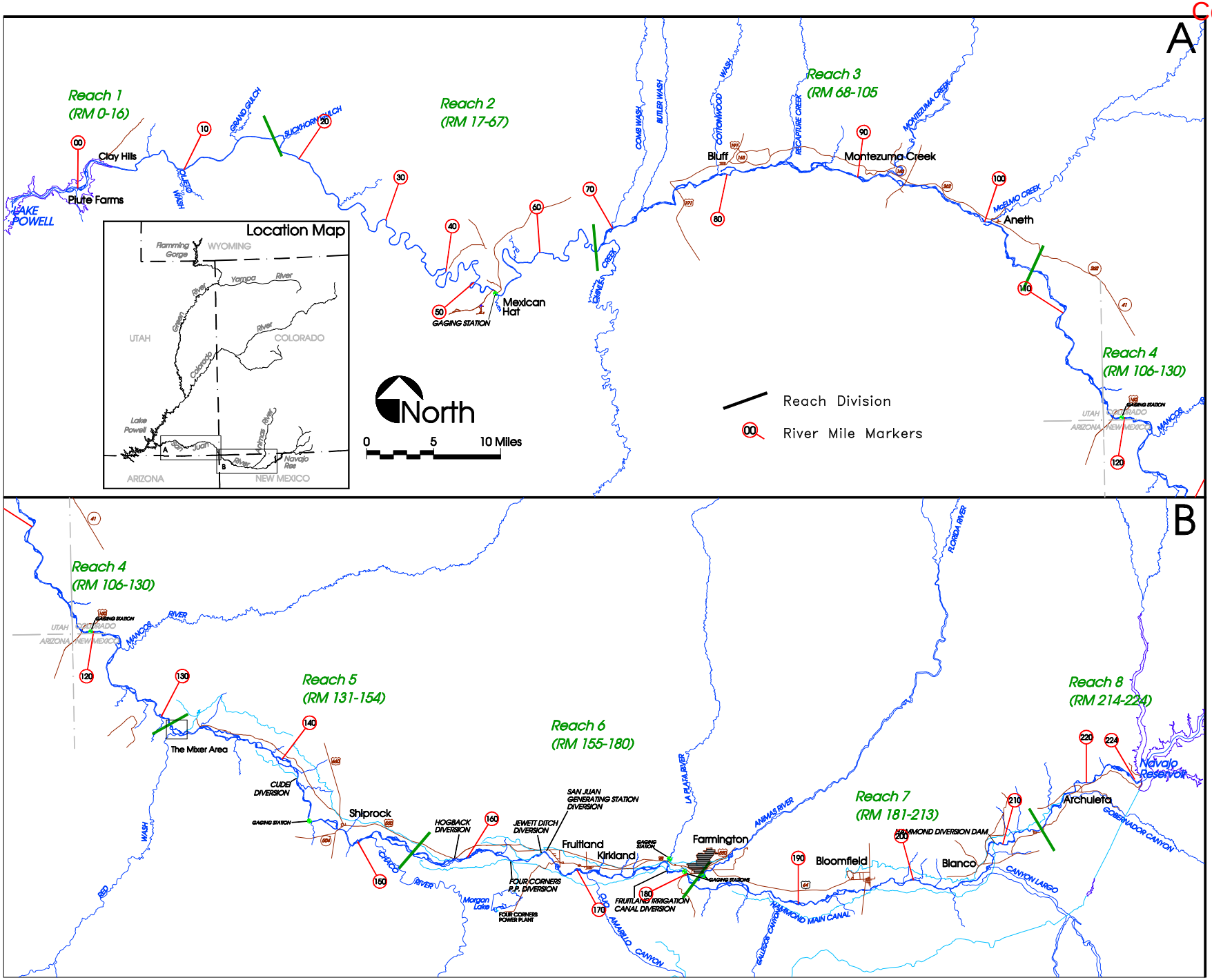

Figure 1.1. San Juan Basin Location Map

Closure of Navajo Dam altered the annual discharge pattern of the San Juan River. The natural flows of the Animas River ameliorated some aspects of regulated discharge by augmenting spring discharge. Regulation resulted in reduced magnitude and increased duration spring runoff in wet years and seriously reduced magnitude and duration spring flows during dry years. Overall, flow regulation by operation of Navajo Dam has resulted in post-dam peak spring discharge averaging about 54% of pre-dam values. After dam closure, base flows were increased substantially over pre-dam base flows.

Since 1992, Navajo Dam has been operated to mimic a "natural" hydrograph with the volume of release during spring linked to the amount of precipitation during the preceding winter. Thus in years with high spring snowmelt, reservoir releases were "large" and "small" in low runoff years. Base flows since 1992 were typically greater than during pre-dam years but less than post-dam years.

The primary study area for most studies conducted under the auspices of the San Juan River Seven Year Research Program, including that reported herein, were accomplished in the mainstem San Juan River and its immediate vicinity between Navajo Dam and Lake Powell. Between Navajo Dam and Shiprock there is considerable human activity within the floodplain of the San Juan River. Irrigated agriculture is practiced throughout this portion of the valley and much of the immediate uplands. Much of the river valley not devoted to agriculture (crop production and grazing) consists of small communities (e.g. Blanco and Kirtland) and several larger towns (e.g. Bloomfield and Farmington). The valley of the Animas River, the San Juan's largest tributary in the study area, is similarly developed. Downstream of Shiprock to Bluff small portions of the river valley (and uplands) are farmed; dispersed livestock grazing is the primary land use. In the vicinity of Montezuma Creek and Aneth, petroleum extraction occurs within the floodplain and the adjacent uplands. Between Bluff and the confluence with Lake Powell, there are few human-caused modifications of the system.

To enhance comparisons among studies and to provide a common reference for all research, a multivariate analysis of a variety of geomorphic features of the drainage was performed to segregate the river into distinct geomorphic reaches. This effort (See Chapter 3 for details) identified eight reaches between Navajo Dam and Lake Powell. The reach locations are shown on Figure 1.1. The following provides a brief characterization of each reach. The details behind the reach definitions appear in Chapter 3.

Reach 1 (RM 0 to 16, Lake Powell confluence to near Slickhorn Canyon) has been heavily influenced by the fluctuating reservoir levels of Lake Powell and its backwater effect. Fine sediment (sand and silt) has been deposited to a depth of about 12 m in the lowest end of the reach since the reservoir first filled in 1980. This deposition of suspended sediment into the delta-like environment of the river/reservoir transition has created the lowest-gradient reach in the river. This reach is canyon bound with an active sand bottom. Although there is an abundance of low velocity habitat at certain flows, it is highly ephemeral, being influenced by both river flow and the elevation of Lake Powell.

Reach 2 (RM 17 to 67, near Slickhorn Canyon to confluence with Chinle Creek) is also canyon bound but is located above the influence of Lake Powell. The gradient in this reach is higher than in either adjacent reach and the fourth highest in the system. The channel is primarily bedrock confined and

is influenced by debris fans at ephemeral tributary mouths. Riffle-type habitat dominates, and the major rapids in the San Juan River occur in this reach. Backwater abundance is low in this reach, occurring most in association with the debris fans

Reach 3 (RM 68 to 105, Chinle Creek to Aneth, Utah) is characterized by higher sinuosity and lower gradient (second lowest) than the other reaches, a broad floodplain, multiple channels, high island count, and high percentage of sand substrate. This reach has the second highest density of backwater habitats after spring peak flows, but is extremely vulnerable to change during summer and autum storm events, after which this reach may have the second lowest density of backwaters. The active channel leaves debris piles deposited throughout following spring runoff, leading to the nickname "Debris Field".

Reach 4 (RM 107 to 130, Aneth, Utah, to below "the Mixer") is a transitional reach between the upper cobble-dominated reaches and the lower sand-dominated reaches. Sinuosity is moderate compared with other reaches, as is gradient. Island area is higher than in Reach 3 but lower than in Reach 5, and the valley is narrower than in either adjacent reach. Backwater habitat abundance is low overall in this reach (third lowest among reaches) and there is little clean cobble.

Reach 5 (RM 131 to 154, the Mixer to just below Hogback Diversion) is predominantly multi-channeled with the largest total wetted area (TWA) and largest secondary channel area of any of the reaches. Secondary channels tend to be longer and more stable than in Reach 3 but fewer in number overall. Riparian vegetation is more dense in this reach than in lower reaches but less dense than in upper reaches. Cobble and gravel are more common in channel banks than sand, and clean cobble areas are more abundant than in lower reaches. This is the lowermost reach containing a diversion dam (Cudei). Backwaters and spawning bars in this reach are much less subject to perturbation during summer and fall storm events than the lower reaches.

Reach 6 (RM 155 to 180, below Hogback Diversion to confluence with the Animas River) is predominately a single channel, with 50% fewer secondary channels than Reaches 3, 4, or 5. Cobble and gravel substrates dominate, and cobble bars with clean interstitial space are more abundant in this reach than in any other. There are four diversion dams that may impede fish passage in this reach. Backwater habitat abundance is low in this reach, with only Reach 2 having less. The channel has been altered by dike construction in several area to control lateral channel movement and over-bank flow.

Reach 7 (RM 181 to 213, Animas River confluence to between Blanco and Archuleta, New Mexico) is similar to Reach 6 in terms of channel morphology. The river channel is very stable, consisting primarily of embedded cobble substrate as a result of controlled releases from Navajo Dam. In addition, much of the river bank has been stabilized and/or diked to control lateral movement of the channel and over-bank flow. Water temperature is influenced by the hypolimnetic release from Navajo Dam and is colder during the summer and warmer in the winter than the river below the Animas confluence.

Reach 8 (RM 213 to 224, between Blanco and Archuleta and Navajo Dam) is the most directly influenced by Navajo Dam, which is situated at its uppermost end (RM 224). This reach is predominantly a single channel, with only four to eight secondary channels, depending on the flow. Cobble is the dominant substrate type, and because lateral channel movement is less confined in this reach, some loose, clean cobble sources are available from channel banks. In the upper end of the reach, just below Navajo Dam, the channel has been heavily modified by excavation of material used in dam construction In addition, the upper 10 km of this reach above Gubernador Canyon are essentially sediment free, resulting in the clearest water of any reach. Because of Navajo Dam, this area experiences much colder summer and warmer winter temperatures. These cool, clear water conditions have allowed development of an intensively managed blue-ribbon trout fishery to the exclusion of the native species in the uppermost portion of the reach.

The studies in this report concentrate on the 359 km of river described as the SJRIP study area. However, the various studies reported here have narrower or broader focus, depending on the nature of the study. Geomorphic characterization studies have been completed for the main San Juan River from Navajo Dam to Lake Powell. Historical analyses have been completed for the San Juan Basin, including some tributaries, although the comparative historic aerial photos are primarily from the main stem of the river. This analysis extends from Navajo Dam to the original confluence with the Colorado River. Habitat mapping extent varies depending on the mapping run, with the most extensive mapping completed from Navajo Dam (RM 224) to the confluence with Lake Powell (RM 0). The Animas River from the Colorado state line to the confluence with the San Juan was also mapped in 1993 for baseline analysis. Habitat Quality studies were completed from Navajo Dam to the confluence with Lake Powell.

HISTORICAL SETTING

Little information on the nature of the San Juan River before man's intervention exists. Bryan (1925) reported an observation from 1849 describing the Chaco River, a tributary to the San Juan, as being 2.4 meters wide and 0.5 meters deep. However, by 1925, Bryan found that the river was 46 to 137 meters wide and 7 to 9 meters deep. This description is consistent with other reports that indicate the start of significant arroyo incision occurring between 1883 and 1890 for the Colorado Plateau (Graf 1987; Mundorff, 1982, Gellis, etal 1991). This rapid erosion of the watershed contributed large quantities of sediment to the San Juan River. Pierce (1917) and Miser (1924) indicated that the sediment load was so high during summer storm runoff that it had the "appearance of a stream of molen red metal, instead of its usual rough, choppy surface". Miser reported seeing fish floating on the surface during such events and locals reported fish kills associated with storm events. Miser attributed these mass loadings to a major change in the valley bottoms of adjacent tributaries which are now heavily eroded. He suggested the main cause to be a combination of overgrazing and climate change.

Unfortunately, no photographs of the river prior to 1883 could be found. An early set of aerial photography taken in 1935 by the Soil Conservation Service shows a broad, sandy channel bottom with little or no vegetation and an extensively braided stream for much of the river below Shiprock,

NM. With the large sediment loading that came as a result of water shed erosion prior to 1935, this condition is likely not representative of the natural channel.

In the early 1940's the sediment load to the San Juan River changed with a reduction in sediment inflow and outflow (Tompson, 1982). Theories for the change include climate change (Leopold, 1976), invasion of tamarisk (Graf, 1978) or the natural evolution of land forms (Gellis et al., 1991). These conditions have worked together to provide a reduction in sediment load and stabilization of the flood plain to allow establishment of vegetation and subsequent channelization of the river.

Since the condition of the river prior to the large sediment loading is unknown, no reliable model exists to describe the requirements to restore habitat to conditions that existed before man's intervention. Even if the nature of the channel prior to man's intervention was known, it is unlikely that changes in the operation of Navajo Dam could restore those conditions. Two many changes have occurred, including large deposits of sand and invasion of non-native vegetation, to allow restoration.

Since restoration of truly natural system is not possible, another approach must be taken. The conditions desirable for the target fish species must be identified based on present use in the San Juan River and other rivers in the Colorado River drainage, the response of those habitats to flow changes and habitat modification determined, and modifications to flow and habitat made to improve conditions for the native fish community. The studies reported here were designed to accomplish this.

CHAPTER 2: HYDROLOGY

BACKGROUND

United States Geological Survey (USGS) flow records for the San Juan River begin in 1911, but are not consistent or complete until about 1929. By this time substantial irrigation development had occurred. While the pre-Navajo Dam hydrology is natural in shape, it is depleted in volume by about 16 percent from natural conditions due to this irrigation development, with most of the depletion coming during the summer months. Since the depletion prior to Navajo Dam was relatively small and the flow was not regulated by major storage reservoirs, the conditions during the pre-dam period (1929-1961) are used to judge effects of later development and the value of future modification of the hydrology for the benefit of the endangered fishes.

Daily flow data recorded by the USGS (Hydrosphere 1998) from 1929 through the present are available for the key points on the San Juan River. These data have been used to analyze the changes in hydrology with time. The San Juan River's hydrology was very different before regulation by Navajo Dam beginning in 1962. Hydrology is discussed separately for the two periods (pre- and post-dam eras) to contrast the change.

Pre-Navajo Dam (1929 to 1961)

Characterized by large spring snowmelt peak flow, lower summer and winter base flows, and punctuated by high-magnitude, short-duration summer and fall storm events, the San Juan River is typical of dynamic rivers in the Southwestern United States. In addition, this system has a characteristically high sediment load, especially in the lower reaches. For the period 1929 to 1961 at the USGS gaging station near Bluff, Utah, approximately 73 percent of the total annual discharge occurred during spring runoff between March 1 and July 31. The median daily peak discharge (peak daily mean discharge as recorded by USGS does not represent instantaneous peak flow) during spring runoff was 10,500 cfs, with a range of 3,810 to 33,800 cfs. The average pre-dam hydrograph (average of all daily flows from 1929 to 1961) for the San Juan River near Bluff is shown in Figure 2.1.

While the spring runoff produces the largest total volume of water, about 30 percent of the time the yearly peak flow does not occur during spring. Furthermore, the maximum daily average discharge for the period during spring is 33,800 cfs, while the maximum daily average discharge annually is 42,500 cfs. This difference is due to summer and fall storm events. These summer and fall storm events have a small impact on the total water supply, but due to the heavy sediment load, they substantially influence habitat formation and maintenance.

The magnitude of summer and fall storm events in the San Juan River Basin is higher in relation to the mean flow than those noted in the Colorado and Green river basins. In the San Juan River, 97 percent of the years between 1929 and 1961 had at least one storm event during the period of August

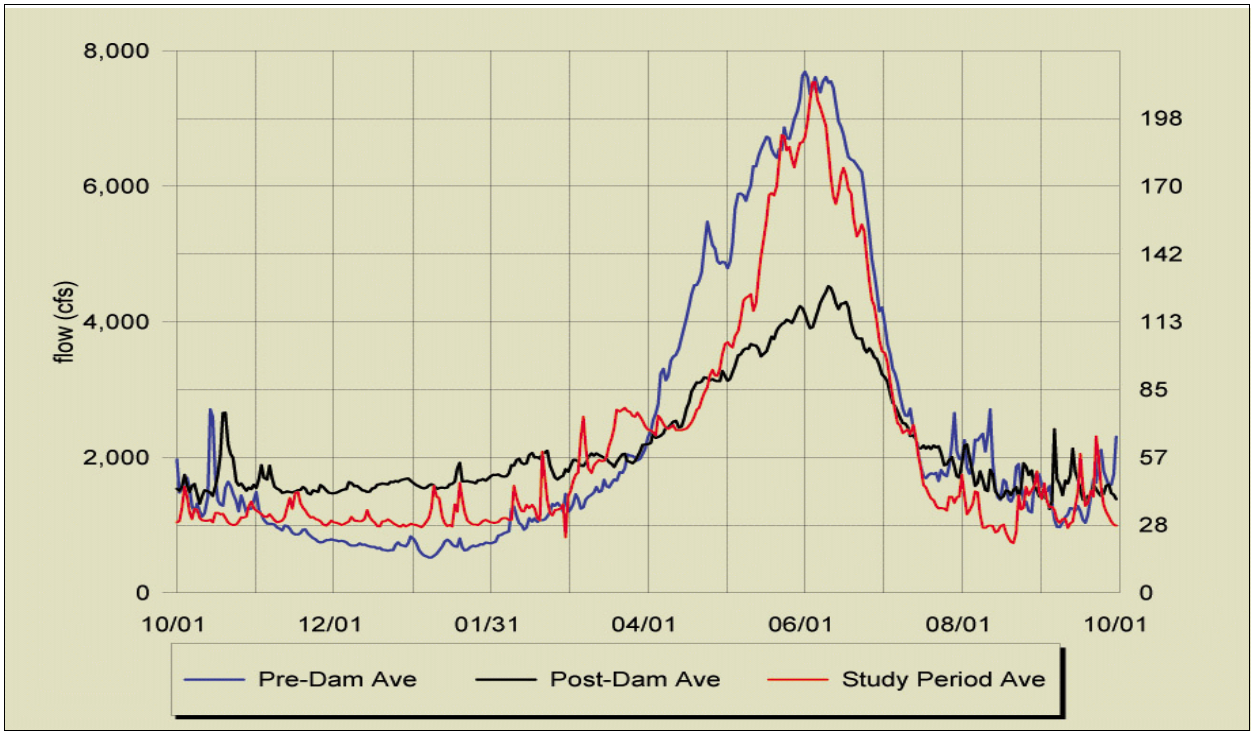

Figure 2.1. San Juan River near Bluff, Utah, average hydrographs for pre-dam, post-dam and 1992-1998 study period.

through November resulting in flows three or more times the average monthly flow for that; 55 percent of the time, the resultant discharge was eight or more times the mean monthly flow, with a maximum daily mean peak to average flow ratio of nearly 13. In comparison, neither the Green River gage nor the Colorado River gage has ever recorded a storm event with a daily mean peak greater than five times the average monthly flow.

The frequency of summer and fall storm events is also higher in the San Juan River Basin. For the period 1929 to 1961, the San Juan River Basin had nearly five times as many days per month with storm events above two times the average base flow, compared with the Green or Colorado rivers. The higher frequency and magnitude of storm events in the San Juan River Basin compared with the Green and Colorado river basins result from the late summer monsoonal influence of the southwestern desert climate. The comparison of average monthly ratios of maximum mean daily flow to daily average flow for the month for the three rivers, along with the average duration of flows above two times the mean monthly flows for the three rivers, appears in Table 2.1.

Annual discharge variability is also a characteristic of the San Juan River. The annual discharge near Bluff for the pre-dam period ranged from 618,000 acre-feet (af) to 4,242,000 af with a median of 1,620,000 af. The maximum flow is 285% of the median while the minimum flow is 41% of the median. This variation in flow is more extreme on the high flow end than the Green or Colorado rivers. For the Green river, the maximum flow is 165% of the median and the minimum 31%. The

maximum discharge in the Colorado is 182% of the median and the minimum 47%. Furthermore, the hydrology appears to follow cyclic patterns of multiple years of high flow followed by multiple years of low flow where up to four sequential years may have total discharge less than 1,000,000 af. This pattern is characteristic of drought/flood desert climate cycles.

Although the pre-dam era is considered relatively natural, irrigation and other water development depletions have occurred annually since the settlement of the San Juan River Basin. As a result, the pre-dam hydrology was not pristine. Summer and winter base flows during the pre-dam period were low but variable. Typically, summer flows were lowest due to irrigation depletions, and periods of near zero flow were not uncommon. Flows of less than 50 cfs have a recurrence frequency of 29 percent, with an average duration of 11 days. Monthly mean flows were as low as 65 cfs.

Table 2.1. Comparison of storm magnitude and frequency for the Colorado River at Cisco gage, Green River at Green River gage, and San Juan River near Bluff gage, 1929-1961.

	RATIO AVE MAX DAILY /AVG MONTHLY DISCHARGE			AVG NO. OF DAYS FLOW EXCEEDED 2 TIMES AVE MONTHLY FLOW		
Month	**Colorado R. at Cisco**	**Green R. at Green R.**	**San Juan R. near Bluff**	**Colorado R. at Cisco**	**Green R. at Green R.**	**San Juan R. near Bluff**
Oct	1.59	1.46	3.08	0.18	0.06	1.67
Nov	1.24	1.24	1.87	0.00	0.06	0.45
Dec	1.26	1.39	1.75	0.03	0.00	0.33
Jan	1.22	1.25	1.83	0.00	0.00	0.42
Feb	1.24	1.34	1.96	0.00	0.03	1.00
Mar	1.41	1.80	1.91	0.03	1.09	0.70
Apr	1.89	1.74	1.81	1.00	0.48	0.58
May	1.72	1.60	1.78	0.48	0.15	0.52
June	1.54	1.42	1.75	0.09	0.00	0.42
July	1.87	1.90	2.70	0.55	0.79	2.09
Aug	1.75	1.62	3.52	0.42	0.12	2.79
Sep	1.84	1.66	3.78	0.39	0.18	2.52
Ave	1.55	1.54	2.31	0.26	0.25	1.12
Mean annual flow - cfs				7,089	5,557	2,420
Mean base flow (August - January) - cfs				3,153	2,265	1,171
Ratio, base flow to mean annual flow				0.44	0.41	0.48

Post-Dam Period (1962 to 1991)

Completion of Navajo Dam and subsequent dam operation substantially altered the natural hydrograph of the San Juan River below the dam. Although the Animas River ameliorated some effects of the dam and maintained an elevated spring runoff, the system overall experienced an appreciable reduction in magnitude and change in timing of the annual spring peak. In years of high runoff, dam releases began early to allow space in the reservoir to store the runoff. In the wettest years, releases continued through the peak season (May and June), but during many years, dam releases in May and June were close to the average base release of about 600 cfs. The peak discharge during the post-dam period averaged 54 percent of the spring peak during the pre-dam period.

Base flows were substantially elevated in the post-dam compared with the pre-dam period. The median monthly flow for the base-flow months of August through February averaged 168 percent of the pre-dam period. Minimum flows were also elevated. The near-zero flow periods were eliminated, with a minimum monthly flow during base-flow periods of 250 cfs compared with 65 cfs for the pre-dam period. Summer storm runoff was not directly affected by the dam, especially in terms of high sediment input, because these events can be generated below the influence of the dam. The average post-dam hydrograph (average of daily flows for 1962 to 1991) is shown in Figure 2.1, allowing comparison with the average pre-dam hydrograph.

OBJECTIVES

Since the outset of the SJRIP, mimicry of a natural hydrograph has been hypothesized as necessary to meet the biological and habitat needs of the fish (SJRIP Biology Committee, 1995). The seven-year research program was designed to test the response of the fish and their habitat to a range of hydrologic conditions to provide the data necessary to quantify the required mimicry in the San Juan River. With this need, the following objectives were established:

- Provide a range of flows in the habitat area that would represent wet and dry conditions with a naturally shaped hydrograph.
- Define release hydrographs that would allow testing shape and magnitude in relation to available water supply.
- Define the relationship of the resulting flows to historic conditions, both pre- and post-Navajo Dam.
- Analyze the effect of Navajo Dam and research period test releases on water temperatures downstream in the San Juan River.

METHODS

Beginning in 1991, Navajo Dam release requests were developed by the research group (Biology Committee beginning in 1993), based on information from the Bureau of Reclamation (Burec) on the available water supply. The release hydrographs were defined in terms of the shape of the ascending limb, magnitude and duration of the peak flow and the shape of the descending limb. Both wet years

and dry years were tested. Due to operating constraints at Navajo Dam, not all requests could be precisely met, but most years the release was close to the requested release. In wet years, extra releases prior to the normal runoff season were necessary to prevent reservoir spills.

USGS gage records were used to assess the resulting hydrograph at Archuleta, Farmington, Shiprock, Four Corners and Bluff. Comparisons of the long term gage record near Bluff, UT to that of the research period were completed to assess the degree of mimicry attained during the research period and allow definition of long term operating criteria.

USGS water temperature data recorded at the San Juan River gages at Archuleta and Shipriock, NM and at the Animas River Gage at Farmington were compared for pre-dam and post-dam conditions to explore the effect of Navajo dam on downstream water temperatures.

Table 2.2. Water temperature monitoring locations and period of record.

Location	RM	Period of Record
Archuleta - San Juan at USGS Gage Location	218.6	7/23/92 to 9/22/98
Blanco - San Juan at US-64 Bridge	207.1	8/7/92 to 2/28/95 (missing 11/21 - 12/9/92)
Bloomfield - San Juan at Highway 44 Bridge	195.6	2/27/93 to 7/17/98
Lee Acres - San Juan at Lee Acres Bridge	188.9	8/8/92 to 12/2/92, 2/26/93 to 4/15/93, 5/27/93 to 9/6/94, 3/9/95 to 10/10/95
Farmington - San Juan at USGS Gage Location	180.1	8/5/92 to 1/16/96
Four Corners - San Juan at USGS Gage Location	119.4	10/7/94 to 3/11/96 *
Montezuma Creek - San Juan at Montezuma Creek Bridge	93.6	8/9/92 to 1/11/93, 2/25 to 3/14/93, 4/14 to 5/10/93, 5/28/93 to 9/21/98
Cedar Hill - Animas at USGS Gage nr Cedar Hill	n/a	8/7/92 to 9/22/98
Farmington - Animas at USGS Gage Location	n/a	8/5/92 to 4/14/97, 5/7/97 to 8/26/97, 10/15/97 to 6/4/98
USGS Data - San Juan at Archuleta	218.6	10/1/50 - 9/30/68 with some missing data
USGS Data - San Juan at Shiprock	148.0	10/1/51 - 9/30/86,9/7/91 - 3/3/93 with some missing data
USGS Data - Animas	n/a	10/1/52 - 9/30/90 with some missing data

Note all locations missing October 1992 data
* installed 8/10/92 but bad data was logged until thermistor was changed in October 1994. Prior to this time is was thought sediment accumulation was causing the warmer readings instead of bad thermistor.

Nine temperature recorders were installed in the San Juan and Animas rivers in July and August of 1992 at the locations shown in Table 2.2. Each station consists of a temperature sensor, lead wires and an OMNIDATA DP-230 data pod. The temperature is sampled every 10 minutes and stored every 24 hours as a maximum, minimum and mean temperature for the day. Also shown in Table 2.2 are the periods of record at each site. Equipment problems impacted the available data.

The USGS has maintained temperature monitoring at Shiprock and Bluff. However, equipment malfunctions have limited the usefulness of these data in recent years and the record at Shiprock terminated in 1992. Shiprock has the best historic record, so having an extended record for this station through the research period was important to the trend analysis. Since the USGS data were incomplete, a Shiprock temperature record was computed from our recorded data based on a linear regression with temperature data at Montezuma Creek and Farmington.

RESULTS

Research releases from Navajo Dam were made every year from 1992 through 1998 (1991 was a control year with no modification to the release) to augment the unregulated flows from the Animas River and provide peak spring runoff flows mimicking a natural hydrograph in the San Juan River below Farmington, NM. Table 2.3 describes the nature of the release each year. The volume of water released in excess of an assumed base release of 600 cfs normally required to meet downstream demands is also shown.

The reservoir release pattern for each year was determined in anticipation of certain flow conditions in the critical habitat range (Farmington to Lake Powell) resulting from the release. However, the flow patterns from the Animas River and other downstream tributaries are not predictable in terms of shape or timing. Therefore, the results anticipated were not always realized. Table 2.4 summarizes the anticipated and actual effects of these releases on downstream hydrology.

The hydrographs at Four Corners for these years appear in Figures 2.2 and 2.3. The flow statistics that apply to these hydrographs appear in Table 2.5. The Four Corners gage is considered the most representative gage for the habitat range and is used in all correlations reported here. However, to do long term statistical comparisons, it is necessary to use the Bluff gage, since the Four Corners gage does not have a long period of record. The statistical comparisons for the Bluff gage are presented in Table 2.6, showing the statistics for the research period with a comparison to the pre-dam (1929-1961) period. The comparison shows that the mean peak flow for the pre-dam period was never reached in any single year during the research period, although the mean runoff volume was exceeded three times. This reflects the limited discharge capacity of the dam and its effect on peak discharge in the river below. Although there are some limitations in the ability of the system to meet the magnitude of pre-dam peak flows, the ability of the system to be managed to produce a more natural hydrograph has been demonstrated. Examination of the statistics for the individual years

shows that a reasonable range of conditions were tested to provide a basis for establishing flow recommendations. Ascending limb, descending limb, breadth and magnitude of peak and total volume of runoff were all varied to provide different hydrologic conditions in each year of the study. Wet, dry and intermediate years were also represented in rough proportion to their natural occurrence.

Table 2.3. Summary of Navajo Dam release hydrograph characteristics during the research period, 1992 to 1998.

YEAR	ASCENDING LIMB	PEAK	DESCENDING LIMB	MATCHED ANIMAS RIVER PEAK	VOLUME ABOVE 600 CFS BASE - AF
1992	6 weeks starting April 13	2 weeks at 4,500 cfs	4 weeks ending July 15	Yes	409,740
1993	Starting March 1, rapid increase to 4,500 (compare with 1987)	split peak, 45 days at 4,500 cfs, 7 days at 4,500 cfs	4 weeks ending July 13	No	773,820
1994	4 weeks starting April 23	3 weeks at 4,500 cfs	6 weeks ending July 28	Yes	486,620
1995	3 weeks at 2,000 cfs in March, ramp to 4,500 over 6 weeks starting April 1	3 weeks at 5,000 cfs	4 weeks ending July 14 (summer flow increased by 200 cfs)	Yes	675,810
1996	1 week starting May 27	3 weeks at 2,500 cfs	1 week ending June 29	No	100,320
1997	3 weeks at 2,000 cfs in March, return to 600-cfs base for 31 days, 10 days starting May 12	2 weeks at 5,000 cfs	6 weeks ending July 16	Yes	433,580
1998	30 days starting April 23	3 weeks at 5,000 cfs	1 week ending June 18	Yes	340,850

Table 2.4. Anticipated and Actual flow conditions achieved in the San Juan River below Farmington as a result of designed releases at Navajo Dam.

YEAR	ANTICIPATED CONDITION	ACTUAL CONDITION
1992	Gradual ascending and moderate descending limbs with a large peak centered near the historical mean	Relatively steep ascending and descending limbs with moderately large peak centered near the historical mean
1993	Long ascending limb, moderate descending limb and large peak centered near the historical mean	Long ascending limb, relatively steep descending limb with moderately large peak centered near the historical mean
1994	Moderate ascending limb, gradual descending limb and large peak centered near the historical mean	Moderate ascending limb, sharp descending limb with earlier reduced magnitude peak
1995	Gradual ascending limb, moderate descending limb and large peak centered near the historical mean	Gradual ascending limb, moderate descending limb and large peak centered later than the historic mean
1996	Sharp ascending and descending limb and low, extended peak designed late to extend the runoff period in this dry year	Sharp ascending and descending limb with low extended, split peak
1997	Sharp ascending limb, gradual descending limb and high, short duration early peak	Sharp ascending and descending limbs and high, split peak centered near the historical mean
1998	First year of applying the proposed flow recommendation with a moderate ascending limb, steep descending limb and high, moderate duration peak centered near the historical mean	Moderate ascending limb, steep descending limb and moderate peak centered near the historical mean.

The hydrograph statistics for the average pre-dam, post-dam and research period conditions are presented in Table 2.7 and the three average hydrographs are plotted in Figure 2.1. Comparison of the statistics in the table and the three graphs demonstrates the more natural like hydrograph that has resulted from re-operation of Navajo Dam during the research period. While the statistics are not directly comparable due to the much shorter time during the research period, some general observations can be made. The apparent decrease in total annual runoff during the research period compared to the pre-dam period is due entirely to increased depletions from the river resulting primarily from the Navajo Indian Irrigation Project (NIIP), the San Juan-Chama Project, and other contracts out of Navajo Dam. With the adjustment for depletions made (Table 2.6), the runoff for this period was actually greater by about 6%.

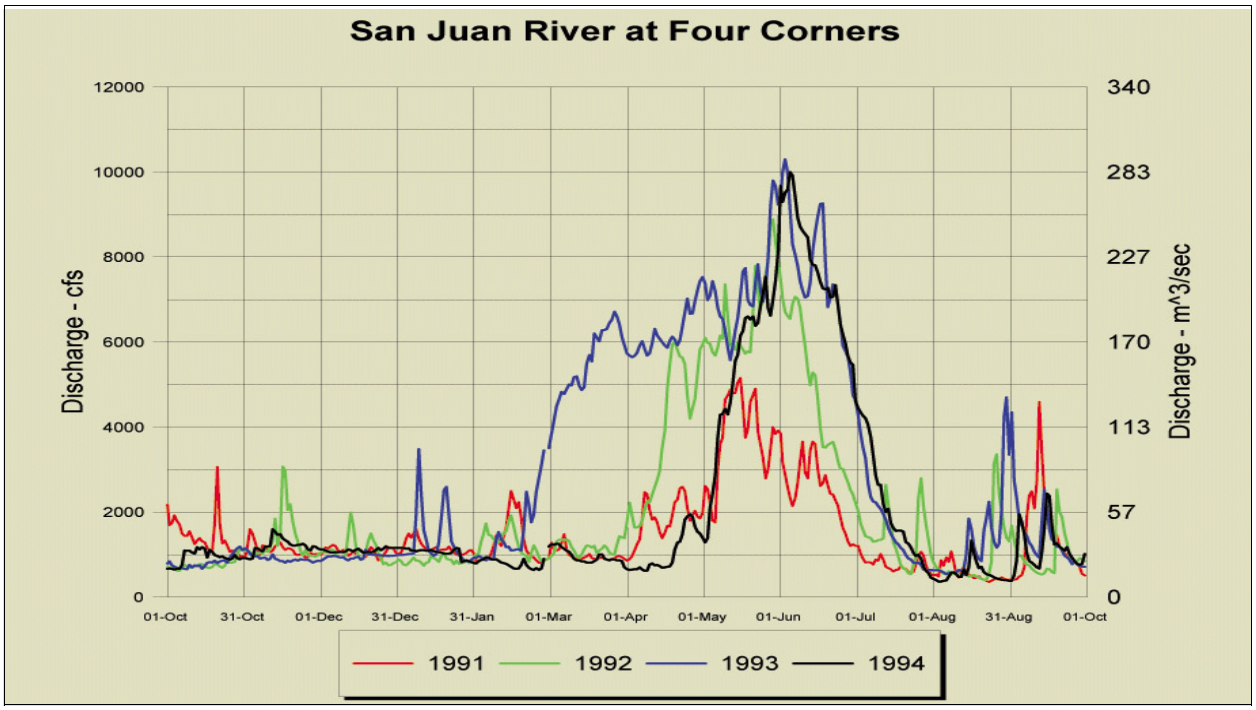

Figure 2.2. Hydrographs for the San Juan River at Four Corners for 1991 - 1994.

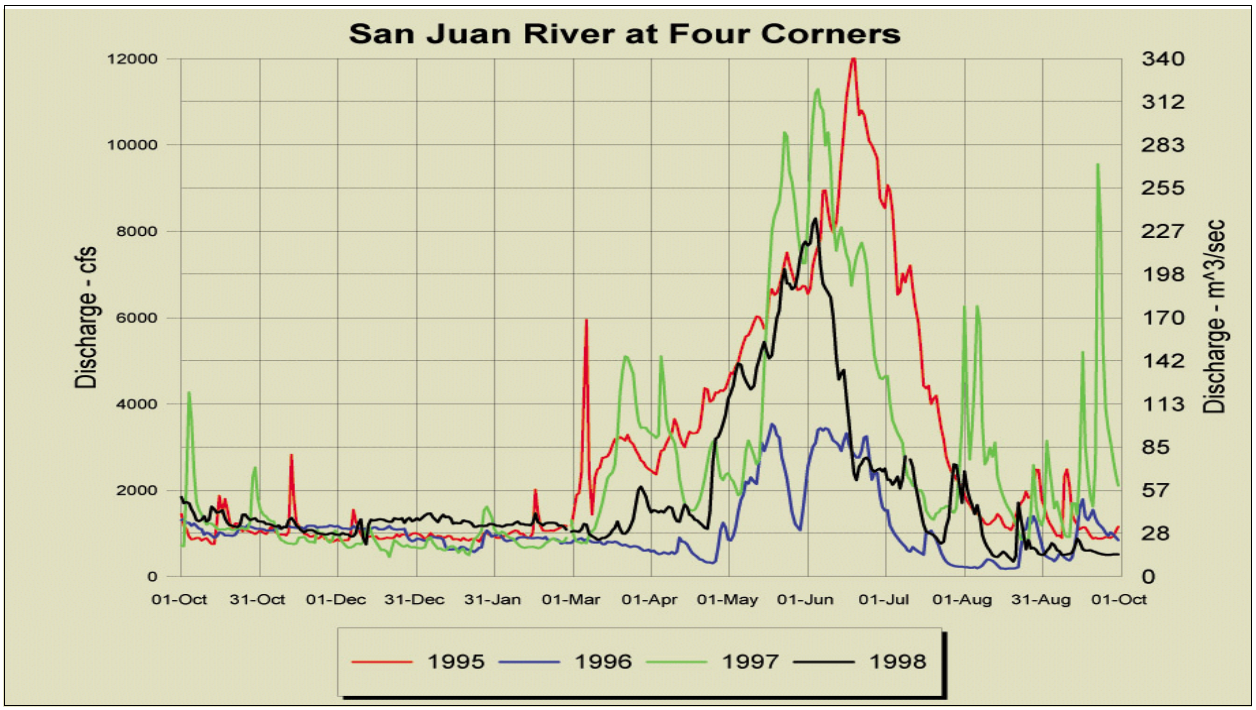

Figure 2.3. Hydrographs for the San Juan River at Four Corners for 1995 - 1998.

Table 2.5. Summary of research flows for the research period, San Juan River at Four Corners, New Mexico.

	1991	1992	1993	1994	1995	1996	1997	1998
San Juan River at Four Corners, New Mexico								
Peak Runoff-cfs	5,160	8,900	10,300	10,000	12,100	3,540	11,900	8,300
Runoff(Mar-Jul)-af	599,459	1,074,795	1,714,328	1,039,601	1,624,927	431,913	1,338,539	855,320
Runoff(total annual)-af	1,086,676	1,512,795	2,216,819	1,448,893	2,102,228	815,795	1,844,019	1,374,229
Peak Date	16-May	29-May	03-Jun	05-Jun	19-Jun	18-May	04-Jun	04-Jun
Days>10,000	0	0	1	0	11	0	10	0
Days>8,000	0	3	16	13	27	0	33	2
Days>5,000	2	54	109	49	72	0	50	31
Days>2,500	46	81	128	67	135	36	100	67
Ave. Daily Flow for month								
October	1,449	769	827	941	1,109	1,091	1,276	1,410
November	1,127	1,356	911	1,210	1,077	1,139	883	1,126
December	1,080	1,088	957	1,105	960	1,088	702	1,191
January	1,173	859	1,358	1,050	918	785	789	1,292
February	1,289	1,298	1,511	781	1,076	899	690	1,211
March	995	1,173	5,463	967	2,782	766	2,255	1,207
April	1,810	3,723	6,188	1,028	3,478	607	2,529	1,801
May	3,739	6,634	7,298	5,251	6,119	2,150	6,000	5,632
June	2,580	4,844	7,701	7,836	9,367	2,925	8,514	4,666
July	801	1,444	1,776	2,170	5,187	715	2,904	1,732
August	556	927	1,348	552	1,564	492	2,310	931
September	1,441	997		1,142	1,193	891	2,365	594

An examination of Figure 2.1 reveals an apparent match of mean peak discharge for the pre-dam and research period. This is somewhat misleading, in that the timing of the peak varied more greatly during the pre-dam period, resulting in a more averaged peak than for the research period. When the peak runoff is averaged without regard to timing, then the difference is apparent (Table 2.7). Both Table 2.7 and Figure 2.1 show the decrease in runoff during the March to July period that occurred primarily on the ascending limb of the hydrograph. The base flow during the fall and winter were closer to pre-dam conditions, although still somewhat elevated.

Table 2.6. Summary of research flows for the pre-dam and research periods, San Juan River near Bluff, Utah.

	1929-61	1991	1992	1993	1994	1995	1996	1997	1998
				San Juan River near Bluff, Utah					
Peak Runoff-cfs	12,409	4,530	8,510	9,650	8,290	11,600	3,280	11,300	7,960
Runoff (Mar-Jul)-af	1,263,890	573,863	1,025,622	1,681,192	887,252	1,503,533	421,001	1,278,795	855,320
(total annual)-af	1,750,643	1,084,540	1,504,916	2,271,912	1,289,521	2,011,415	797,821	1,893,403	1,374,229
Peak Date	31-May	16-May	29-May	30-May	06-Jun	19-Jun	16-Jun	05-Jun	04-Jun
Days>10,000	14	0	0	0	0	6	0	8	0
Days>8,000	23	0	4	13	1	19	0	22	0
Days>5,000	46	0	44	109	41	68	0	46	28
Days>2,500	82	42	79	128	64	137	37	95	56
Ave Daily Flow for month-cfs									
October	2,863	1,628	716	885	1,054	1,145	1,123	1,521	1,639
November	1,858	1,173	1,479	1,013	1,160	1,123	1,181	982	1,213
December	1,405	1,009	1,187	995	1,066	1,033	1,065	769	1,212
January	1,336	1,053	860	2,053	1,047	1,007	739	832	1,391
February	2,115	1,541	1,517	2,256	838	1,175	819	807	1,352
March	3,250	1,179	1,205	5,741	1,081	2,970	739	2,552	1,321
April	7,881	1,684	3,296	6,369	928	3,298	599	2,676	1,686
May	12,484	3,357	6,278	6,840	4,680	5,753	1,974	5,629	5,424
June	13,078	2,474	4,590	7,136	6,055	8,749	2,874	8,000	4,159
July	4,825	807	1,624	1,787	1,961	4,158	798	2,358	1,559
August	3,548	650	1,020	1,195	529	1,581	476	2,497	1,096
September	2,844	1,470	1,219	1,456	976	1,349	860	2,756	708
Frequency of exceedence - annual		67%	52%	36%	58%	39%	91%	39%	58%
Frequency of exceedence - runoff		88%	55%	39%	55%	39%	94%	42%	58%
Frequency of exceedence - peak		94%	61%	58%	61%	41%	100%	45%	67%
Uniqueness		Control	early ave.	early ascent	late ave.	late peak	dry	narrow runoff	early ave.
			storm @ spawn					storm @ spawn	storm @ spawn

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Table 2.7. Comparison of hydrograph statistics for pre-dam (1929-1961), post-dam (1962-1991) and research period (1992-1998) for the San Juan River near Bluff, Utah.

PARAMETER	1929-1961 PRE-DAM PERIOD			1962-1991 POST-DAM PERIOD			1992-1998 POST-DAM PERIOD		
	Average	**Minimum**	**Maximum**	**Average**	**Minimum**	**Maximum**	**Average**	**Minimum**	**Maximum**
Peak Runoff - cfs	12,409	3,810	33,800	6,749	2,660	15,200	8,656	3,280	11,600
Runoff (Mar-Jul) - af	1,263,890	352,551	3,361,882	891,712	177,190	2,458,190	1,093,245	421,001	1,681,192
Runoff (total ann) - af	1,750,643	618,101	4,241,998	1,587,242	611,196	3,266,017	1,591,888	797,821	2,271,912
Runoff (total ann) - af, adjusted for pre-dam depletions							1,862,000	1,068,000	2,542,000
	Years	**Total Yrs**	**Frequency**	**Years**	**Total Yrs**	**Frequency**	**Years**	**Total Yrs**	**Frequency**
Peak>10,000 cfs	18	33	55%	6	30	20%	2	7	29%
Peak>8,000 cfs	22	33	67%	11	30	37%	5	7	71%
Peak>5,000 cfs	30	33	91%	16	30	53%	6	7	86%
Peak>2,500 cfs	33	33	100%	27	30	90%	7	7	100%
AF>1,000,000	18	33	55%	12	30	40%	4	7	57%
AF>750,000	22	33	67%	14	30	47%	6	7	86%
AF>500,000	30	33	91%	20	30	67%	6	7	86%
	Ave. Date	**Std Dev.**		**Ave. Date**	**Std Dev.**		**Ave. Date**	**Std Dev.**	
Peak Date	31-May	23		01-Jun	35		06-Jun	7	
Flow Duration	**Avg all yrs**	**Avg flow yrs**	**Maximum**	**Avg all yrs**	**Avg flow yrs**	**Maximum**	**Avg all yrs**	**Avg flow yrs**	**Maximum**
Days>10,000 cfs	14	27	76	3	15	48	2	7	8
Days>8,000 cfs	23	34	81	8	22	84	8	12	22
Days>5,000 cfs	46	51	108	28	52	124	48	56	109
Days>2,500 cfs	82	82	140	67	74	150	85	85	137
Base Flow	**Median**	**High 10%**	**Low 10%**	**Median**	**High 10%**	**Low 10%**	**Median**	**High 10%**	**Low 10%**
August	1,156	4,782	300	1,566	3,242	407	1,096	2,497	476
September	1,033	3,383	201	1,174	3,279	478	1,221	2,760	708
October	1,000	2,551	400	1,608	3,317	635	1,123	1,639	716
November	752	1,387	497	1,199	3,205	765	1,160	1,479	982
December	667	1,325	434	1,288	3,389	711	1,065	1,212	769
January	609	1,267	471	1,440	3,226	582	1,007	2,053	739
February	872	2,265	572	1,661	3,188	823	1,175	2,256	807

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Storm Influence

The San Juan River is heavily influenced by high intensity summer and fall advective storms. These storms produce short duration flow increases that are heavily sediment laden and have been associated with deterioration of habitat quality in the San Juan River (See Chapters 3, 6 and 7). In the flow recommendation report (Holden, 1999), the conditions that impacted habitat quality were described, based on calibration to observed impacts from storm events. A storm-event day was defined in that study as a day in which the daily gain in flow between Farmington, New Mexico and Bluff, Utah, and the daily flow at Bluff, Utah, were each more than 150 cfs greater than the preceding 5-day average. A storm-event day was given a weight of 2 if the gain in flow was 3,000 cfs or more. In the flow/habitat model presented in that report, a year in which there were more than 12 storm-event days during August through December was determined to be a year in which the backwater habitats were filled with sediment (perturbated) to the point that flushing was required to restore them. Figure 2.4 shows the frequency distribution of storm-event days for the period 1931 - 1998 for the San Juan River at Farmington, New Mexico and near Bluff, Utah. This figure shows that at Bluff, Utah, the number of storm-event days exceeded the 12-day threshold about 50% of the time. Field observations of river substrate condition through the summer suggested that these perturbating conditions occur more frequently and with greater severity at downstream locations. The plot of storm-event days for Farmington confirm this observation. Figure 2.4 shows that at Farmington, New Mexico, the 12-day threshold was exceeded only about 10% of the time. The shorter gage record and Shiprock and Four Corners, New Mexico did not allow full comparison, but indicate for the shorter period that most of the increase in storm-event frequency occurs below Four Corners, although some increase in frequency over Farmington is likely.

The obvious conclusion is that spawning bars and backwater habitats would be less disrupted and more easily maintained in the upper reaches of the river, particularly between Farmington and Four Corners.

Water Temperature

The average daily temperature for the San Juan River at Archuleta and at Shiprock are plotted on Figure 2.5. The averages plotted for Archuleta are 1951 - 1961 (pre-dam) and 1964 - 1968 (post-dam). The Shiprock Averages are for the period 1951 - 1961 and 1964 - 1986. Also shown on the plot are the data for Shiprock, averaged over the research period, 1992 - 1998. From March 13, 1993 to September 30, 1998, the Shiprock data is synthesized from a linear regression equation that predicts San Juan at Shiprock temperature from San Juan at Farmington and San Juan at Montezuma Creek temperature based on the following equation developed utilizing 127 values of coincident temperature record from the fall of 1992 through March 13, 1993.:

$$WT_{Shiprock} = 0.4342*WT_{Farmington} + 0.618\ WT_{Montezuma\ Cr.} - 0.654\ (R^2 = .997,\ p < .001)$$

Where WT = water temperature in °C.

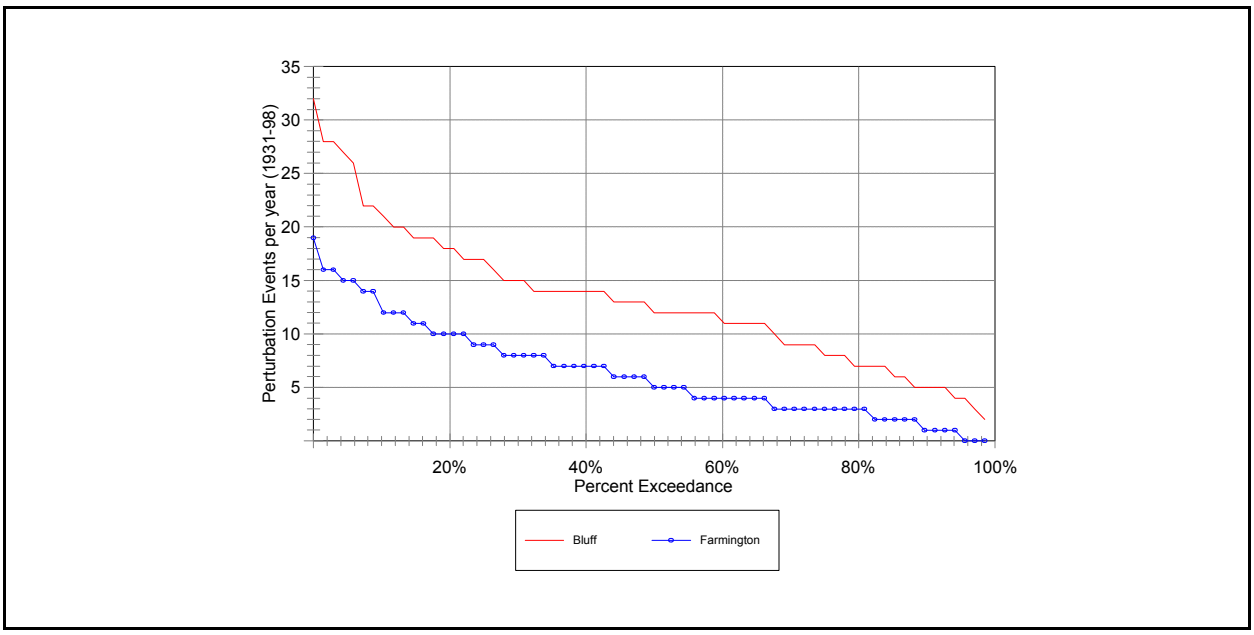

Figure 2.4. Frequency distribution of storm-event days for the San Juan River at Farmington, New Mexico and near Bluff, Utah, 1931-1998.

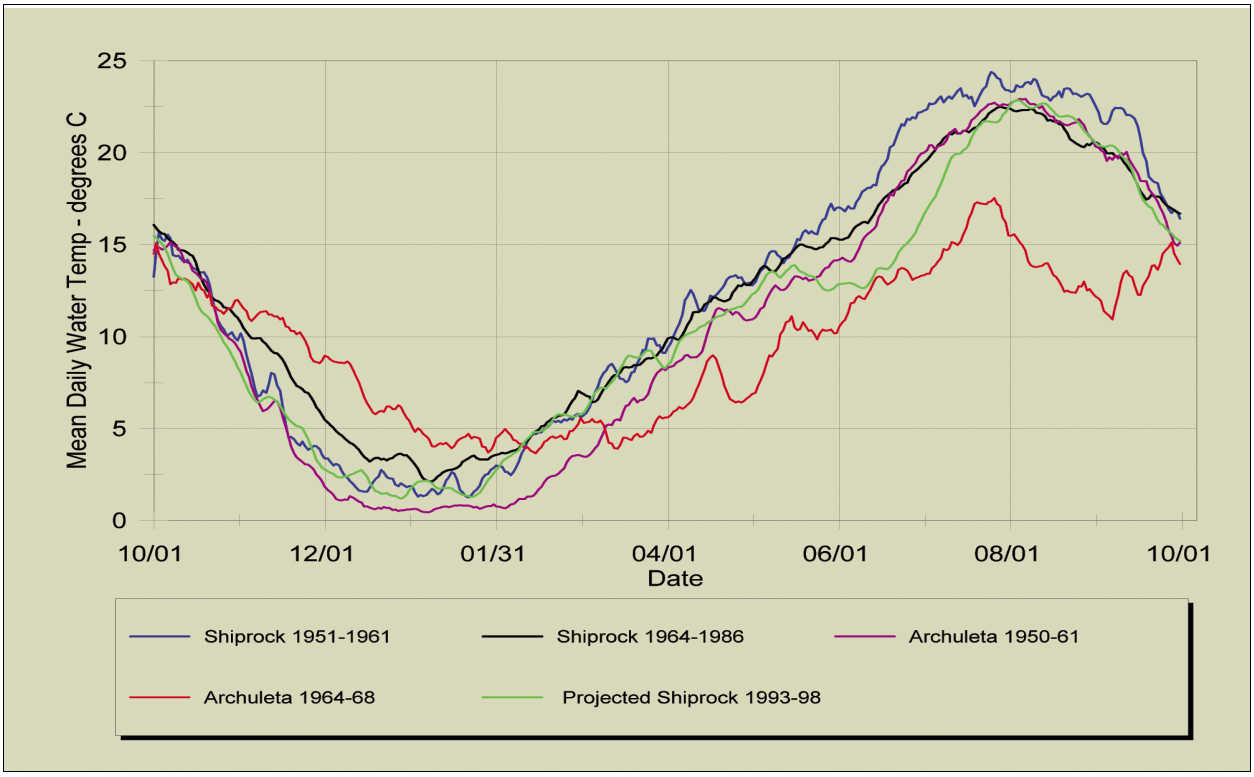

Figure 2.5. Seven-day running mean daily water temperature for the San Juan River at Archuleta, New Mexico, and at Shiprock, New Mexico during pre-dam, post-dam and research flow periods.

Comparing the Archuleta pre- and post-dam temperature profiles, the effect of Navajo Dam is obvious. The monthly average temperature is as much as 9 °C cooler in the summer and as much as 6°C warmer in the winter since regulation by Navajo Dam began when comparing the two time periods. Since the second time period is rather short, a check on Animas River temperatures for the same two periods was made. It was found that the 1964 - 1968 period was about 0.75 °C warmer than the 1951-1961 period. Therefore, the impact of Navajo Dam on water temperature at Archuleta is at least as great as that shown. The effect of Navajo Dam at Shiprock is less pronounced due to solar heating in this intervening 70 miles of river and the effects of Animas River inflow. Though less pronounced than the effect at Archuleta, the effect is similar. The 1964 - 1986 period is about 2 °C cooler in the spring and summer and as much as 2.5 °C warmer in the winter.

By comparing the 1993 - 1998 period to the earlier periods the incremental effect of re-operation of Navajo dam on temperatures downstream can be determined. The plot shows a temperature depression during runoff (May and June) that is attributable in part to cooler temperatures in the Animas during this period compared to the 1964-86 period. However, the cooler Animas water accounts for only about ½ of the temperature difference between the 1964-86 and the 1992-1998 Shiprock temperature. The impact of the increased release of the cool reservoir water is a suppression in temperature of about 1.5° C during runoff.

With a threshold spawning temperature of 20 °C for Colorado pikeminnow, the effect of Navajo Dam without reoperation is a delay in reaching the threshold temperature of about 15 days. With re-operation and the resulting release of cool water during spring runoff, the date the threshold is reached was extended about 7 more days.

Prior to dam construction, this threshold temperature was reached at Archuleta about11 days earlier than the present date at Shiprock. After dam completion, Archuleta has not reached the threshold temperature of 20 °C. This cooling condition could have the effect of both delaying spawning and moving it further down river.

DISCUSSION

Review of the pre-dam and post-dam hydrograph and flow statistics demonstrate the substantial impact imposed on the hydrology of the San Juan River by the operation of Navajo dam. The spring peak was materially reduced, while the winter base flow was substantially increased, leading to less variability in the flow and an appreciable departure from the pre-dam hydrograph.

The test flow period clearly demonstrated the ability to operate Navajo dam in a manner that would mimic a natural hydrograph and ameliorate some of the impact of the dam on hydrology. This is especially true for the present level of depletions, but applies for additional levels of depletion as well. Figure 2.1 shows that much of the hydrograph shape can be restored. Comparison of the winter flows, however, indicates the importance of being able to reduce winter releases from Navajo dam below the minimum of 500 cfs maintained during the test flows. Winter flows were maintained higher

than during pre-dam conditions, reducing the availability of that volume of water for spring releases and improved mimicry during both periods of time.

While, on average, it appears that the potential exists for adequate mimicry, there are extreme conditions that cannot be met. With the present release capacity of Navajo Dam at 5,000 cfs, the ability to produce large spring floods below Farmington has been diminished. The impact of this reduction will be discussed more fully in Chapter 3. Further, historic minimum summer through winter base flows would likely not be matched, both as a result of restrictions on minimum releases and a desire to maintain more flow in the river to benefit the fish during these times.

Not only were flows impacted, but the temperature regime in the river was altered. The post-dam water temperatures in the summer at Shiprock are now cooler than pre-dam at Archuleta. With re-operation and increased releases during spring runoff, the depressed temperatures will extend further down river. The net result is a further loss in range for temperature critical activities of over 140 km. While the program has the goal of expanding range, the opportunity may be limited by temperature suppression. Further studies are needed to determine if this temperature suppression is limiting range in otherwise suitable habitat and the options available to correct it if it is found to be a problem

CONCLUSIONS

- Navajo Dam Operation from 1962-1991 substantially altered the hydrograph of the San Juan River to its confluence with Lake Powell.
- The hydrology of the San Juan River is subject to more variation in the summer and fall due to storm activity than the Green or upper Colorado rivers.
- Mimicry of the natural hydrograph is possible with restoration of a more natural spring peak and reduced winter base flow.
- The test flows achieved during the 7-year research period represented a range of wet and dry years as well as a range of hydrograph shapes suitable for testing response of conditions that might be expected under a new operation scheme.
- While storm events effect habitat quality in the entire San Juan River, the frequency of habitat-perturbating events at Farmington, New Mexico is only about 1/2 that at Bluff, Utah. Further, the conditions requiring habitat flushing only occur about 1/5 as frequently at Farmington as at Bluff.
- Navajo dam has modified the temperature regime in the San Juan River by lowering summer and raising winter water temperatures. The net effect is a further shortening of potential range of the native fish during the summer. This temperature modification is increased by releasing water in a pattern required to mimic a natural hydrograph.

CHAPTER 3: GEOMORPHOLOGY

BACKGROUND

The contact geology of the San Juan River Basin ranges in age from Precambrian to Holocene. The lithology at the headwaters of the San Juan Mountains is primarily crystalline, igneous, and metamorphic. Sedimentary sandstone, siltstone, and shale of both marine and continental origin underlie the lower river reaches found in the study area (Thompson 1982). Much of the floodplain and adjacent terraces within the study area are overlain by quaternary sand, gravel, and cobble deposits. These alluvial deposits were derived from the resistant igneous and metamorphic rock of the river headwaters, thereby providing a rich source of durable cobble throughout the study area (Miser 1924, O'Sullivan et al. 1957). The active sediment load (bedload and suspended sediment) in the system mainly originates from the highly erodible sedimentary rock and aolian sand deposits.

The geomorphology of the system is heavily influenced by the large sediment load resulting from high intensity storm runoff on the un-protected, highly erodible watershed, primarily south and west of Navajo dam.. The first major sediment source in the study area, Canyon Largo, occurs 19 mi downstream of Navajo Dam. The frequency of similar ephemeral tributaries with high sediment loads increases downstream, thereby disproportionately increasing total sediment load relative to flow in the main river. The result is an extremely high sediment load in the lower reaches of the river. This large, active sediment load in the lower river plays an important role in the formation and maintenance of instream habitat.

Both flow and sediment load have varied over time, due both to natural climatic cycles and man's influence. These changes have altered the sediment transport regime in the system with alternating periods of deposition and scour. This history and its influence on channel form have been examined and are reported here.

The geomorphology varies considerably in the study area. While the gradient does not vary greatly, it is generally steeper in the upper portion of the river and flatter in the downstream portion, gradually changing over the full reach (Figure 3.1). The lower 110 km and upper 15 km are canyon bound, while the middle section flows through valleys of varying width. Some cobble exists in the substrate throughout the study reach, with the exception of the lower 16 miles, but the percent composition relative to sand decreases with distance downstream. Through the valley reach, the system is primarily characterized as anastomosed or multi-channeled, with heavy to moderate riparian vegetation, moderate slope, and low channel sinuosity. Human-induced impacts include enhancement of riparian vegetation due to irrigation return flow, elevated groundwater adjacent to irrigated lands, and the presence of five diversion dams between RM 140 and RM 180 which affect bed elevation. The details of the variation in geomorphological characterization are provided as a result of studies described in this Chapter.

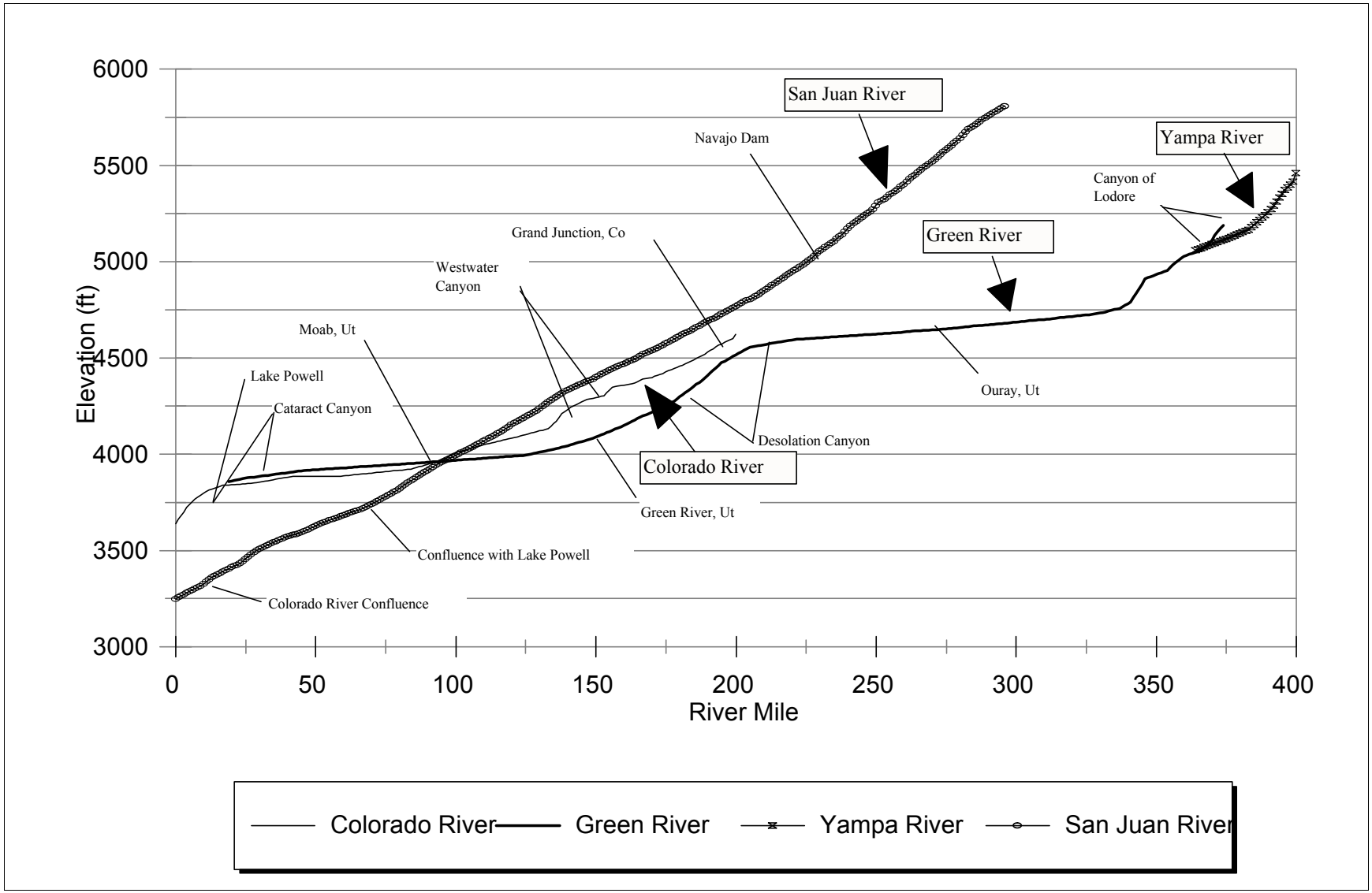

Figure 3.1. San Juan River Gradient

OBJECTIVES

Historical Analysis of Fluvial Morphology

It has been hypothesized by those that have studied the endangered fish in the San Juan River, that a major contributor to the decline of the species has been the loss of the natural flow regime and its effect upon habitat for the endangered fish (SJRIP, 1991). An understanding of the nature of the fluvial morphology of the river prior to regulation by Navajo Dam and the change associated with regulation is helpful in testing this hypothesis. The objective of the historical analysis of fluvial morphology of the San Juan River is to determine changes that have occurred over time as a result of natural forces and man's influence in the basin, including regulation by Navajo Dam.

Geomorphological Characterization

The entire river from Navajo Dam to Lake Powell does not likely respond the same to flows. To aid in the understanding of response, geomorphologically distinct reaches were defined to refine the characterization of the river.

Channel Geometry Analysis

A key objective of the seven year research study was to determine the response of the San Juan River Channel morphology to hydrographic conditions resulting from the range of research releases from Navajo Dam. (SJRIP, 1995 The long range plan). One of the responses deals with the change in the channel geometry as a result of the various test flows. The channel geometry studies were completed to determine the general response of the channel in terms of depth, width and complexity, to the new flow regime.

Cobble Substrate Characterization

The production of clean cobble for spawning areas is dependent upon entrainment of cobble during high flow periods just prior to spawning and deposition of the cobble under conditions that allow it to be placed relatively cleanly, without significant sand and fines to fill the interstitial spaces. An important part of determining flow requirements for the endangered fish species is an understanding of the conditions required to entrain cobble of the size necessary for proper spawning. To fully understand the process, the size of the substrate to be moved and the hydraulic conditions required to move it must be determined and compared to the conditions that exist at critical locations in the river.

Suspended Sediment Analysis

Changes in the hydrology of a system change the sediment transport regime. Sediment concentration measurements during runoff were made to allow comparison of the new sediment transport conditions during runoff to the change in cross-section measurement. Secondarily, the sediment concentration data were compared to historic data for validation.

METHODS

Historic Analysis of Fluvial Morphology

Historical aerial photography has been obtained from the 1930's, 1950's, 1960's and 1980's. No single flight was available for any one year, so aerial photography from multiple years in close proximity were used to obtain full coverage for a given time period. The flight years and river coverage are provided in Table 3.1 for each of the four time periods. The analysis was completed for geomorphological reaches three through eight. Reaches one and two are canyon bound, were not expected to exhibit changes in channel morphology and were not included in the analysis. Of the six reaches analyzed, four (reaches three through six) are within the critical habitat for the endangered fish.

This aerial photography was optically registered to 4:1 enlargements of USGS quad sheet base maps. The bankfull river channel was hand plotted in the rectification process and then digitized for analysis. The data were processed in ArcCad, a geographic information system extension for AutoCad that produces ArcInfo coverages. Cross-tabulations of island area, island count and channel area by river mile were produced for analysis.

Water surface area could not be compared due to the range of flowrates at which the photography was taken. Analysis was limited to a comparison of the bankfull channel area, island area and island count as a measure of change in channel capacity and complexity. Unfortunately, channel complexity during low flow conditions could not be compared since much of the photography was not obtained during low flow conditions.

Geomorphological Characterization

Observations over the past three years of field work and data review indicate variability in the geomorphological characteristics of the San Juan River between Navajo Dam and Lake Powell. It was theorized that channel morphology and aquatic habitat may respond to hydrologic conditions differently in different sections of the river. Therefore, defining reaches that are geomorphologically distinct could aid in analysis of the system to better understand the response to the hydrograph.

Forty-nine individual data sets in eight categories were developed. These data sets were used to define distinctly different river reaches.

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Table 3.1. Aerial photography coverage by river mile used in the historical analysis for the periods 1935-1937, 1950-1952, 1959-1962, and 1986-1988.

1935-1937 Series*			1950-1952 Series		
Photo Date	RM	Flow Rate at closest gage (cfs)	Photo Date	RM	Flow Rate at closest gage (cfs)
1935	66-77	N/A	02-Oct-52	66	1,000
1934	77-97	N/A	04-Nov-52	67-69	461
1935	94-224	N/A	01-Oct-52	70-72	1,040
			14-Oct-52	73-75	579
			26-Jun-50	76-96	2,200
			28-May-55	97-98	4,780
			04-Sep-52	99-102	816
			07-Oct-52	103-106	714
			11-Nov-52	107-111	768
			04-Sep-52	112-118	816
			26-Jun-50	119-120	534
			14-Sep-52	121-125	607
			22-Aug-52	126-132	607
			06-Oct-52	133-134	930
			15-Aug-52	135-141	607
			28-Nov-50	144-158	828
			28-Nov-50	159-176	350
			12-Nov-50	177-190	224
			28-Nov-50	191-201	216
			12-Nov-50	202-223	324
			28-Nov-50	224	216

1959-1962 Series			1986-1988 Series		
Photo Date	RM	Flow Rate at closest gage (cfs)	Photo Date	RM	Flow Rate at closest gage (cfs)
28-Aug-59	66-75	1,270	28-May-88	66-99	1,700
06-Sep-61	76-93	697	28-May-88	100-129	1,680
06-Sep-59	94-99	238	28-May-88	121-150	1,610
28-Aug-59	100-106	1,270	14-Jun-86	151-158	5,180
31-Aug-59	107-113	730	14-Jun-86	159-169	5,770
06-Sep-59	114-116	238	18-Jun-86	171-180	5,630
14-Aug-62	117-158	395	18-Jun-86	181-193	1,750
14-Aug-62	159-180	526	17-Jun-86	194-202	1,510
14-Aug-62	181	597	18-Jun-86	203-214	1,750
17-Aug-62	182-199	345	29-Jul-86	215-224	3,230
24-Aug-62	200-224	315			

* Dates of 1934-1935 photography not available to determine flow rate

River Valley Geometry

Valley width was determined utilizing generalized geology maps of the basin prepared by USGS 1965, USGS 7.5 minute quadrangle maps and 1986-1988 aerial photography. The boundary of the alluvial San Juan River valley was mapped on the USGS quadrangle base utilizing the generalized geology maps as the first level of interpretation with elevation break and aerial photography interpretation as the means of refinement. The boundary definition used as a refinement to the small scale geology maps was the existence of bedrock at the edge of the valley defined by two adjacent 20 ft contours with verification of this boundary with aerial photography. The valley boundaries were digitized into the GIS system and the mean width per river mile computed.

Below RM 68, the valley width was taken as the width of the water surface at the highest flowrate for which habitat mapping was completed (approximately 257 m^3/sec (9,090 cfs)). For this canyon bound reach, this is a reasonable approximation of valley width and allows extension of the data set for the full length of the study area.

Channel Contact Geology

In November 1994 river channel contact geology was mapped from the confluence of the Animas and San Juan rivers (RM 181) to the beginning of the canyon reach at the Chinle Creek confluence (RM 68). The mapping was not comprehensive, but consisted of mapping the location and extent of cutbanks along the main channel and then identifying the material in these cutbanks. Cutbanks were defined as vertical or near vertical banks exhibiting erosional characteristics. Layered material was noted with each layer being characterized as one of the classifications shown in Table 3.2. In addition, any channel contact with bedrock or talus slopes was also noted. Mapping cutbanks not only allowed an assessment of the longitudinal distribution of cobble, gravel, sand and bedrock contact, but an assessment of channel stability as well.

Contact areas were mapped from a boat by visually noting the beginning and ending of cutbanks or bedrock contact and marking these locations and the classifications on prints of aerial videography flown 8 November 1994. This information was transferred to scale rectified base maps by projection and the lengths measured for each segment. A database of the length of each contact type by river mile was constructed for data analysis.

Riparian Vegetation

Riparian vegetation was identified and mapped from the confluence of the Animas and San Juan Rivers (RM 181) to the confluence of Chinle Creek (RM 68) during November 1994. The base map used consisted of prints of the November 1994 videography at a nominal scale of 1:3000. Vegetation complexes were categorized as shown in Table 3.3. Three density ranges of each vegetation type were categorized. Vegetation complexes were delineated on the aerial videography prints based on interpretation of the videography and ground inspection. Complexes were mapped that could be identified from the river side as the mappers floated past, extending the range away from the river by

Table 3.2. Stream channel contact geology descriptions used in mapping.

Code	Description	Code	Description
S	Sand, 2mm and smaller	RR	Riprap stabilized
SGr	Sandy Gravel, > 25% gravel	BR	Bedrock stabilized
SCb	Sandy Cobble, > 25% cobble	BR + SS	sandstone
Gr	Gravel , <3" diameter	BR + SiS	siltstone
GrS	Gravelly Sand, < 25% gravel	BR + Sh	shale
Cb	Cobble > 3" diameter	TA	Talus stabilized
GrCb	Gravelly Cobble, < 25% gravel		

Table 3.3. Vegetation types and codes used in mapping riparian vegetation.

	Percent Cover		
Vegetation Type	1-25%	26-75%	76-100%
	Code		
Cottonwood Canopy	1	2	3
Russian olive canopy	4	5	6
Tamarisk canopy	7	8	9
Willow canopy	10	11	12
other tree species	13	14	15
upland herbaceous understory	21	22	23
upland shrub understory	24	25	26
wetland herbaceous understory	27	28	29

common visual signature on the video prints. This method limited the extent of mapping possible to something less than the full flood plain. However, the width of coverage was sufficient to allow assessment of the riparian vegetation that could potentially influence channel pattern and riverine habitat.

The delineated vegetation polygons were optically projected onto the same base map set used for habitat registration and then digitized for analysis in the GIS system. Since the full extent of riparian vegetation was not mapped, a method of standardization was needed to allow analysis of

longitudinal distribution. A 30 meter wide band on either side of the main channel was selected as the standard. In braided locations one channel was selected that represented the main channel at about 28 m^3/sec (1,000 cfs). In areas of small islands, the outer channel banks became the boundaries and the vegetation on the islands excluded from analysis, leaving just the 30 meter band of vegetation on either side of the channel.

To assess distribution of plant species, the percent density (midpoint of the mapping category) was multiplied by the area of all polygons that contain that species or type and extracted from the database by river mile. Therefore the analysis reflects both extent and density in a lumped term. However, the area and density are preserved separately in the database if needed.

Channel Gradient

Channel gradient was determined from USGS 7.5 minute quadrangle maps. It was assumed that the general channel gradient was constant between contour intervals. Channel slope by river mile was computed by linear interpolation between contour intervals. While channel slope calculated in this manner is not accurate locally, it reflects the average slope of longer reaches of river with acceptable accuracy. For the purpose of defining the average slope of a selected river reach, the method is appropriate.

Channel Pattern

Channel pattern was assessed by measurement of two parameters: sinuosity and braiding. Sinuosity is defined as the length of the thalweg of the river divided by the length of the valley trend. Valley trend was determined from USGS 7.5 minute quadrangle maps on which the valley boundaries had been drawn. The valley trend line was drawn centered in the river channel but aligned with the general trend of the valley. This line was digitized and the length of the line per river mile determined. In computing sinuosity a moving 3-river mile length of channel from the 1992 digitization was divided by a moving 3-river mile length of valley trend. In the canyon, the valley trend was taken as the same length as the channel, since the river cannot meander inside the valley constraints. In the lower 14 miles where the thalweg is meandering in the sand bottom, the sinuosity is under-estimated, but it is still very close to 1.0 because of the narrow confines of the meander.

Channel complexity was assessed by measurement of island area by river mile. In as much as island area and channel complexity vary with flowrate, island area was assessed at each of the flowrates for which habitat was mapped. The average values at high (June 1993, 1994), intermediate (July 1993) and low flows (November 1992, October 1993, and August 1994) were computed and these averaged data sets used in analysis.

Tributary Influence

For the full length of the river from Navajo Dam to Lake Powell, the location and type of tributaries was noted. All perennial tributaries were identified and the river mile and side of river entry noted in the database. In addition, major ephemeral tributaries, those contributing substantial amounts of

sediment to the system, were identified in the same manner. This data set was used in channel reach definition and will be used in assessing localized impact on geomorphology and habitat if such relationships exist.

Man's Influence

Nine categories of man's influence were mapped: adjacent irrigation, bridges, diversion dams, oil wells in the flood plain, pipeline crossings, borrow pits, ponds, roads and sewage treatment facilities. To be included, the facility had to be adjacent to the river channel or in the flood plain. For roads, they had to exhibit some potential control on the river channel, usually demonstrating the existence of a levee along the channel. These categorical variables were entered by river mile as existing or not existing.

Aquatic Habitat

Six categories of aquatic habitat data were used in the analysis from six mapping trips. The categories used were: total water surface, low velocity (backwater, embayment, eddy & pool), riffles/chutes, sand types (sand shoals, sand bars), cobble types (cobble shoals, cobble bars) and island area. The categories were averaged for low, intermediate and high flow conditions as described under Channel Pattern. Island area was used as part of the channel pattern description and the sand and cobble types were used in conjunction with the channel geology information.

Identify River Reach

All of the above described data sets were used to identify distinct river reaches. Table 3.4 summarizes the data sets used and the coverage of each data set. The procedure used to identify distinct reaches consisted of three steps:

1. Identify test reaches based on general survey information.

   The river was divided into test reaches based on general observations derived from the surveys. These test reaches appeared to be distinctly different, but the boundaries between reaches were not precisely known and the degree of difference was not quantified. The test reaches selected are described in Table 3.5.

2. Select a model to find differences between reaches.

   After trying several different statistical models, a multi-variate model called linear discriminant analysis was chosen. This model was originally developed by Fisher (1936) to allocate individuals to one of several populations on the basis of a measurement of a multidimensional random variable on the individual river mile in this case.

Table 3.4. Data sets used in channel reach definition analysis.

HABITAT - m^2/mi	Coverage - River Miles	
Total Water Surface Low Velocity Types Riffles/Chutes Cobble Type Island 3 mi average	High Flow Intermediate Flow Low Flow	0 - 224 0 - 158 0 - 224
RIPARIAN VEGETATION - m^2/mi	68 - 180	
Cottonwood Russian Olive Tamarisk Willow Upland Herbaceous Upland Shrub Wetland Herbaceous		
CHANNEL - 3 mile average	0 - 224	
Valley Width - m Channel Slope - ft/ft Sinuosity		
STREAM CHANNEL	68 - 180	
Bedrock - m/mi Total Cutback Contains Sand Contains Gravel Contains Cobble Sand Only Gravel Only Cobble Only		
CATEGORICAL VARIABLES	0 - 224	
Adjacent Irrigated Area - % Major Tributary - Ephemeral Major Tributary - Perennial Bridge Diversion Oil Well Pipe Crossing Borrow Pit Pond Road Sewage Treatment		

Table 3.5. Location descriptions of general reaches in San Juan River having different characteristics.

Reach	Description
1	Waterfall/Lake Powell influenced reach
2	Canyon bounded reach up to Chinle Wash
3	Chinle Wash to Aneth
4	Aneth to Mixer
5	Mixer to Hogback diversion
6	Hogback diversion to Animas confluence
7	Animas confluence to Blanco
8	Blanco to Navajo Dam

Discriminant analysis treats the measured variables as random variables, each set arising from two or more populations. Linear combinations of the measured variables are constructed which exhibit properties of maximum variance and no covariance. These linear combinations, canonical variates, form a new set of linearly independent variables which maximize the "distances" between each population. During the course of the analysis, statistically insignificant variables can be eliminated. Finally the question is - given the chosen set of variables, are the population "distances" sufficiently large enough to distinguish between populations? If so, then assign unknown individuals with a known degree of uncertainty to a population. We were not interested in this last step. Instead we wanted to use the statistical information gathered during the process to determine which variables are the most important in defining the reaches, if the division of the San Juan River into eight reaches was justified and to define the division points.

3. Use the model to find reaches and validate results.

The analysis was first restricted to variables only measured along the entire river. From Table 3.4 these variables are those belonging to conditions of high and low flow, channel parameters and the categorical variables. Later as a cross-validation on the reach designations for 3 through 6, we also added the vegetation/channel contact variables and reran the analysis on the restricted set of reaches.

Channel Geometry Analysis

Four separate studies were completed. The first set of studies examined the response of channel geometery to flow at newly established locations throughout the lower 6 reaches of the river comprising the critical habitat of the endangered fish. The second analyzed long term change in channel geometry at USGS gage locations, examining scour and deposition in response to flow. The third examined the impact of change in channel geometry on channel complexity. The fourth analyzed the change in channel capacity as a result of changes in channel geometry during the study period.

Cross-Section Measurement in Representative River Transects

In 1992, eleven river transects, indicated as "RT" cross-sections, were established with permanent monuments. The sites were selected to be representative of overall channel capacity change. The eleven transects were placed at the end of long runs at a control section immediately upstream of a channel split. The locations are shown in Figure 1.1.

At each transect a benchmark was established by embedding a brass monument in concrete. On the opposite river bank, a tree or other stable landmark was used to both mark the cross section and attach a cable that was used for stationing across the river during surveying. The entire cross section of the river was surveyed. Channel bottom elevations were measured every five to ten feet, depending on the width of the river. All elevations were tied to the newly established benchmark. The benchmark at each transect was assigned an arbitrary elevation of 100 feet. Subsequent surveys of the same cross section were tied to the same bench mark allowing accurate comparison of changes in bed elevation with time. Surveys were completed pre- and post-runoff, typically in February or March and again in August.

In addition to surveying each transect, the proportion and type of primary substrate were estimated. The major classifications were cobble, gravel and “fines”.

All measured cross sections and subsequent calculations of scour and deposition are maintained in AutoCAD. In addition to cross section information, substrate conditions are also stored in AutoCAD.

Fifteen additional transects were established in 1993 to more closely monitor channel change in the vicinity of 1993 suspected spawning sites and in areas that exhibited significant change in 1993. Eight are located in the “mixer” reach (RM 129 - 134), five in the reach between RM 83 and RM 88 referred to as the “debris field” and two in the reach between RM 0 and RM 14 (Clay Hills). Those in the mixer cover locations of suspected spawning in 1993 and 1994, locations of significant cobble movement or locations to provide information for hydraulic modeling. The reach between RM 83 and RM 88 is an area of significant change exhibited in 1993. Large sand and cobble bars were built by the high flows and the channel moved substantially. Since backwaters form downstream of these sand bars, these transects were located to better understand the development of the bars and associated backwaters under different flow conditions. The reach between RM 0 and RM 14 is in

the backwater area from Lake Powell. This reach is not like any other reach in the river. The gradient is low, the channel meanders between sand bars and shoals within the limit of the canyon walls and substantial areas of low velocity habitat exist at low flow relative to other river reaches. These transects will provide data to document the relative permanence of these backwaters. The locations of these transects are shown in Figures 3.2 through 3.4. Table 3.6 summarizes the transect surveys completed during the last 7 years, including the date of the first survey.

The RT and Clay Hills cross-sections were analyzed to determine local deposition and scour and change in average bed elevation with time. The change in percent cobble in the substrate with time was also analyzed. The same analyses were performed for the mixer and debris field transects, but in this case the change was analyzed for the four measurements taken over the runoff period and compared to the volume of flow and peak discharge for each period. This more detailed sampling of the mixer and debris field transects was conducted during the period 1994 - 1996. In 1997 the sampling frequency was decreased to twice yearly. In 1998, in an effort to transition from research to long term monitoring and reduce cost, measurement of all cross-sections was completed only after runoff in August.

Channel Response to Flows at USGS Gage Locations

To assess the changes seen at the surveyed transects during the 7-year study period against long term change, data collected at USGS gaging sites on the San Juan River were examined to determine changes in cross sectional area with time. The stations at Bluff, Shiprock, Farmington and Archuleta were selected for analysis.

At each station, field discharge notes were obtained for the period of record. The field discharge notes contain distance-depth data which were used to plot the river bed profile in an attempt to determine changes with time. It is important to note that in plotting these data, all distances to the river bed are taken from the water surface, which obviously fluctuates with stage. When the location of data collection for the rating measurements is sufficiently close to the gage datum, then these data can be corrected to a fixed datum. When that is not the case, some other means of control, such as a fixed point of the river bottom on bedrock, is required.

All extracted data were digitized and plotted to determine change in cross section with time. The change in average channel cross sectional area from an arbitrary datum was plotted against time to determine the state of the river (scour or deposition) over time.

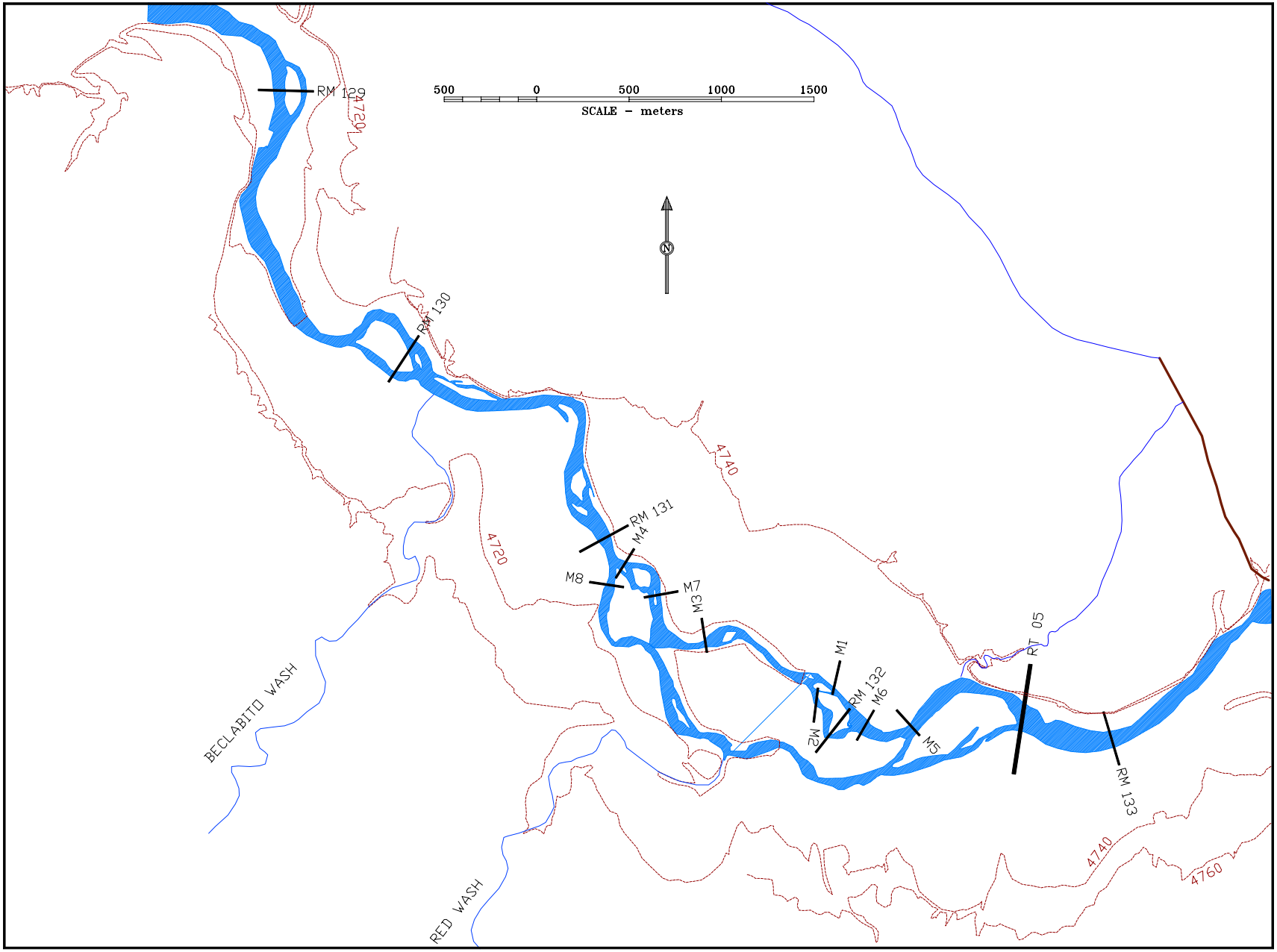

Figure 3.2. San Juan River Transect Locations in the "Mixer" Detail Reach

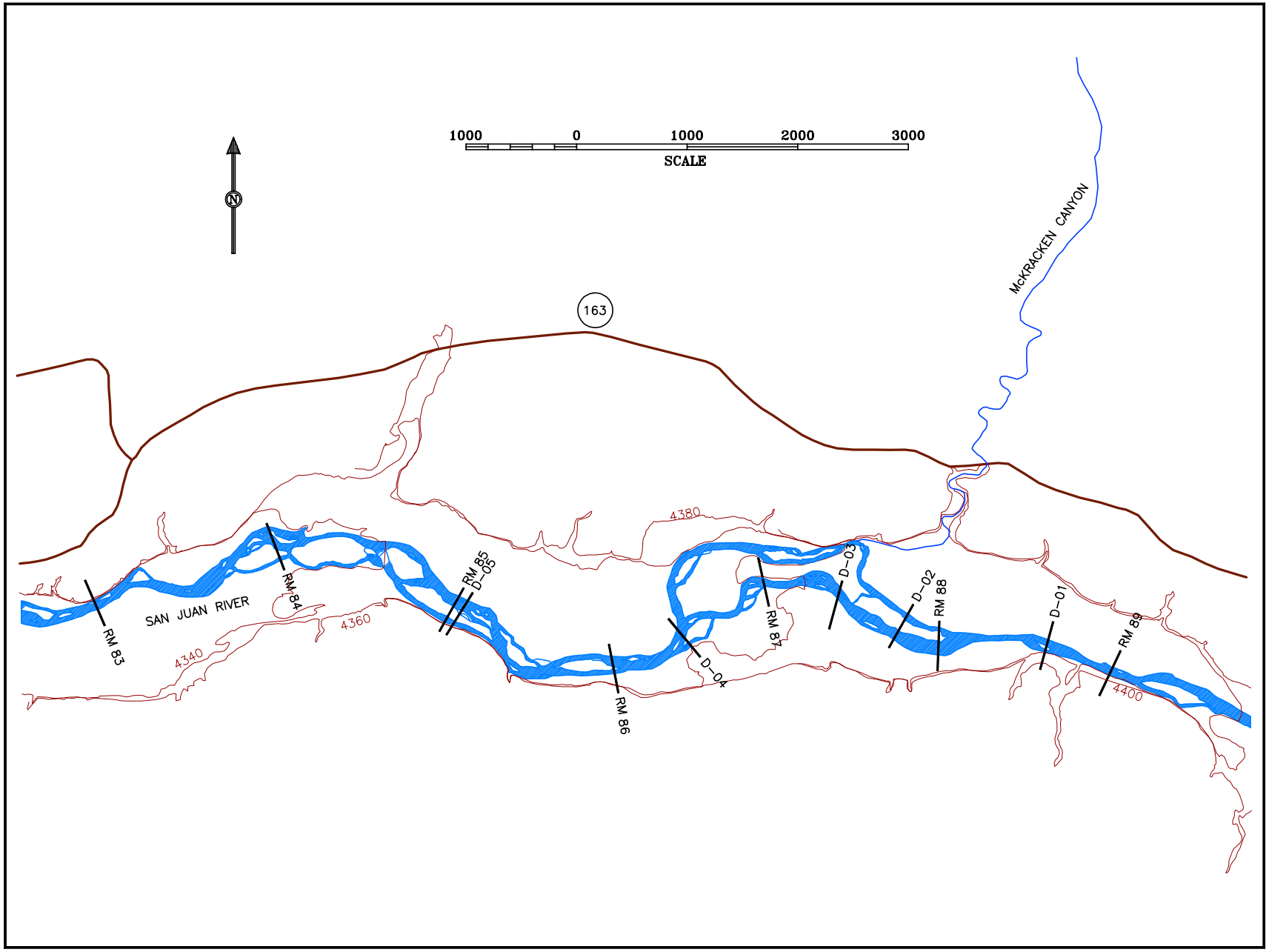

Figure 3.3. San Juan River Transect Locations in the "Debris Field", RM 83 to RM 88

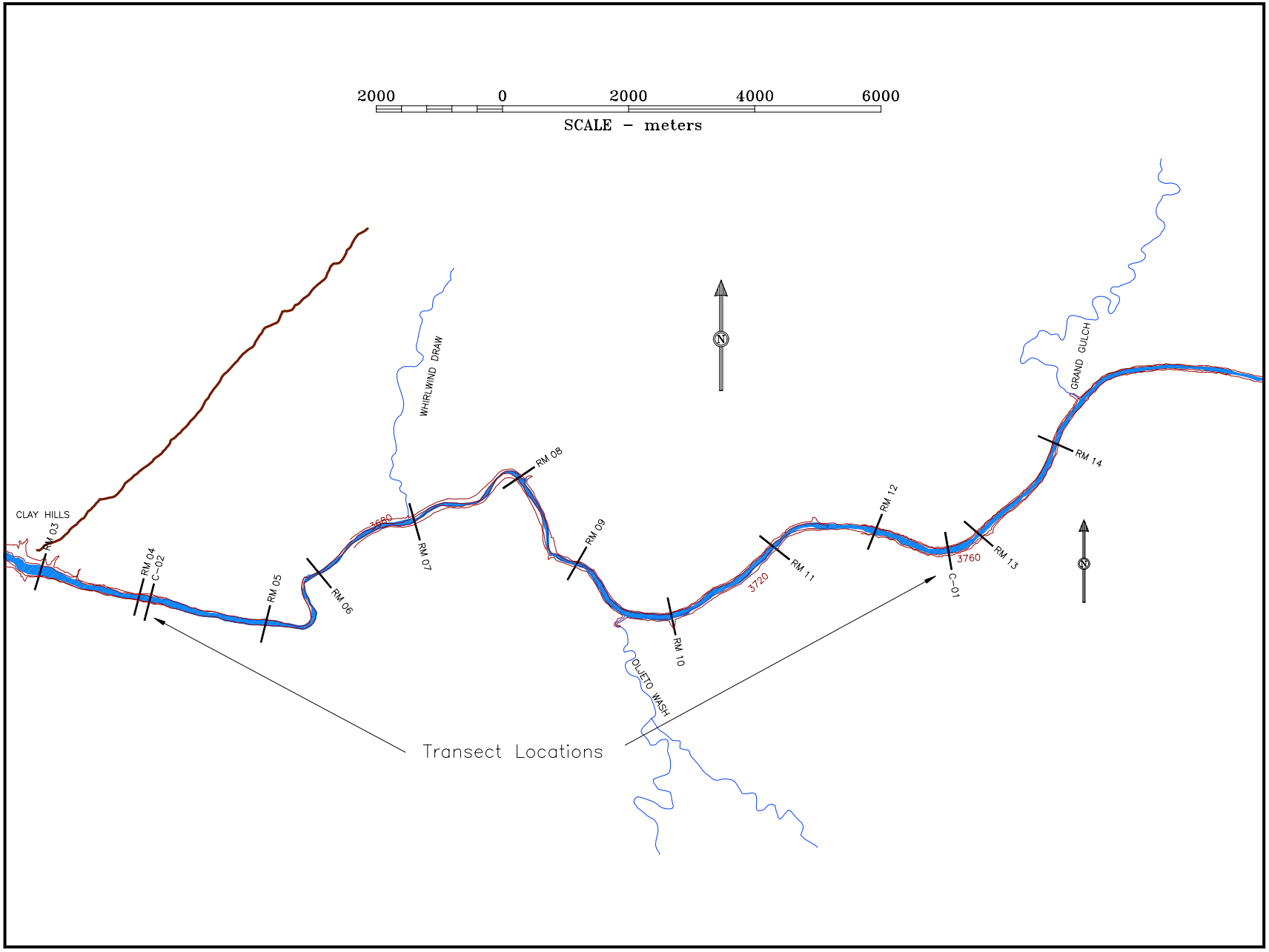

Figure 3.4. San Juan River Transect Locations, RM 0 to RM 14

Table 3.6. Transect survey locations and summary of completed surveys.

Transect	Geo-morphic Reach	River Mile	First Survey Date	Number of Surveys Completed	Location Description
RT-01	6	168.30	March 17, 1992	14	Fruitland
RT-02	5	154.40	March 17, 1992	13	below Hogback
RT-03	5	142.70	March 17, 1992	13	Shiprock
RT-04	5	136.60	March 17, 1992	13	below Cudei
RT-05	5	132.70	March 18, 1992	13	upstream of mixer
RT-06	4	124.00	March 18, 1992	13	upstream of Mancos
RT-07	4	122.10	March 18, 1992	13	downstream of Mancos
RT-08	3	104.30	March 18, 1992	13	Aneth
RT-09	3	90.80	March 19, 1992	13	Montezuma Creek
RT-10	3	82.30	March 19, 1992	13	Bluff
RT-11	3	70.00	March 19, 1992	13	Combs Wash
M-01	5	131.90	February 20, 1993	15	Mixer
M-02	5	131.85	February 22, 1993	21	Mixer
M-03	5	131.50	February 21, 1993	21	Mixer
M-04	5	131.10	February 21, 1993	18	Mixer
M-05	5	132.30	September 21, 1993	19	Mixer
M-06	5	132.10	September 21, 1993	18	Mixer
M-07	5	131.30	September 21, 1993	17	Mixer
M-08	5	131.20	September 21, 1993	18	Mixer at Redwash
D-01	3	88.50	September 22, 1993	18	Debris Field
D-02	3	87.50	September 22, 1993	18	Debris Field
D-03	3	87.20	September 22, 1993	16	Debris Field
D-04	3	86.20	September 23, 1993	18	Debris Field
D-05	3	83.00	September 23, 1993	18	Debris Field
C-01	1	12.70	October 28, 1993	10	Grand Gulch
C-02	1	4.10	October 29, 1993	10	Clay Hills

Flow Modification Impact on Channel Complexity

Modification of the flow regime to restore more natural spring runoff after 30 years of altered flows as a result of the operation of Navajo dam could cause a change in channel complexity. To examine the impact of the altered flow regime on overall channel morphology, channel complexity, as measured by changes in total number of islands within each reach, was analyzed using habitat mapping coverage in a geographic information system (GIS). Only Reaches 3, 4, and 5 were used in this analysis because mapping for these reaches was the most temporally comprehensive throughout the 7-year research period than the upstream reaches, and Reaches 1 and 2 have no islands because of canyon restraints. Channel complexity was analyzed in two ways: the overall correlation between discharge and number of islands, and the chronological effect of flow regime on island count during the 7-year research period.

It has been hypothesized in the SJRIP that secondary channels are an important component of the aquatic habitat in the San Juan River (Propst, 2000). If channel scour caused a reduction in islands, secondary channels would be lost. Monitoring island count with time allows assessment of this potential for channel simplification. To assess the impact on habitat diversity, the trend of habitat diversity was also examined for this time period during low flow conditions. Habitat diversity was assessed by computing the Shannon-Weaver habitat diversity index (Shannon and Weaver, 1963) by river mile for each habitat sampling run. The index is computed as

$$SWI = -\sum_{i=1}^{n} \frac{count_i}{totalcount} \cdot \log(count/totalcount)$$

Where

SWI	=	Shannon-Weaver Index
n	=	number of habitat categories (31)
$Count_i$	=	number of habitats of the ith category in the river mile
Total count	=	the total number of habitats in the river mile

The index increases with increased diversity, reaching a maximum of 1.49 (log of 31) for the categories mapped in the San Juan. Only the wet habitat categories are included in the analysis.

Bankfull Channel Capacity

In 1996, four single-channel reaches about 0.4 km in length containing five cross-sections each were surveyed between RM 133 and RM 174. Flow in these reaches was modeled using the U.S. Army Corps of Engineers flow model, HEC-RAS. The model was calibrated to surveyed water surface profiles over a range of flowrates at each model reach and the roughness coefficient calibrated for the model. Bankfull flows were predicted to begin when one of the five cross-sections exhibited out-of-bank conditions.

Since the RT series were first surveyed prior to research flows and have been surveyed twice annually since that time, an assessment of channel capacity and the change in channel capacity was made, using the calibrated roughness coefficient from the modeled reach and applying the Manning equation:

$$Q = (w\, d^{5/3}\, S^{1/2})/n$$

Where

Q = discharge, cfs
w = width, ft
d = average depth, ft
S = water surface slope, ft/ft

and

n = roughness coefficient

Since water surface elevations were surveyed each time the cross-sections were surveyed, sufficient information was available to allow calculation of water surface slope. The survey with the greatest flow (1,170 to 1,950 cfs, depending on the date of survey) was selected as the calculation closest to the bankfull condition for purposes of slope computation. Using the calibrated roughness coefficient of 0.027, the Manning equation was solved for slope, knowing flow, width, and cross-sectional area from the surveys. Bankfull flow at each cross-section for spring 1992 and fall 1997 surveys was then computed, assuming that the gradient did not change.

Cobble Bar Characterization

The production of clean cobble for spawning areas is dependent upon entrainment of cobble during high flow periods just prior to spawning and deposition of the cobble under conditions that allow it to be placed relatively cleanly, without significant sand and fines to fill the interstitial spaces. An important part of determining flow requirements for the endangered fish species is an understanding of the conditions required to entrain cobble of the size necessary for proper spawning. To fully understand the process, the size of the substrate to be moved and the hydraulic conditions required to move it must be determined and compared to the conditions that exist at critical locations in the river.

Characterization of Bed Material in Suspected and Potential Spawning Bars

Suspected spawning bars in the San Juan River were identified from radio tracking of adult squawfish during the summer of 1994. During the fall of 1994, thirteen sites were identified that had visual similarity to the sites utilized during spawning in 1993 and 1994. After normal spawning time was over, multiple samples of substrate material were measured at each of the sites. Table 3.7 summarizes and describes these locations. From this list of sampled sites, a subset of 4 sites was selected that represented conditions that were thought to be most suitable for spawning or had exhibited use during spawning time in the past. These locations were studied in more detail for an extended period of time. The selected sites for extended study are indicated in Table 3.7.

At each site, samples were collected in a linear or cross-sectional pattern, usually within or across the chute. At multiple locations parameters included: pebble counts and depth to embeddedness. Particles larger than 1 cm were measured utilizing the point count method (Wolman 1954) in the same vicinity. Size-frequency plots were prepared for both the cobble and interstitial material. Only the material 1 cm or greater in diameter was included in the frequency analysis, with the assumption that this larger material formed the bar structure, with the smaller materia being interstitial. Prior to 1998, the intermediate cobble cross-sectional diameter was used as the size designator. In 1998, an aluminum plate was prepared with square openings of from 1 cm to 10 cm in 1 cm increments and in 2 cm increments from 10 to 20 cm, representing equivalent sieve sizes. Cobble larger than 20 cm is measured as in previous years. A correlation between intermediate diameter and sieve size was completed to understand the relationship between the two measurement methods and to adjust previous years' data to equivalent sieve sizes for better consistency, provided a significant difference was found.

Table 3.7. Cobble bar sampling locations.

Location	Geomorphic Reach	Description	Years Sampled
RM173.7	6	Upstream end of tributary debris bar*	1995, 96, 97, 98
RM172	6	Upstream end of mid-channel bar	1995, 96
RM169	6	Middle chute of mid-channel bar	1995,96
RM168.4	6	Three chutes (N, M, S) below mid-channel island*	1995, 96, 97, 98
RM163	6	Upstream end of mid-channel bar	1995, 96
RM137.7	5	Upstream end of secondary at large mid-channel bar complex	1995
RM137.3	5	Upstream end of point bar below mid-channel bar complex	1995
RM132	5	Main Bar suspected spawning location in 1993, 1994 (compare to Sites 1 and 3 from previous studies)*	1994, 95, 96, 97, 98
RM131.2-RW	5	Red Wash bar 1993 spawning site (compare to Site 4 from previous studies)	1994, 95, 96
RM131.2 Main	5	Main Channel Bar suspected spawning site, numerous fish contacts in 1994 (Compare to Site 5 from previous studies)*	1995, 97, 98
RM 109.8	4	bar at upper end of island. Radio-tagged fish location in 1995 during spawning	1995
RM 88	3	Small bar on inside curve in active area of river	1995
RM 82	3	Three chutes in debris area RM 81.85, 81.9 & 81.95	1995
RM 78	3	Chute at upper end of island	1995
RM 76.6	3	Chute at confluence of secondary & main channel above Sand Island Boat Ramp	1995

* Extended period study sites.

A similar set of data was collected in 1994 on the Colorado River (RM 168.8) where Colorado pikeminnow were found adjacent to a newly formed cobble fan. The same sample methodologies were utilized at this site. Bed material size distribution from all sites was compared to similar bed material size distribution from a known spawning bar at RM 16.5 on the Yampa River (Harvey, et al. 1993). This comparison was made as a check on the probability of the material found being suitable for spawning of Colorado Squawfish.

Depth of Open Interstitial Space in Cobble Bars

One of the important conditions for a cobble bar to be suitable for spawning is adequate depth of clear interstitial space or depth to embeddedness. Several methods of obtaining a measure of cobble bar embeddedness have been described in the literature. Platts, et. al. (1983) describe a method of assessing embeddedness that estimates the portion of the surface area of the larger size particles in a bar that are covered with fine sediments, giving a rating system from 1-5 to describe the degree of embeddedness. Unfortunately, the method does not deal with the issue of the depth to embedded material.

McNeil (1964) described a sampling method utilizing a single tube worked into substrate material to retrieve a sample of the substrate, but the method extracts a disturbed core and does not allow measurement of the open interstitial space.

Cryogenic sampling methods (freeze core) have been developed utilizing both single and multiple tubes that allow an assessment of open interstitial space as well as substrate material size (Everest, et. al (1980). The method is effective but is material and labor intensive, limiting the number of samples that can economically be collected. The method was tried and found to be too cumbersome to allow characterization of large areas.

The method settled upon is that described by Osmundson and Scheer (1998) where a measurement to the embedded layer is made by working a hand between the larger particles of a bar until sand is encountered and measuring the depth from the top of the surrounding cobble to the point that sand is contacted. The method was first developed for application in this study and employed and reported by Osmundson and Scheer (1998). The method is fast and requires minimal training and equipment to perform. Many measurements can be taken in a short period of time and underwater sampling is possible. To allow comparative evaluation of numberous bars and to assess variation on an individual bar, this method is superior to other methods examined.

The cobble bars from which substrate measurements were made were also sampled for the depth to the embedded layer (open interstitial space). Each cobble bar was sampled on a 0.7 to 1.3 meter grid. The depth from the top of the cobble to a point at which the interstitial space was filled with sand was measured at each point (depth to embedded layer). Each sample point was surveyed with a total station to determine relative x,y position and elevation. These measurements were then plotted in a three-dimensional surface plot to allow assessment of the variation in depth. In addition, a frequency distribution of depth to embeddedness was prepared for each site.

Topographic Changes in Cobble Bars

One suspected and two potential spawning bars were surveyed with total station survey equipment with local horizontal and vertical control. The suspected bar at RM 132 was surveyed from 1995 through 1998. The potential bars at RM 173.7 and RM 184.4 were surveyed from 1996 to 1998. Three-dimensional surface plots were prepared for each survey. Changes between survey dates were determined by subtracting the previous surface from the present surface. These changes are also shown as three-dimensional surface plots.

Cobble Transport Analysis

For long-term cobble bar formation and maintenance, the system must be capable of transporting an adequate size and quantity of cobble into the appropriate areas. In addition to assessing bankfull discharge at channel cross-sections, the study reaches described in Section Bankfull Channel Capacity were modeled to determine the discharge necessary to transport cobble through the intervening low-gradient reaches between bars. The method employed to determine this relationship involved examining critical dimensionless shear stress (Shield's stress), a parameter estimating the pressure applied to the bed substrate by the overflowing water velocity and depth, for the existing bed material. Incipient motion (the point at which particles begin to move) of the median particle diameter (D_{50}) of bed material is theorized to occur when the critical shear stress, $J^*_{c50,}$ is in the range of 0.02 (Andrews 1994) to 0.03 (Parker et al. 1982). This value varies from river to river and may even fall outside this range. Under conditions of incipient motion, the gravel just begins to move slightly and transport rates are very low (Pitlick and Van Steeter 1998). As the dimensionless shear stress increases, the number of bed particles in transport increases rapidly. By the time the dimensionless shear stress reaches 0.06 (Andrews 1994), a majority of the particles on the bed's surface are in motion. Appreciable transport will occur at condition of average motion, where most particles can be moved, but at a moderate rate. Andrews (1994) found transport of particles as large as the 80th percentile with dimensionless shear stress in the range of 0.032 to 0.042. The three conditions of transport examined in this study are initial or incipient motion (J^*_{c50} = 0.02 to 0.03), average motion (J^*_{c50} = 0.030 to 0.045), and full motion (J^*_{c50} = 0.045 to 0.060).

Low Velocity Habitat Creation and Maintenance

An understanding of the formation and stability of low velocity habitat in the system is important to an evaluation of the nursery habitat availability and the conditions necessary to produce and maintain the habitat. In the late summer of 1994, three sand/cobble bars in the lower river were topographically surveyed with a total station, registering the survey to permanent control at each site. The bars selected were typical of those that form with good backwater potential behind the bar. Each bar was surveyed again in each subsequent year as a comparison to the 1994 data and to relate change to hydrology. Table 3.8 lists the location and survey dates of each of the bars surveyed.

Table 3.8. Sand/cobble bar survey locations and dates.

Description	Location - RM	Survey Dates
Debris Field 1, River Right	88.1	8/24/94, 10/7/94, 3/5 /95, 8/14/95, 10/12/95
Debris Field 2, River Left (includes D-4 Transect)	86.4	8/24/94, 10/7/94, 3/5/95, 3/14/95, 10/12/95
Clay Hills (at C-2 Transect)	4.1	8/25/94, 10/6/94, 3/4/95, 3/15/95, 10/13/95

Three-dimensional plots were prepared for each survey and the surfaces of the two surveys compared to document change. The change was analyzed in terms of the intervening hydrograph. River stage also plays a large role in availability of backwaters. Where possible the stage/backwater area relationship for these sites was examined in the 14 to 28 m^3/sec (500 - 1,000 cfs) range. Stage-discharge data were not available to extrapolate the range of flows beyond that shown. In some cases the bed elevation had changed too greatly to allow development of a stage discharge relationship at a particular site.

These main channel bars support only a small percentage of the backwater habitat in the San Juan River. A large portion of the backwater habitat occurs at the mouths of secondary channels after flow recession. These backwaters require periodic flushing for long term maintenance. To measure flow conditions necessary to maintain backwaters, two ephemeral secondary channels that form backwaters were selected for surveying and modeling. The first is located on river left just downstream of the Montezuma Creek Bridge (RM 93 to 93.5), and the second is approximately 1.6 km upstream of Sand Island Campground (RM 77.3 to 77.5) on river left. These backwaters have formed each year during base flow (low, stable, non-storm effected flows between spring runoff events) conditions, indicating relative stability, although the size and depth of the backwaters have varied.

These reaches were surveyed in detail in 1996. During that year, flow conditions were inadequate to flush these backwaters (Figure 2.5). A total of 10 surveys were completed in 1997, beginning on May 13 and continuing through August 19. During that time, a correlation between secondary and main channel flow was developed to predict flow in the secondary channels. Suspended sediment concentration was measured about twice weekly during this time to provide data for later modeling.

Suspended Sediment Analysis

Sediment Sampling

A suspended sediment sampling program was implemented in March 1992 for sites on the San Juan and it tributaries. A DH-59 depth integrating suspended sediment sampler was used with the "equal transit rate method of sampling." This method requires that samples are collected at equally spaced

verticals in the flow cross section. The transit rate of the sampler must be uniform and the same in all verticals. The composite sample from all verticals represents the mean suspended sediment concentration. Laboratory analysis determines the sediment concentration in mg/l.

Ecosystems Research Institute, Inc. in Logan, Utah has done all the suspended sediment analysis to date. EPA Method 160.2 was used. This method consisted of filtering a small volume, typically 25 ml or less, of sample though a previously weighed 40 to 60 micron glass fiber filter. The filter was dried in an oven at 103 to 105/C for one hour. It was then put in a desiccator to cool for 24 hours. The filter was re-weighed. The weight difference is the mass of suspended solids in the sample. Dividing the mass of the solids by the original volume of filtered sample yielded the concentration in mg/l.

Beginning in 1995, intermediate sampling twice per week was added to better assess sediment inflow during intervening storm events. These intermediate samples were single point samples in each cross-section, correlated to the full sample sets at the cross-section for interpretation of results. Samples were taken from the locations and on the dates shown in Table 3.9.

A review of the sediment data collected since 1992 indicates that a number of the sampling data points were influenced by storm events. Sediment concentration/flow relationships were examined for full data sets and those filtered to remove storm influenced data points. In addition, the sediment discharge relationships for each site during the ascending and descending limb of the hydrograph were analyzed. The suspended sediment concentration and grain size distribution was used in the sediment transport analysis for backwater flushing.

Sediment Transport Analysis

Sediment transport analyses were completed to characterize cobble transport/flow relationships for maintenance of cobble bars. Fine sediment transport modeling was conducted to study the mechanisms of backwater flushing in typical backwaters. The methods and results of these studies are reported in the San Juan River Basin Recovery Implementation Program Flow Recommendation Report now in print. The results are not reproduced here, although the data collection and analysis were a part of these studies.

Table 3.9. Sediment sample locations and number of samples taken each year.

Location	1992	1993	1994	1995	1996	1997	1998
San Juan River at Lee Acres Bridge	5	6	6	7	5		
San Juan River at Farmington*	5	6	6	7	5	8	6
San Juan River at Fruitland	5	6	6	7	5	8	6
San Juan River at Shiprock*	5	6	6	7	5	8	6
San Juan River at Four Corners*	5	6	6	7	5	8	6
San Juan River at Montezuma	5	6	6	7	5	8	6
San Juan River at Bluff	5	6	6	7	5	8	6
San Juan River at Mexican Hat	5	6	6	7	5	8	6
Miller St. Animas	5	6	6	7	5	8	6
La Plata River		4	2	5	5	8	4
Red Wash		1	1	4			
Mancos River		4	3	6	3	8	6
McElmo Creek		6	6	7	5	8	6
Montezuma Creek Wash		2	2	5			1
Cottonwood Wash		1	1	5			
Arroyo 46.9		2		5			
Combs Wash		1		5			
Chaco Wash				6	2	3	5
Chinle Wash				4		5	4
* Spot sampling at these sites				37	36	48	44

RESULTS

Historic Analysis of Fluvial Morphology

Table 3.10 summarizes the bankfull water surface area, island count and island area by geomorphological reach for the four time periods analyzed. The data are also summarized for all reaches analyzed and for reaches three through six, the critical habitat reaches.

In the 1930's the San Juan River, especially in the lower reaches, was a broad, heavily braided sand bottomed river with little vegetation. This is particularly true for Reach 3, where the river is over 1,000 m wide in several locations, with an average width of 472 m. This period was preceded by some very large fall floods in 1991 and 1927. The gage was not established in 1911, but the stage at Shiprock during this October storm event was 6.7 m.. After gage establishment a peak discharge of 80,000 cfs on 11 Aug 1929 produced a stage of 1.75 m, so it is estimated that the discharge in 1911 was well over 100,000 cfs. In 1927, a flood of 70,000 cfs was reported at Bluff. In 1929, a peak flow of 80,000 cfs was measured at Shiprock. It is hypothesized that these large floods, the result of high intensity thunder storms and extensive lower basin runoff, deposited large quantities of sand in the river, particularly in the lower reaches, accounting for the broad, sand bottomed river.

Between the 1930 and the 1950 data sets, channel surface area decreased by 21% in the critical habitat area. Island count dropped by 36% during the same period, but island area increased by 22%. Reach 3 exhibited the greatest decrease in bankfull channel surface area and the greatest increase in island area, although the number of islands decreased somewhat. Reach 7 exhibited the least change in surface area. While the overall island area increased, the three uppermost reaches decreased in island area while the three lower reaches increased.

The most noted difference between the 1930 and 1950 data sets was the increase in riparian vegetation. This is partly due to natural re-vegetation after the earlier floods and the appearance of tamarask for the first time in the basin. Between 1937 and 1950, the greatest magnitude flood was 42,500 cfs (daily mean flow), with five years having mean daily peak flows above 20,000 cfs. Based on the sediment studies conducted during this period (Thompson, 1982), these floods appear to be less sediment laden than the earlier large magnitude events. The average annual sediment load between 1930 and 1942 was 47,200,000 tons per year. Between 1942 and 1973, the average dropped to 20,100,000 tons per year, with the major shift occurring in 1942. With lower sediment concentrations and high flow magnitudes, it was possible for these floods to transport large quantities of sand out of the system. The combination of an increase in riparian vegetation and decrease in sediment load lead to the narrower river. Large islands formed in the lower portion of the river as the channel incised and the islands vegetated.

Between the 1950 and 1960 data sets, the bankfull channel surface area decrease by an additional 6% with the 1930's data set as a base. The number of islands decreased by an additional 28% and the island area decreased dramatically to just 29% of the area in the 1930's. All reaches exhibited this dramatic change in island area while only reach three decreased in channel surface area.

Table 3.10. Summary of historic aerial photography analysis of changes in channel morphology of the San Juan River from four periods, 1934-35, 1950-52, 1959-62 and 1986-88.

Reach	3	4	5	6	7	8	Total	3-6 sum	3-6 % of
RM	67 - 104	105-130	131-154	155-180	181-213	214-224	67-224	67-180	1930's
				Bankfull Channel Surface Area - m^2					
1934-35	28,873,702	12,419,696	11,060,156	6,478,302	10,528,228	2,042,540	71,402,624	58,831,856	
1950-52	19,686,966	11,551,580	10,121,519	5,019,738	10,380,251	1,834,507	58,594,560	46,379,802	79%
1959-62	15,879,905	11,392,510	10,023,784	5,610,641	10,358,396	1,654,169	54,919,404	42,906,840	73%
1986-88	6,774,785	11,010,636	9,774,228	3,972,724	10,301,457	1,452,946	43,286,776	31,532,374	54%
				Island Count - number					
1934-35	133	101	229	153	209	24	849	616	
1950-52	125	84	135	49	142	24	559	393	64%
1959-62	42	53	70	56	70	4	295	221	36%
1986-88	191	125	149	97	140	36	738	562	91%
				Island Area - m^2					
1934-35	3,785,916	2,026,358	6,697,942	3,685,329	4,465,273	380,616	21,041,435	16,195,546	
1950-52	6,312,228	2,841,759	8,308,199	2,215,718	3,056,857	112,696	22,847,457	19,677,904	122%
1959-62	1,432,291	978,474	2,131,334	222,963	1,091,938	74,360	5,931,360	4,765,063	29%
1986-88	3,558,910	2,597,722	5,859,658	1,236,571	1,860,320	657,279	15,770,460	13,252,861	82%
				Mean Bankfull Width - m					
1934-37	472	297	312	155	198	115	284	326	
1950-52	322	276	286	120	195	104	233	257	79%
1959-62	260	272	283	134	195	93	219	238	73%
1986-88	111	263	276	95	194	82	172	175	54%

The riparian vegetation is even more dense in the 1959-62 data set than earlier and the bankfull channel is much simplified. Many of the secondary channels that were clean in the 1950 photography are heavily vegetated. During the period between the 1950-52 and 1959-62 data sets, the maximum daily peak discharge was 26,000 cfs in 1957, with no other values above 20,000 cfs and only two others above 10,000 cfs. Cumulatively, this is the driest decade on record. This reduction in flow in conjunction with the increase in riparian vegetation (tamarask were well established in the system by this time) likely resulted in the vegetation of the secondary channels and the loss of channel complexity.

Between the 1959-62 and 1986-88 data sets the channel surface area decreased by an additional 19%, with most of the change in reaches three and six. The number of islands dramatically increased, reaching 91% of the 1930's abundance. Island area also recovered to 82% of the 1930's level.

Navajo Dam began regulating the San Juan River in 1962. With this regulation came a further reduction in flood flows, but an increase in base flows. The mean annual peak flow is 10,160 cfs for this period, compared to 10,900 cfs for 1950-1961 period and 17,775 cfs for the 1935-1950 period. The maximum daily average flow for this period was 26,700 cfs in 1973. The impact of regulation is evident when examining the peak discharge in relation to the total annual runoff for the three periods. The peak discharge is about the same for the periods 1950-1961 and 1962-1988, while the latter period had an average annual runoff of 1.7 million acre-feet and the earlier period only 1.4 million acre-feet.

The other noted change in the basin during this 1960 to 1988 time period is the introduction of Russian olive into the basin. Survey notes from 1962 never mention Russian olive, while every stream channel and old secondary channel in the basin is now heavily vegetated with Russian olive. It is the dominant vegetation type, especially in areas of channel braiding an broad flood plains. During high flow, the riparian Russian olives dislodge and form debris piles in the river. At low flow these debris piles form islands and rapidly vegetate. During the next flood flow, they accumulate sediment and grow, becoming islands. This process is thought to have heavily influenced the increase in islands and added to channel complexity since the 1960s.

Channel cross-section surveys completed in 1962 and 1993 show that the channel has narrowed and deepened slightly during this time period (Bliesner and Lamarra, 1994) consistent with the findings of the aerial photography comparisons.

In addition to the changes in flow and vegetation, a second shift in the cumulative sediment plot came in 1973 with a further reduction in sediment load from an average of 20,100,000 tons per year to 10,100 tons per year. All of these changes have resulted in a much different channel than existed in the 1930's. While regulation of the flows with Navajo dam have had an influence on these changes, that influence has likely not been as great as that of the change in sediment load, natural hydrology and riparian vegetation.

Figures 3.5 through 3.8 present aerial photographs of an area in Reach 3 from RM 84 to RM 86 taken in 1934, 1952, 1961 and 1988. The sequential change discussed in this section can be seen by comparing these four photographs. Although the flowrates are not the same for all photographs, the conditions of the bankfull channel and the differences in vegetation can be noted. Vegetation was established and the channel became much more defined between 1934 and 1952, but the greatest change in vegetation occurred between 1961 and 1988. There was relatively little change between 1952 and 1961 for this location.

Geomorphological Characterization

River Valley Geometry

The distribution of valley width by river mile from the confluence of the San Juan River with Lake Powell to Navajo Dam is shown in Figure 3.9. The mean valley width per mile was computed as the valley area divided by the length, placing the river mile perpendicular to the general river trend where the river mile crossed. The data are presented as 3-mile running averages. The upper reach of the river from Navajo Dam to about RM 208 is canyon bound. The valley then broadens down to about Farmington, where it is constricted by bedrock on either side of the river. Between Farmington and Shiprock the valley broadens. The broadest area of the valley is just below Shiprock. From RM 140 to RM 127 the valley narrows to about ½ its width through the main irrigated area and remains at this general width (about 1,000 meters) until entering the canyon at the confluence with Chinle Creek. Below this point it is about 1/20 its width in the main irrigated area. It should be noted that the width may be somewhat overestimated in the irrigated areas due to difficulty in interpreting the boundary of the alluvial valley. The slopes to the river are more gradual and the signatures on aerial photography masked because of the irrigation. While the area may be somewhat over stated in this reach, the general trends hold.

Channel Contact Geology

The distribution of river cutbanks and the material makeup of these cutbanks is shown in Figure 3.10. The top of the area plot for cobble represents the total length of cutbanks per mile on a 3-mile running average basis. The value is the sum of both sides of the river so it is theoretically possible to have more than one mile of cutbank per mile of river. The values for sand, cobble and gravel are weighted to account for areas that are uniformly sand, gravel or cobble as well as those areas that contain sand, gravel or cobble, such as areas of sandy cobble or gravelly sand.

The other category of geologic contact is bedrock (including talus slope). The length of bedrock contact per mile of river is shown as the top area on Figure 3.10. The value is the difference between the top and bottom of the area graph for bedrock.

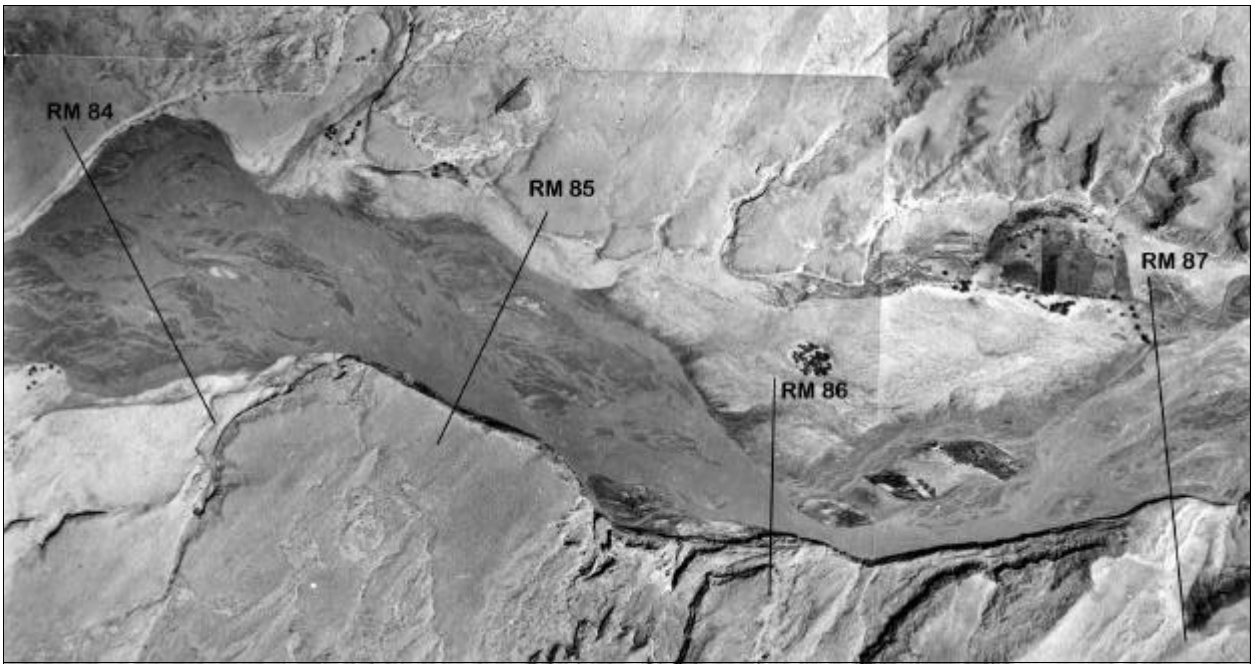

Figure 3.5. Aerial photograph of the San Juan River between RM 84 and RM86 taken in 1934.

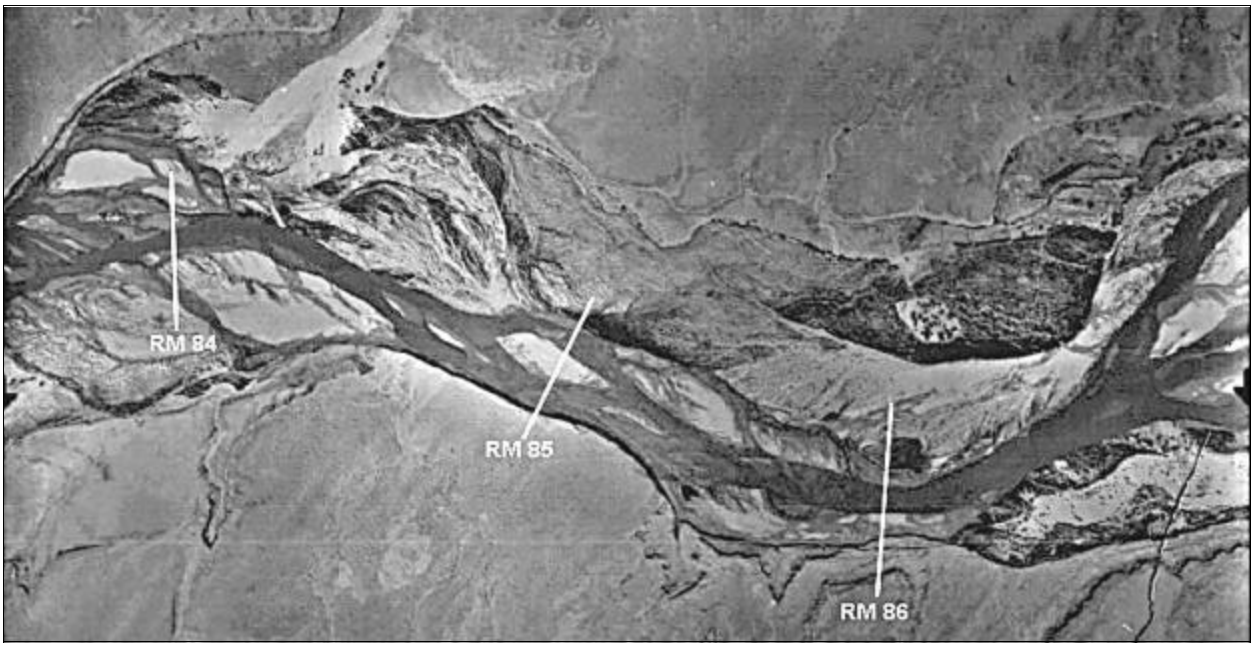

Figure 3.6. Aerial photograph of the San Juan River between RM 84 and RM86 taken in 1952.

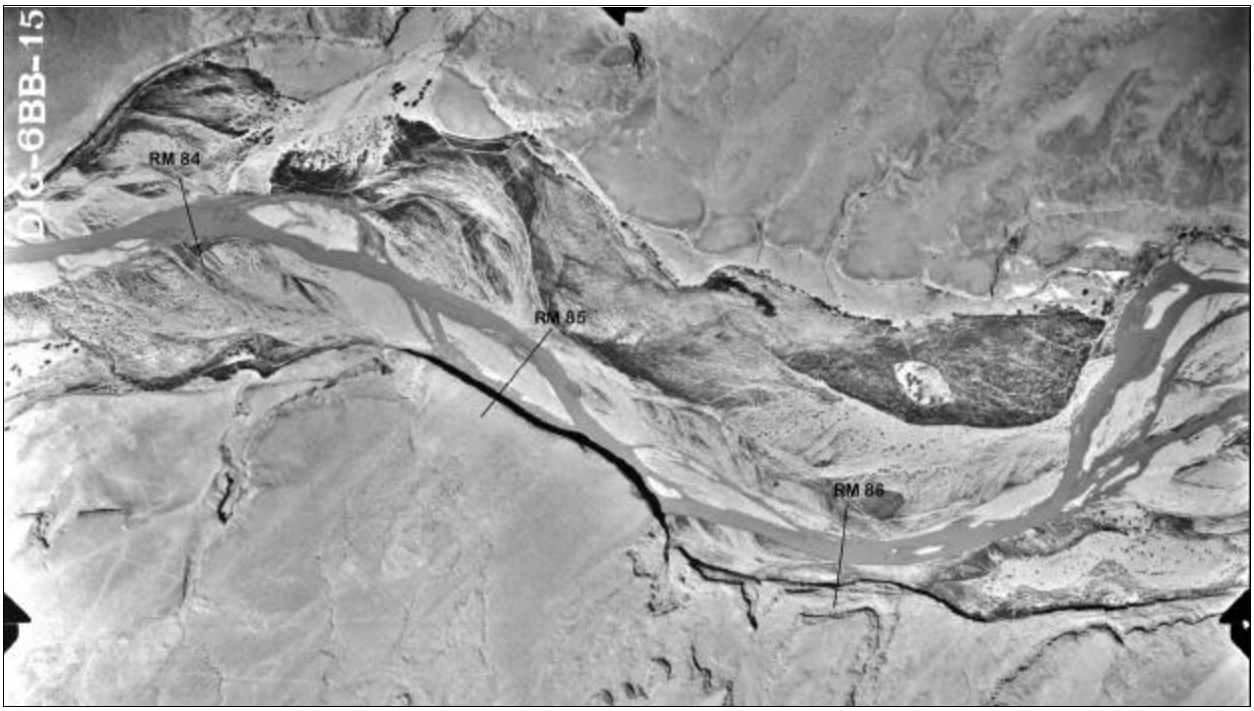

Figure 3.7. Aerial photograph of the San Juan River between RM 84 and RM86 taken in 1961.

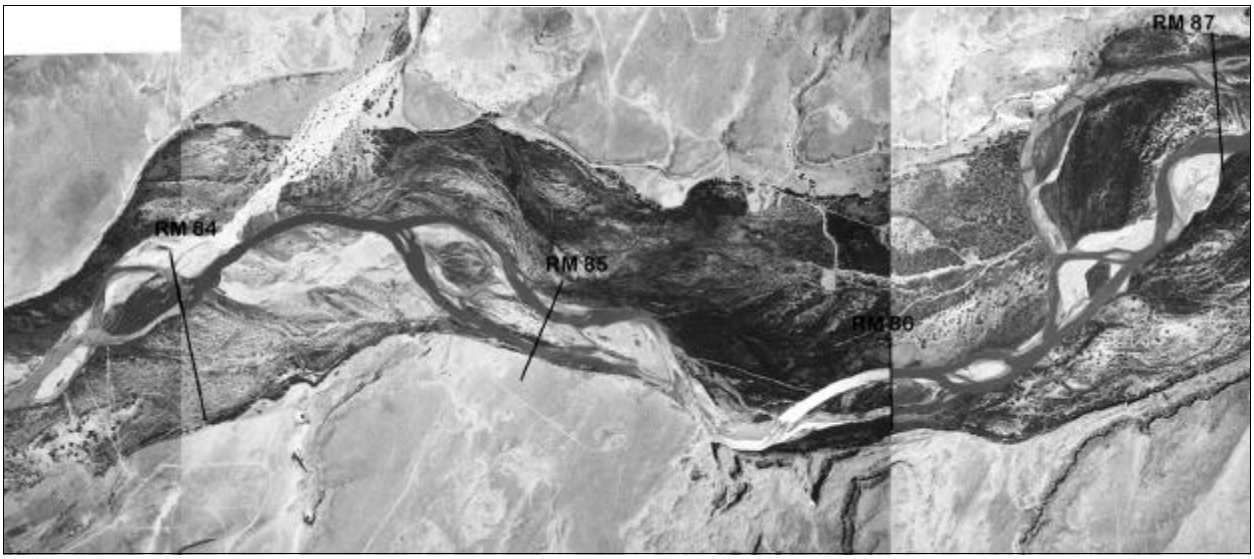

Figure 3.8. Aerial photograph of the San Juan River between RM 84 and RM86 taken in 1988.

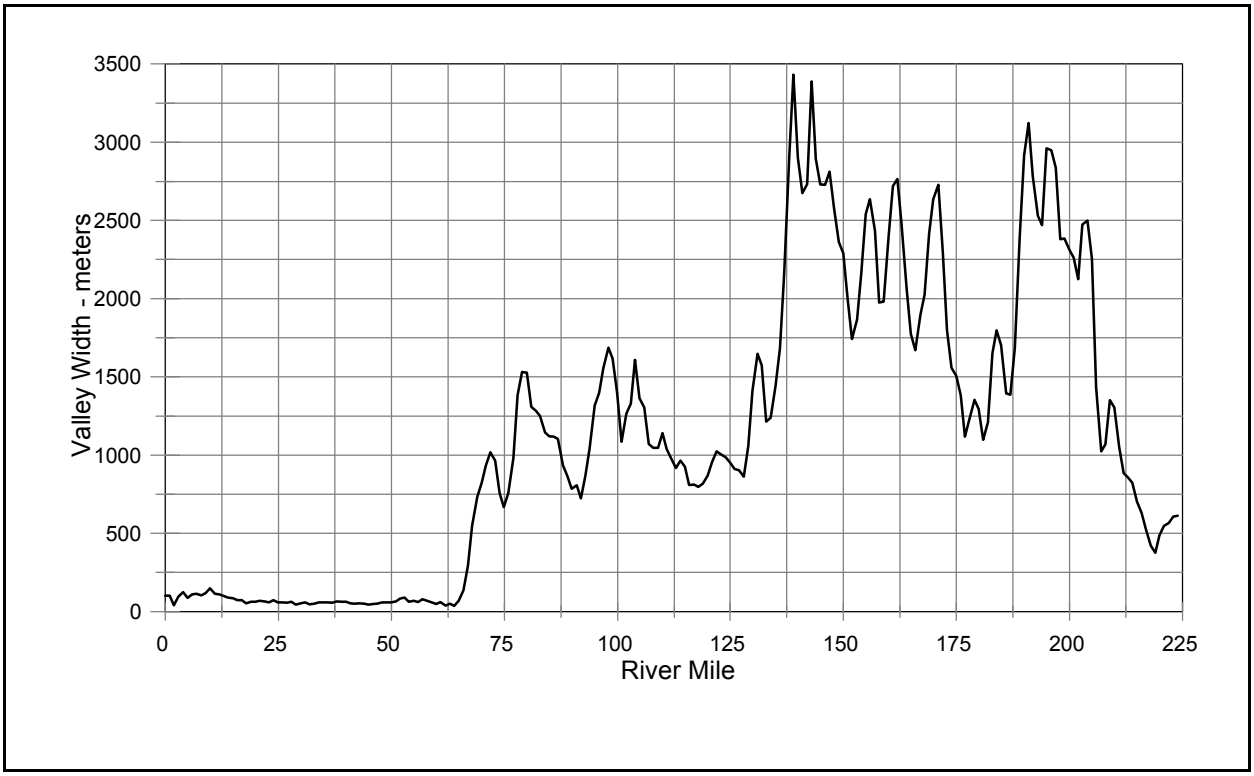

Figure 3.9. Valley Width by River Mile for the San Juan River

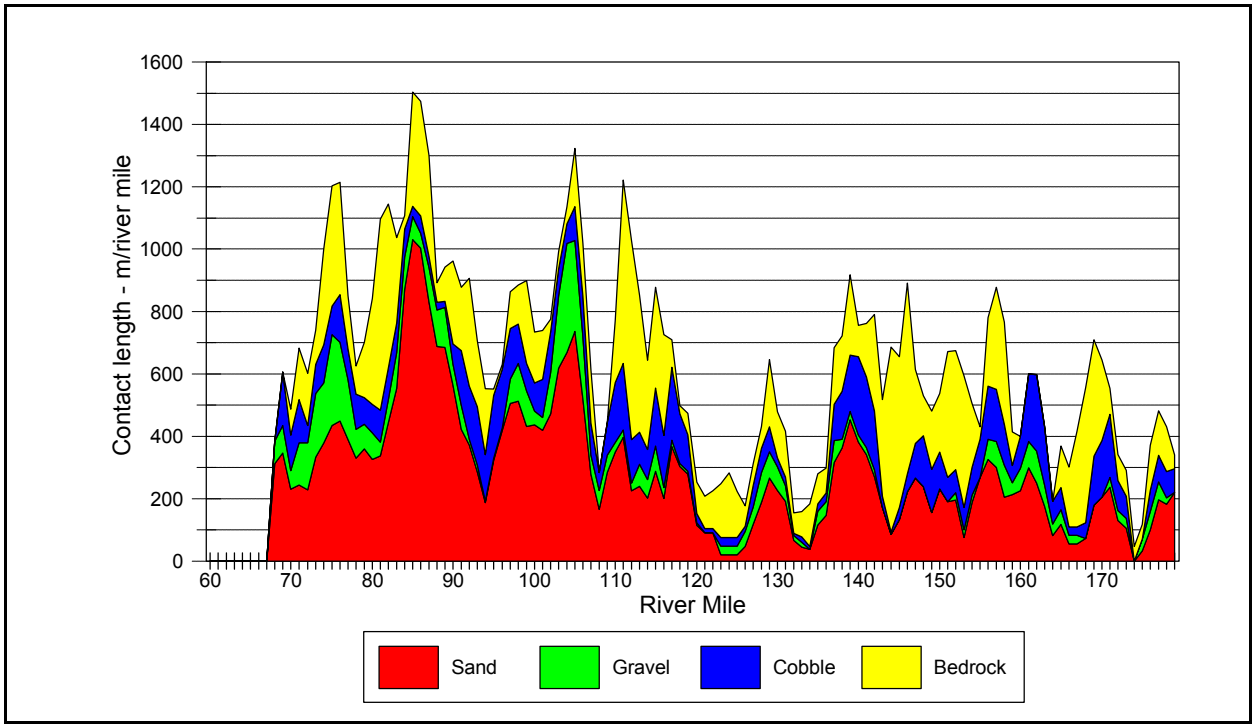

Figure 3.10. Three-Mile Running Average Channel Contact Geology (cutbank or bedrock) for the San Juan River.

In general, the total cutbank length per mile increases with distance downstream from the Animas River confluence. The maximum lengths occur in an area that has been termed the "debris field" (RM 82 to RM 90) because of the large deposition of trees and brush in the channel. The channel is very active in terms of lateral movement in this reach, which is confirmed by the large amount of cutbanks.

Also the proportion of sand is high in this area, reflecting the heavy sand loading of the system in the downstream reaches.

The area of least cutbank activity occurs between RM 119 and RM 127. This is an area of relatively straight channels with an increase of bedrock and cobble control and some natural levee formation in the straight reaches which have stabilized the banks. The valley width is still over 1,000 meters in this reach so there is opportunity for lateral movement except for the naturally stabilized channel. A second area of channel stability occurs between RM 132 and RM 135. There are areas of active channel movement in this reach, but the low proportion of sand and relatively higher proportion of cobble in the area tends to stabilize the banks such that the channel change occurs more as overland flooding in the braided areas with subsequent cobble bar formations rather than cutbanks. Even though this area is braided, the main channel is relatively straight with more gradual bends and heavily vegetated banks that resist erosion.

The "mixer" lies midway between these two relatively stable reaches. It is characterized by moderate cutbank activity with a moderately high proportion of gravel. The active reaches above and below the two stable reaches on either side of the mixer show more cutbanks with much higher proportions of cobble and very little gravel.

It should be noted that cobble and gravel are plentiful throughout the reach mapped. Even in areas of low cutbank activity, there is abundant cobble. This high proportion of cobble and reduced sand content in the upper reaches of the river appear to have a stabilizing influence on the channel.

For the reach of river mapped (RM 68 to RM 179) sand predominated the cutbanks at 64%, with cobble constituting 22% and gravel 14%. While this is representative of the cutbank areas it may not reflect the distribution in the river banks as a whole. When examining trends, sand and gravel increase in proportion with distance downstream from the Animas confluence while cobble decreases. The proportion of cobble decreases from about 33% at the upper end to 17% at the lower end, while gravel increases from 8% to 16%. The proportion of sand increases from 59% to 66% from upstream to downstream. The trend is toward increasing cutbanks and decreasing bedrock control with distance downstream in this reach.

Riparian Vegetation

The distribution of the five main vegetation classifications (upland shrubs and herbaceous vegetation not included) is shown in Figure 3.11. Riparian vegetation density increases from the confluence of the Animas River downstream to about RM 130 and then declines rapidly between RM 130 and RM 110. Between RM 110 and RM 105, density again increases to about the level near

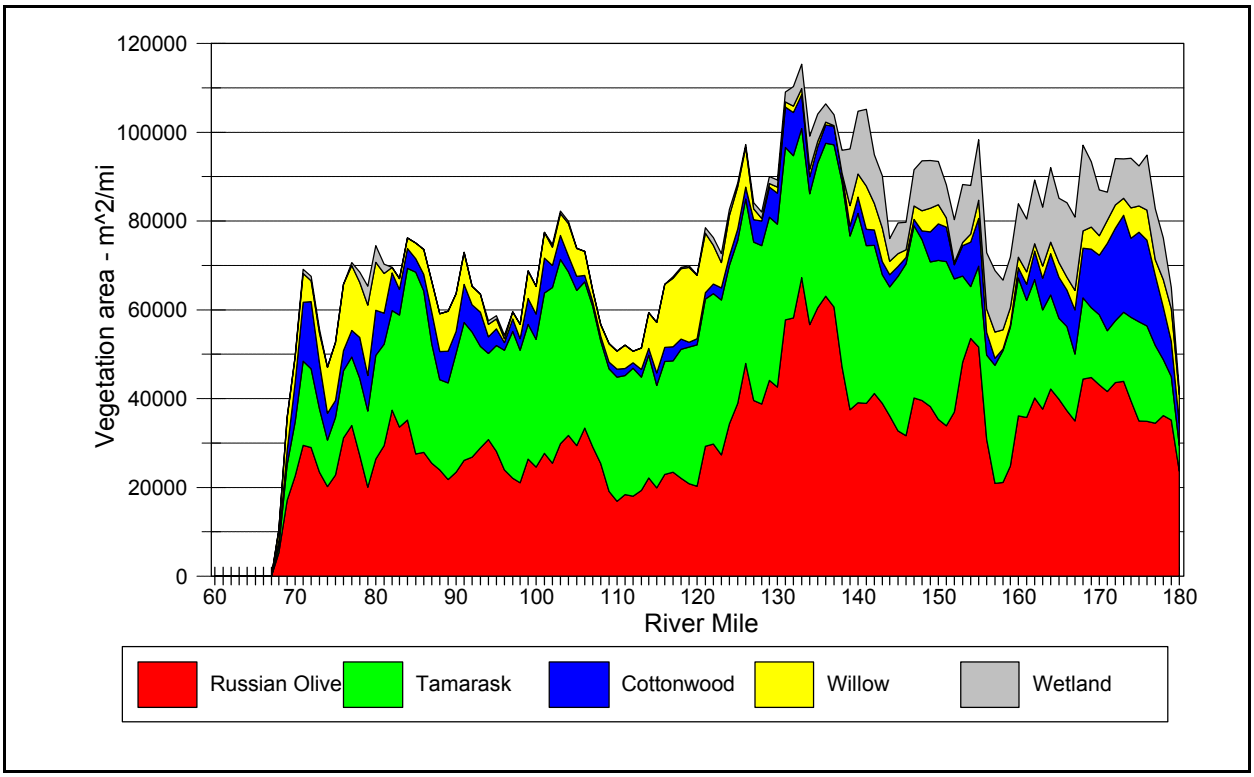

Figure 3.11. Main Channel Riparian Vegetation Area per River Mile for the San Juan River (3 mile running average).

Fruitland (RM 160) and remains relatively constant to the end of mapping at RM 68. Below RM 68 the riparian vegetation is sparse and not influential on channel morphology, since the canyon confines the channel.

Table 3.11 summarizes the relative abundance of each vegetation type mapped. Figure 3.12 shows the distribution of relative abundance for the five main types. Russian olive is the most abundant type, followed by tamarisk. Russian olive composition is relatively stable through the system with a few peaks and valleys but not much of a longitudinal trend. Tamarisk begins low, increases rapidly by about RM 160 and then is relatively constant until RM 115. Between RM 115 and RM 85 the relative abundance is at its highest level with a rapid decrease to the end, corresponding to an increase in willow. Cottonwood abundance is the highest at the two ends of the mapping range with the lowest values between about RM 100 and RM 165. Wetland plant abundance corresponds very closely to adjacent irrigation areas. Below RM 138 the wetland plant abundance is very low to non-existent. There is an increase in willow abundance between RM 112 and RM 125 that corresponds with a decrease in Russian olive and precedes an increase in tamarisk. As tamarisk increases, willow abundance decreases.

Table 3.11. Relative abundance of vegetation by type.

	Relative Abundance - %		
Type	Average	Maximum (5 mile)	Minimum (5 mile)
Russian Olive	37	53	26
Tamarisk	30	49	10
Cottonwood	7	17	1
Willow	6	18	1
Wetland Herbaceous	5	18	0
Upland Herbaceous	6	26	1
Upland Shrub	9	19	0

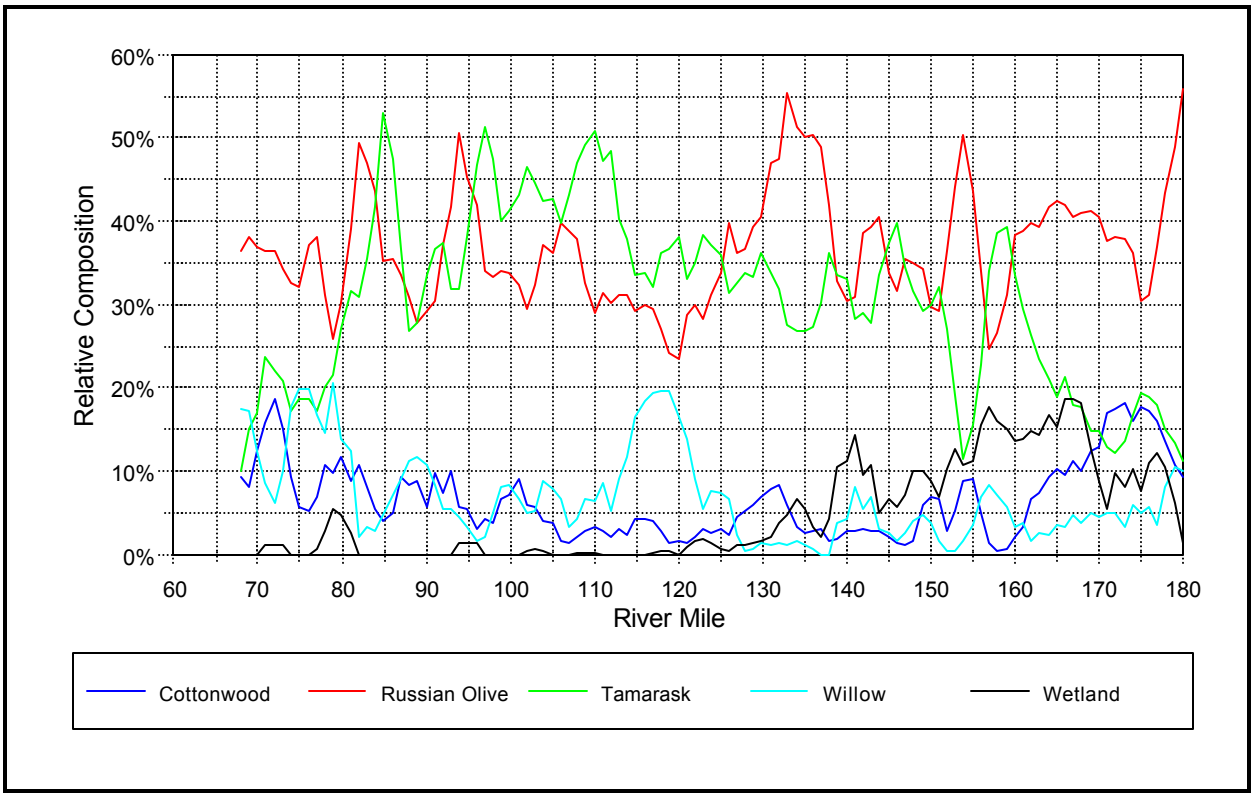

Figure 3.12. Relative Composition of Riparian Vegetation for the San Juan River (3 mile running average).

Channel Gradient

The channel gradient by river mile is shown in Figure 3.13 presented as a 3-mile running average. The gradient is moderately flat for about 5 miles below Navajo Dam, steepening to its maximum gradient within about 18 miles of the dam. There is a general but small decrease in slope to about RM 140. Between RM 135 and RM 70 the river maintains a moderately flat gradient before it steepens in the canyon reach. The flattest reach of the river is between RM 0 and RM 14, where the slope averages about 0.05%. This flat slope is not natural, but is due to the backwater effect of Lake Powell, deposition of sediment and subsequent rerouting of the river over a higher sandstone bluff at RM 0. If the channel moves off the bluff, as it appears to be doing, the gradient will steepen, restoring itself to a gradient closer to that of the river in this reach before inundation by Lake Powell.

Channel Pattern

The 3-mile running average channel sinuosity is presented in Figure 3.14. The values shown are significantly different than those reported in 1992 due to the revised method of computation discussed under **METHODS**. Previously, the sinuosity was the highest in the canyon reach. Under the correctly calculated values for the conditions in the San Juan basin, the lowest sinuosity occurs in the canyon. The standard dividing point between straight and meandering channels occurs at a sinuosity of about 1.5 with the exception of two locations. The sinuosity is always below 1.5, so the river would not be classified as meandering.

Other Parameters

The categorical parameters dealing with tributary and man's influence on channel morphology are summarized in the following section. Aquatic habitat parameters utilized in reach definition analysis are also summarized in the next section.

Identify River Reaches

Utilizing the above referenced data sets, the eight reaches previously identified were verified and the boundaries between the reaches established. Table 3.12 presents the reach definitions and the mean value of each data set for each reach. Not all data sets were equally important in determining boundary divisions and testing for difference. The most significant variables (statistically, not geomorphologically) in descending order were: *valley width*, *adjacent irrigated lands, low-flow sandy area, sinuosity, high-flow island area, high-flow total water area, channel slope, low-flow riffle area* and *low-flow total water area*. This order of importance was determined from values of univariate F-tests. The mean values of the significant variables within the reaches that were utilized in the model are shaded in Table 3.12.

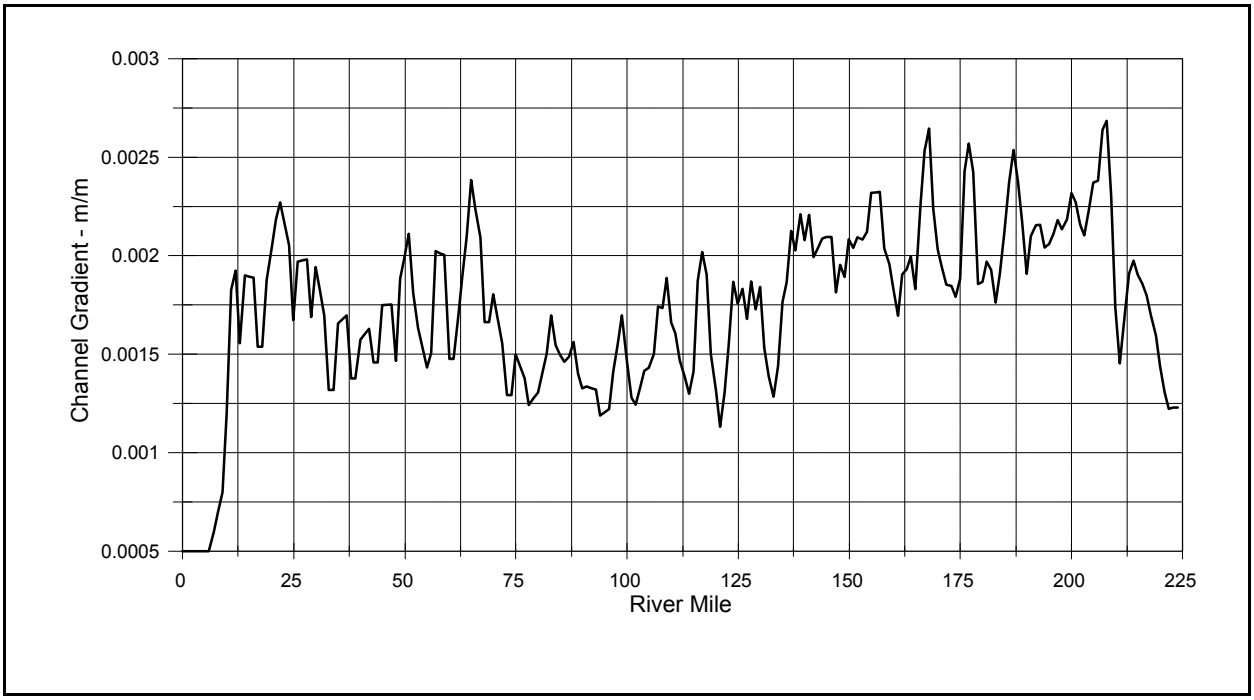

Figure 3.13. Three-Mile Running Average Channel Gradient for the San Juan River.

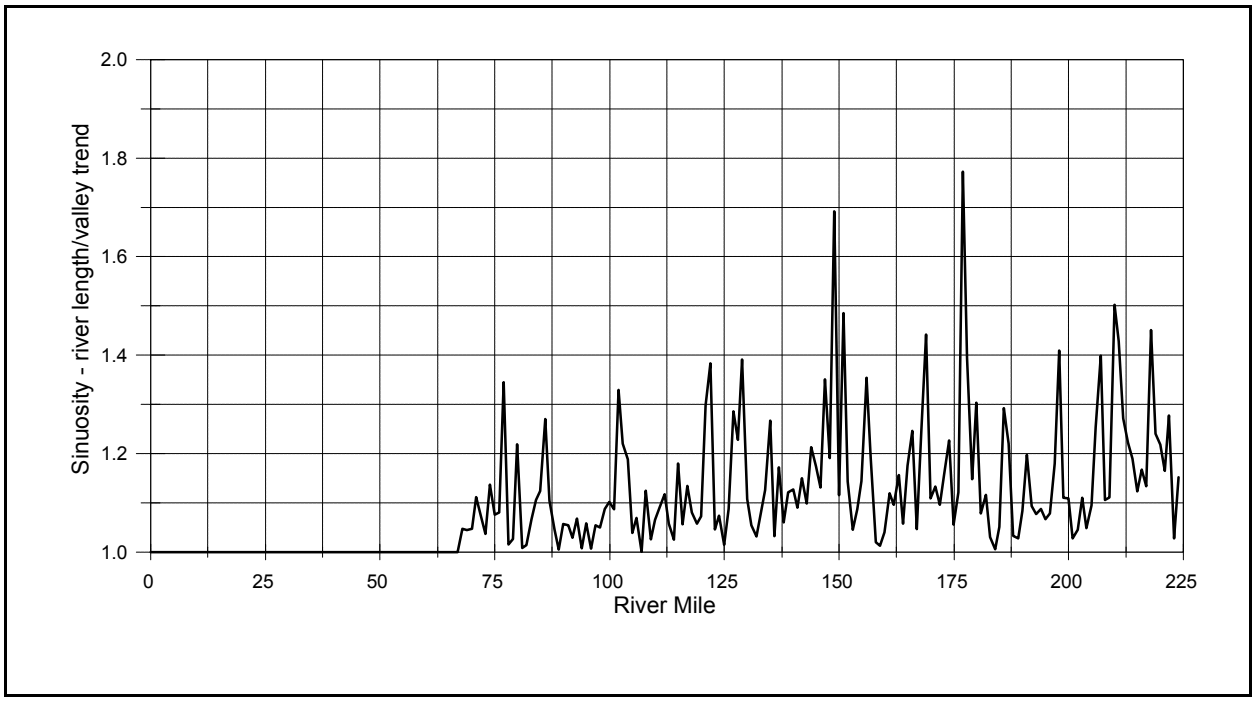

Figure 3.14. Three-Mile Running Average Channel Sinuosity for the San Juan River.

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Table 3.12. Reach definitions, variables considered and their mean values within reach utilized in delivering geomorphologically different reaches.

CATEGORY	REACH	1		2		3		4		5		6		7		8
	RIVER MILE	0-16		17-67		68-105		106-130		131-154		155-180		181-213		214-224
HABITAT - m^2/mi																
High Flow	Total Water Surface	152,314	≠	97,161	≠	199,049	≠	171,983	≠	206,925	≠	133,983	≠	102,519		150,883
	Low Velocity Types	1,920		2,015		1,481		1,893		1,861	≠	946		1,241		13,642
	Riffles/Chutes	42	≠	27,697		30,139		31,237		43,041	≠	10,816	≠	3,713	≠	13,050
	Sand Type	5,704	≠	363	≠	15,132	≠	2,794		3,224	≠	760		1,615		3,370
	Cobble Type	0		43	≠	3,726	≠	1,208		1,471	≠	632		364	≠	1,692
	Islands 3 mi average	0		109	≠	84,708	≠	117,354	≠	266,896	≠	58,403		52,958		53,469
Intermediate Flow	Total Water Surface	136,072	≠	74,415	≠	123,940		119,980		122,787						
	Low Velocity Types	4,646		1,192	≠	2,136		2,256		2,546						
	Riffles/Chutes	3,827	≠	19,013		14,373	≠	25,268	≠	38,382						
	Sand Type	43,108	≠	1,962	≠	8,932		6,923		3,392						
	Cobble Type	1,011		2,342	≠	7,139		7,785	≠	3,655						
	Islands 3 mi average	200		320	≠	51,940	≠	82,210	≠	188,055						
Low Flow	Total Water Surface	114,291	≠	72,142	≠	113,314	≠	104,522		107,422	≠	92,933	≠	77,043		94,636
	Low Velocity Types	2,239	≠	890	≠	1,897		2,026	≠	4,328	≠	8,929	≠	732	≠	17,921
	Riffles/Chutes	9	≠	16,865		14,683		16,113	≠	26,164		26,641	≠	6,746	≠	30,260
	Sand Type	26,112	≠	1,125	≠	7,195		5,526	≠	2,918	≠	586		1,337		0
	Cobble Type	309	≠	1,522	≠	2,572	≠	4,036		3,197		2,584		3,185		2,988
	Islands 3 mi average	0		173	≠	44,473	≠	71,249	≠	196,178	≠	21,675	≠	46,921		60,728
RIPARIAN VEGETATION - m^2/mi																
	Cottonwood					6,094	≠	2,847		4,909	≠	10,043				
	Russian Olive					26,643		28,701	≠	46,053	≠	35,119				
	Tamarisk					25,167	≠	31,224		32,536	≠	19,124				
	Willow					6,592		7,393	≠	3,007		4,499				
	Upland Herbaceous					1,811		7,182	≠	15,801	≠	9,569				
	Upland Shrub					7,897	≠	7,056	≠	2,349		2,647				
	Wetland Herbaceous					524		718	≠	8,737		11,509				
Note that shaded rows show significant variables																

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Table 3.12. (Continued)

CATEGORY	REACH	1		2		3		4		5		6		7		8
	RIVER MILE	0-16		17-67		68-105		106-130		131-154		155-180		181-213		214-224
CHANNEL - 3 mile average																
	Valley Width - m	102	≠	66	≠	1122	≠	986	≠	2299		2028		1957	≠	574
	Channel Slope - ft/ft	0.00105	≠	0.00178	≠	0.00143	≠	0.00164	≠	0.00193	≠	0.00209		0.00213	≠	0.00160
	Sinuosity	1.00000		1.00001	≠	1.09096	≠	1.12311	≠	1.16862		1.18715		1.15081	≠	1.19527
STREAM CHANNEL																
	Bedrock - m/mi					206		182		243		140				
	Total Cutbank					713	≠	324		323		316				
	Contains Sand					93.6%	≠	96.4%		86.2%		84.6%				
	Contains Gravel					29.7%	≠	31.1%	≠	7.8%	≠	26.5%				
	Contains Cobble					34.6%		64.0%		62.2%		58.1%				
	Sand Only					86.1%	≠	66.4%		68.7%		41.0%				
	Gravel Only					21.3%	≠	9.3%		6.2%		10.8%				
	Cobble only					15.2%		21.7%		23.2%		25.3%				
CATEGORICAL VARIABLES																
	Adjacent Irrigated Area - %	0.0%		0.0%		23.7%		0.0%		83.3%		100.0%		100.0%		30.0%
	Major Tributary - Ephemeral	0		0		6		3		2		0		2		2
	Major Tributary - Perennial	0		0		2		1		1		3		1		0
	Bridge	0		1		4		1		1		2		2		1
	Diversion	0		0		0		0		1		4		1		1
	Oil Well	0		2		4		0		0		0		0		0
	Pipe Crossing	0		0		1		0		2		1		0		0
	Borrow Pit	0		1		1		0		0		0		0		5
	Pond	0		1		6		2		2		0		0		0
	Road	2		1		6		0		0		0		0		0
	Sewage Treatment	0		0		3		0		3		3		0		0
Note that shaded rows show significant variables																

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Based on the results of discriminant analysis, a table of predicted versus assigned reach numbers was generated. The reaches at the boundaries were reassigned to the neighboring reach. The analysis was repeated to verify that the assigned boundaries between reaches matched those predicted by the model.

The final reach boundaries are shown in row 2 of Table 3.12. The final frequency assignment of river miles within reaches is shown in Table 3.13.

As seen from Table 3.13, the discriminant function found from the analysis predicts Reaches 1 and 8 perfectly, Reaches 2 and 6 with one out-of-place river mile, Reaches 4 and 7 with two out-of-place river miles and Reaches 3 and 5 with five out-of-place river miles. Reaches 3, 4, 5, 6 and 7 are the least distinct of the reaches and show the most overlap. In spite of this ambiguity, the reach assignments are very good (Pearson chi-squared test statistic = 1332.356 with probability = 0.000 that there is no relationship between the assigned and the predicted reaches). The predicted reach assignments may become better if the vegetation and channel-contact surveys are extended to the whole length of the river. The out-of-place river miles come not from the boundaries, but from inside the reaches. For this reason the boundaries of the reach assignments, shown in row 2 of Table 3.12, are the best statistical estimates.

Table 3.13. Frequency two-way table categorized by assigned and predicted reaches.

Assigned Reaches	Predicted Reaches							
	1	2	3	4	5	6	7	8
1	**17**	0	0	0	0	0	0	0
2	0	**50**	0	0	0	0	0	**1**
3	**1**	0	**33**	**4**	0	0	0	0
4	0	0	**2**	**23**	0	0	0	0
5	0	0	0	**1**	**19**	**3**	**1**	0
6	0	0	0	0	0	**25**	**1**	0
7	0	0	0	0	**1**	**1**	**31**	0
8	0	0	0	0	0	0	0	**11**

The difference in reaches can be illustrated by plotting some significant variables (standardized to plot on same scales) versus river mile. Figure 3.15 is a plot of *valley width, adjacent irrigated lands, low-flow sandy area, sinuosity,* and *high-flow island area*. Note how the variables shift in values between reaches. Not only do the mean values shift up or down, but the vertical spread or variances are different between reaches. These dissimilarities in the San Juan River imply that (1) the characteristics of proposed reaches are different and (2) the chosen variables are useful in defining separate habitat reaches.

Between the reach columns in Table 3.12 is the unequal symbol, ≠, denoting the values bracketed on the left and on the right are significantly different at the 95% or greater confidence level. The two-sample *t*-test was used to compare the means of the two groups of variables between each pair or reaches. For the variable, *high-flow total water area*, the mean values were all different between neighboring reaches except Reaches 7 and 8. For the variable, *high-flow low velocity type*, the mean values were all the same between neighboring reaches except Reaches 5 and 6 which were significantly different. Changes in the mean values which are different between reaches would be of special interest in monitoring changes along the river during the study.

River Geometry Analysis

Cross Section Measurement for RT Series Transects

Figure 3.16 shows the mean bed elevation for each of the RT series transects from March 1992 through August 1998. The March 1992 survey was used as the baseline and the relative elevation of each transect was set to 1.0 meter. If there has been net deposition since March 1992 the relative bed elevation will be greater than 1.0 meter. Conversely, if the elevation is less than 1.0 meter, scour has occurred. Due to a survey error in March 1992, RT-07 has no data point for the first survey. The relative elevation in July 1992 for this transect was set at the mean of the other transects to allow comparison from July 1992 on.

Table 3.14 summarizes the response of each transect. While the transects were selected to represent similar conditions in the river some variation in sites is unavoidable. The position of the transect relative to channel splits, the gradient at the location of the transect, the alignment of the channel (e.g. on a bend, straight, etc.) and the substrate conditions vary somewhat among the transects and influence the channel response.

Figure 3.17 shows the mean bed elevation as an average of all RT transects (RT-08 excluded). On average, the pre-runoff surveys show a greater mean bed elevation than the post-runoff surveys. The average pre-runoff mean bed elevation has dropped in each of the study years through 1996. The post-runoff mean elevation also decreased in each study year through 1995, with increases from the previous year in 1996 and 1998.

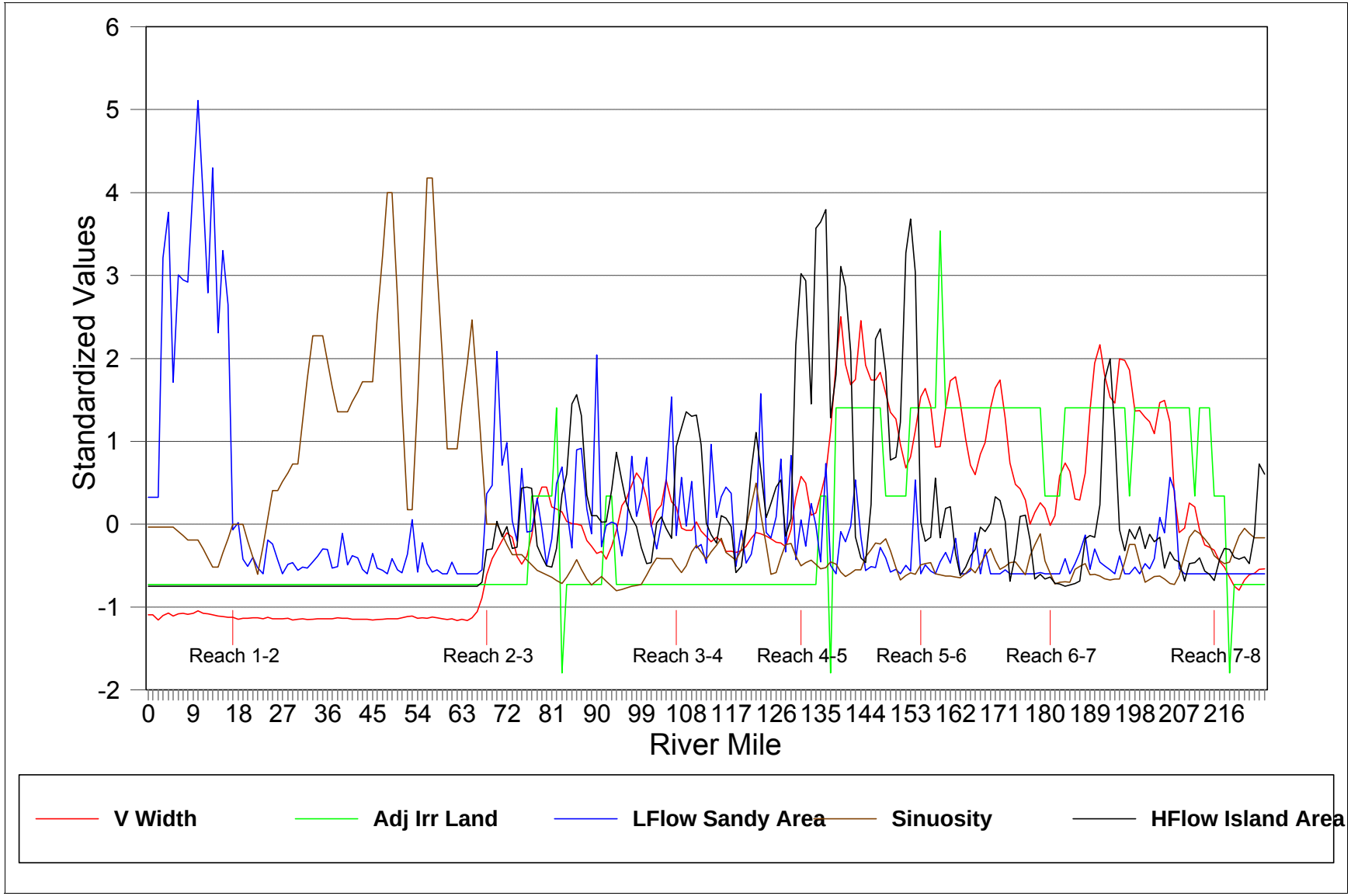

Figure 3.15. Distribution of Normalized Key Parameters used in Reach Definition.

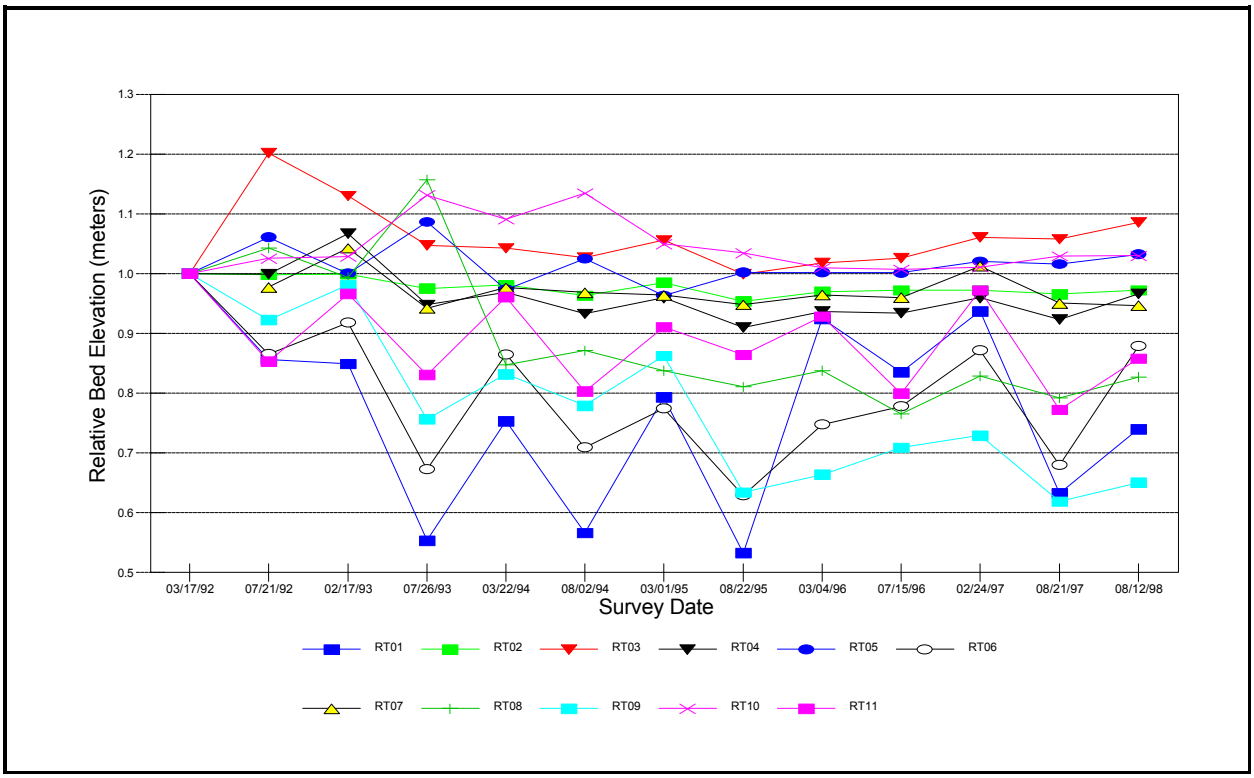

Figure 3.16. 1992-1998 Relative bed elevation for each of the RT transects on the San Juan River.

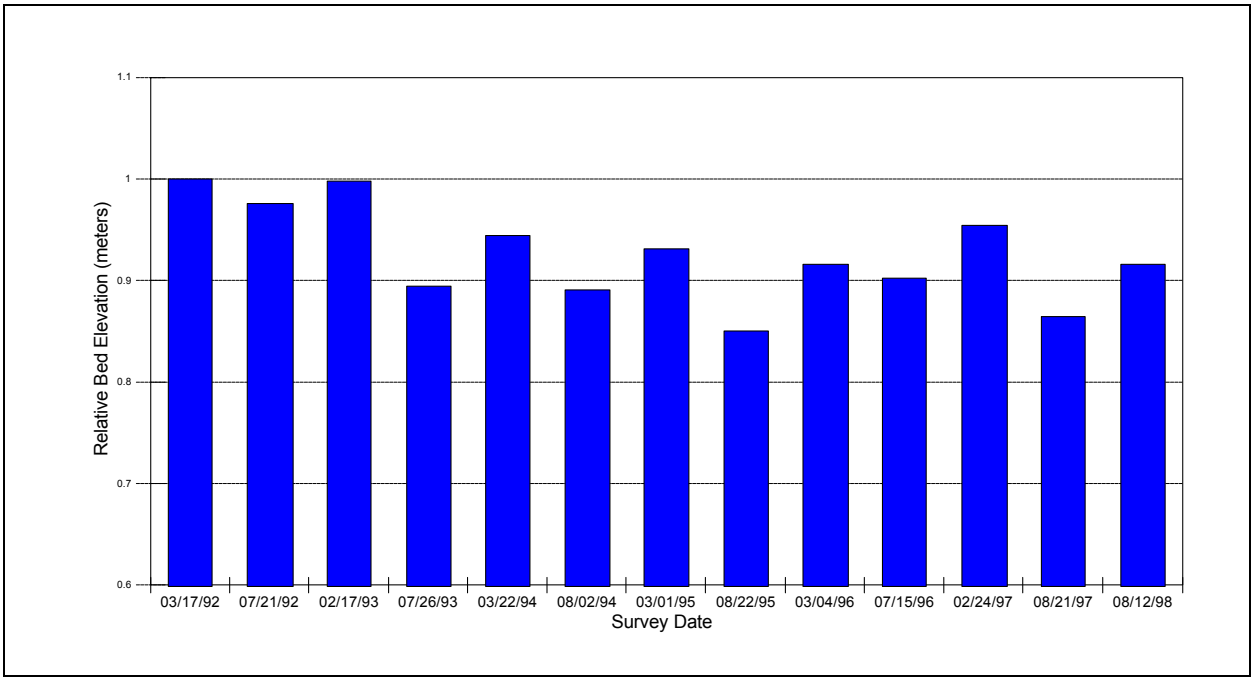

Figure 3.17. 1992 - 1998 Average relative bed elevation for RT series transects, on the San Juan.

Table 3.14. Summary of RT-series transect changes with time.

Transect	Net Change- m 1992-1998	Description of the Pattern of Change
RT-01	-0.26	Rapid scour to 1993, dynamic di-annual change, reached minimum elevation in 1995
RT-02	-.03	Gradual scour, little di-annual change, minimum in 1995
RT-03	.09	Initial deposition, subsequent scour, minimum in 1995, gradually increasing since
RT-04	-.03	Initial deposition, rapid scour in 1993, stable since with some diannual variation, minimum in 1995
RT-05	.03	Typically deposits during runoff and scours at low flow, minimum before runoff in 1995, gradually increasing since
RT-06	-.12	Substantial initial scour, minimum in 1995, large diannual variation
RT-07	-.05	Relatively stable with small diannual variation. Minimum in 1993 and 1998.
RT-08	-.17	Relatively stable except for the loss of an irrigation reservoir on the right bank in 1993 that caused large scour. Minimum in 1996.
RT-09	-.35	Large scour in 1993 and 1995. Minimum in 1997
RT-10	.03	Deposited until 1995, minimum in 1996. Relatively stable, largest scour (1995) was between runoff events
RT-11	-.14	Strong diannual pattern, minimum in 1997
MEAN	-.09	Diannual pattern with minimum in 1995
MEAN w/o RT-08	-.05	RT-08 scour is artificial due to reservoir embankment failure. Not included in analysis

Using the 1992 through 1997 data (1998 could not be used since there was no spring sample), mean elevation change during runoff was correlated to runoff volume at Four Corners, peak discharge at Four Corners and prior deposition (accumulated deposition since the previous low elevation). Discharge and elevation change data used in the analysis appear in Table 3.15. The results of the regression analyses appear in Table 3.16 for the individual transects and the average of all transects.

The best regression model for the average of all transects correlates the change in mean bed elevation during runoff to the March through July runoff and the previous non-runoff deposition. In years when runoff did not scour to the previous year's level, the accumulated deposition was used. When averaging the scour and deposition for 10 transects (RT-08 was removed from the analysis due to the failure of a reservoir bank on the right abutment), runoff scour was linearly correlated to runoff volume and previous deposition ($R^2 = 0.95$, $n = 5$, $p = .05$). Averaging the response across transects removes much of the random variability among transects. The resulting regression relationship well represents the average change, but will not predict the change at any given cross-section.

A second regression analysis was performed utilizing all the transect data, rather than averaging the response of the transects. With 50 data points, the regression is significant, but only explains a little over half of the variability seen when using the model used for the average condition(see Table 3.16 for regression results). The correlation is improved to explain about 62% of the variability when the % cobble before runoff and the % cobble after runoff are added to the model. The predicted changes in mean cross-section elevation using these models are plotted in Figure 3.18 plotted against the measured change for each of the surveys at each transect. The same trend of increasing scour with increasing flow and increasing previous year deposition is shown. The resulting scour appears to be influenced by the amount of cobble present before and after runoff. Sour decreases with increased cobble before runoff and increases with increasing cobble after runoff.

Table 3.15. Discharge at Four Corners and elevation change data for RT cross-sections.

Year	Annual Total	Mar-Jul Total	Apr-Jun Max	Scour During Runoff	Deposition Between Runoff	Cumulative. Deposition Between Runoff[1]
	Acre Feet		cfs	m	m	m
1991	1,084,775	573,863	5,160			
1992	1,510,148	1,074,795	8,900	-0.024		
1993	2,212,941	1,714,328	10,300	-0.104	0.022	0.022
1994	1,446,358	1,039,601	10,000	-0.054	0.050	0.050
1995	2,098,551	1,624,927	12,100	-0.081	0.041	0.041
1996	814,368	431,913	3,540	-0.014	0.066	0.066
1997	1,880,723	1,319,155	11,900	-0.091	0.052	0.104

[1] Includes previous year's deposition remaining after scour in years when scour is less than deposition.

Table 3.16 Results of regression analysis of channel change (scour or deposition) during runoff at RT cross-sections vs runoff and change during previous non-runoff period.

Transect	R^2	n	p	Intercept	Flow Coeff.	Previous Change Coeff.
average - scour = $f_{\text{peak cfs}}$	0.62	6	0.06	.026	-9.19E-06	
average - scour = $f_{\text{runoff af}}$	0.78	6	0.02	.022	-6.94E-08	
average - scour = $f_{\text{runoff af \& deposition}}$	0.95	5	0.05	.033	-7.13E-08	-0.257
all - scour = $f_{\text{runoff af \& deposition}}$	0.53	50	<.01	.069	-8.07E-08	-0.642
all - scour = $f_{\text{runoff, deposition, \% cobble before runoff and \% cobble after runoff}}$	0.62	50	<.01	.0074	-5.73E-08 .0017 (% cobble before)	-.4192 -.001 (% cobble after)
following expressed as scour = $f_{\text{runoff af \& deposition}}$						
RT-01	.90	5	.10	.050	-1.93E-08	-0.167
RT-02	.72	5	.28	.010	-2.19E-08	0.110
RT-03	.92	5	.08	.030	-5.11E-08	0.369
RT-04	.82	5	.18	.047	-4.50E-08	-1.044
RT-05	.75	5	.25	-.024	3.12E-08	-0.455
RT-06	.85	5	.15	0.145	-1.92E-07	-0.363
RT-07	.85	5	.15	0.039	-1.56E-08	-1.447
RT-09	.97	5	.03	0.164	-2.09E-07	-0.366
RT-10	.58	5	.42	0.003	4.09E-08	0.809
RT-11	.69	5	.31	0.084	1.047E-08	-1.772
Reach 6 - average	.94	5	.06	.023	-1.04E-07	-0.129
Reach 5 - average	.78	5	.22	.020	-2.86E-08	-0.018
Reach 4 - average	.82	5	.18	.095	-1.18E-07	-0.4417
Reach 3 - average	.85	5	.15	.012	-4.96E-08	-0.458

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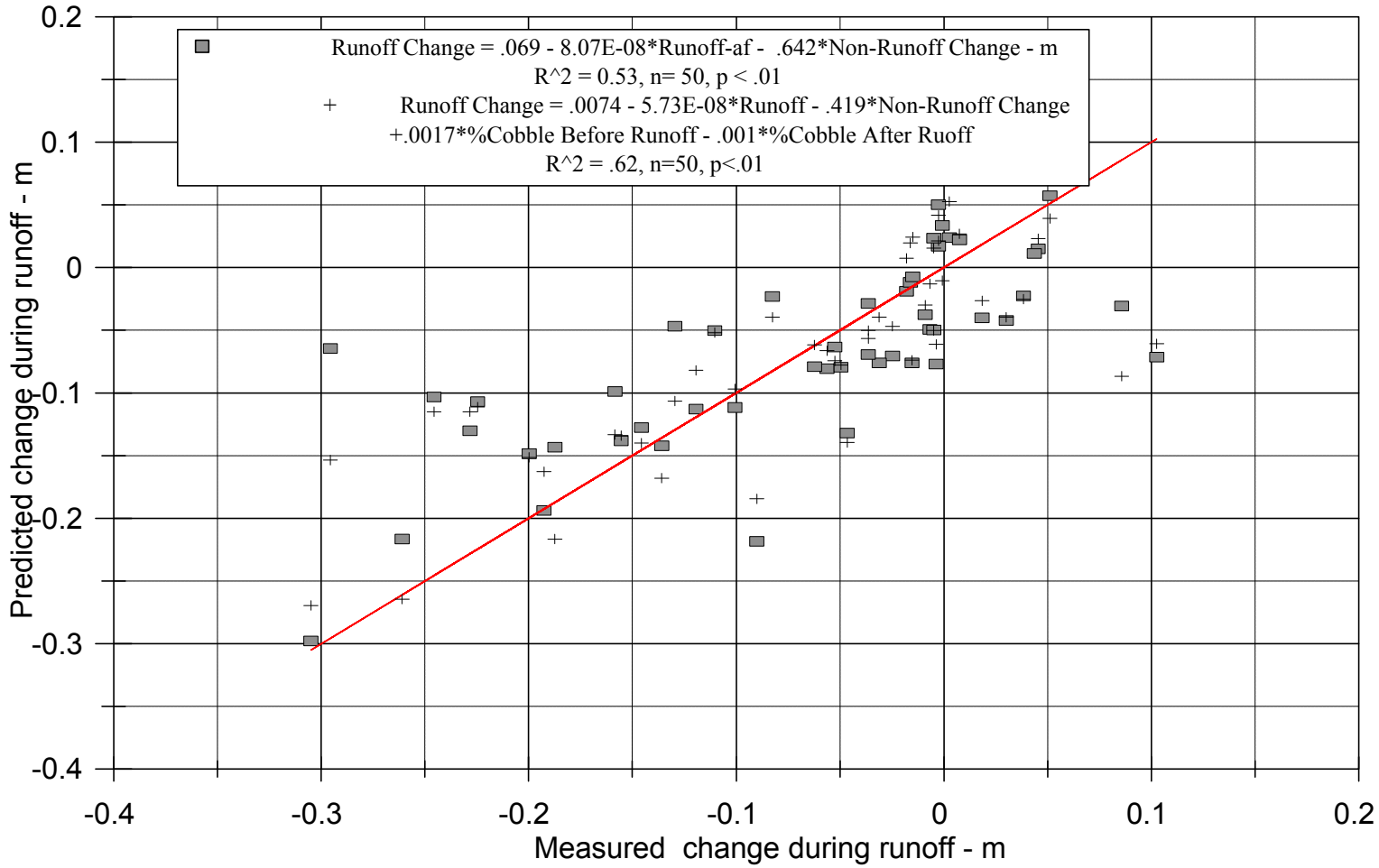

Figure 3.18. Predicted vs measured channel change in response to runoff for all RT transects in the San Juan River (1993-1997).

The resulting regression models for both the averaged data and the full data set show the same trend of increasing scour with increasing flow volume and increasing previous year deposition. In both models, deposition can occur when the flows are below a certain level, although the predicted thresholds are different.

Table 3.16 also shows the regression results for each individual cross-section. In this case, only one relationship is significant at the 95% level and three at the 90% level. The models vary depending on the response of the cross-sections, with two (RT-5 and RT-10) showing increased scour with decreased flow (deposition during runoff, scour during non-runoff).

Also shown in Table 3.16 are the regression results for data averaged by reach. In this case, RT-02 is averaged with RT-01 for Reach 6, even though RT-02 is actually 1 mile into Reach 5. Although the R^2 values are better, in general, than the single transect regressions, none are significant at the 95% level and only one at the 90% level. The models in each case do suggest increasing scour with increased flow and previous deposition, similar to the average of all transects.

The natural variability in transects is obvious in the examination of Tables 3.14 and 3.16 and Figure 3.16. Careful examination of the actual response of the cross-sections with consideration of their position in the river explains most of this variability. For example, RT-05 is located downstream of a sharp channel bend to the right and accumulates sediment during high flow conditions in the lee of the point bar. At low flow this material is eroded. RT-10 is positioned such that the right side of the transect is just downstream of a diagonal cobble bar that proceeds downstream to form a mid-channel island below the transect. At high flow the drop over the bar is submerged and material deposits behind the bar. At low flow the gradient steepens in this location and the deposited material erodes.

The portion of cobble substrate for these cross-sections is highly variable but has increased during the research period, both before and after runoff. Table 3.17 presents the cobble percentages during each survey for the RT cross-sections. The cobble portion of the substrate at the RT cross-sections reached their peak following runoff in 1993. This was the year of highest volume runoff and the lowest sediment load. 1995 had nearly the same volume, but the sediment load was higher due to some storm influence. 1997 and 1998 were both heavily storm influenced on the descending limb of the hydrograph, resulting in more fine sediment. Typically low flow years like 1996 and 1998 have the least cobble substrate after runoff, although this can be effected by storm inflow prior to survey as occurred in 1997 and 1998.

Table 3.17. Percent cobble substrate for the RT series transects on the San Juan River (1992-1998).

	Survey Date												
Transect	03/17/92	07/21/92	02/17/93	07/26/93	03/04/94	08/02/94	03/01/95	08/22/95	03/04/96	07/15/96	02/24/97	08/21/97	08/12/98
RT01	0%	26%	22%	100%	5%	85%	7%	87%	13%	24%	0%	30%	36%
RT02	50%	54%	86%	100%	87%	85%	84%	87%	85%	68%	88%	86%	72%
RT03	33%	47%	65%	87%	80%	66%	62%	73%	69%	65%	55%	60%	60%
RT04	35%	35%	75%	88%	59%	87%	65%	90%	77%	80%	63%	74%	65%
RT05	16%	0%	30%	70%	66%	67%	62%	70%	42%	63%	55%	67%	60%
RT06	19%	0%	24%	43%	13%	23%	16%	38%	32%	26%	18%	23%	20%
RT07		69%	61%	80%	69%	80%	66%	90%	78%	92%	72%	88%	79%
RT08	26%	46%	57%	20%	16%	11%	14%	13%	17%	22%	13%	25%	13%
RT09	38%	38%	46%	73%	35%	50%	35%	44%	58%	46%	34%	33%	19%
RT10	50%	78%	65%	79%	88%	35%	77%	57%	73%	75%	61%	60%	72%
RT11	3%	13%	11%	47%	11%	43%	3%	13%	14%	59%	8%	23%	25%
Average	27%	37%	49%	72%	48%	58%	45%	60%	51%	56%	42%	52%	47%

Cross Section Measurement for Mixer Transects

Figure 3.19 shows the mean bed elevation for each of the mixer series transects from February 1993 through July 1998. Transects 1-4 were first surveyed in February 1993. Transects 5-8 were first surveyed in September 1993. All data were normalized to use the July/September 1993 survey as the baseline and the relative elevation of each transect was set to 1.0 meter for that survey.

Figure 3.20 shows the average relative bed elevation for M-3 through M-8 transects. M-1 and M-2 were not included in the average. M-1 experienced a channel course change in 1993. A new main channel was formed in a location of a small secondary channel, subsequently filling the old main channel. M-2 was the location of the formation of the new main channel, requiring a change in the width of the survey. It filled on the left and scoured on the right, without a lot of net change. However, after the change, the cross-section ran diagonally across the new channel and became impossible to survey at high flows. It is not included in the average due to the loss of these data points.

Table 3.18 summarizes the response of each transect. These transects are more variable in nature than the RT series and tend to represent more dynamic locations. They were also surveyed more frequently to better determine the response to the ascending and descending limbs of the hydrograph. The general trend during most runoff periods is to exhibit scour on the ascending limb and deposition on the descending limb. In all years except 1997, scour is greater during the non-runoff period than during runoff. The dynamics at these locations are much different than at the RT cross-sections. The gradient is typically higher and they are located in areas of significant cobble movement and channel change. The extreme example is RT-01 with over 1.0 m of fill as the channel was isolated during one runoff event.

Most of these cross-sections have exhibited a pattern of scour since mimicry of the natural hydrograph was initiated in 1992, similar to the RT cross-sections and greater in magnitude. Further, the pattern of stability that is seen in the RT surveys is not apparent, with 1997 being the lowest year to date and the 1998 survey shows an average elevation below the earlier years. Stability is not yet evident. However, this is a historically dynamic area and these locations have historically changed more than other areas of the river. The lack of stability in six years of data is not alarming.

Table 3.19 presents the cobble percentages during each survey for the mixer series cross-sections. Cobble percentages are generally higher and less variable for these surveys than for the RT series. There is no statistically significant difference in the average cobble percentages with time.

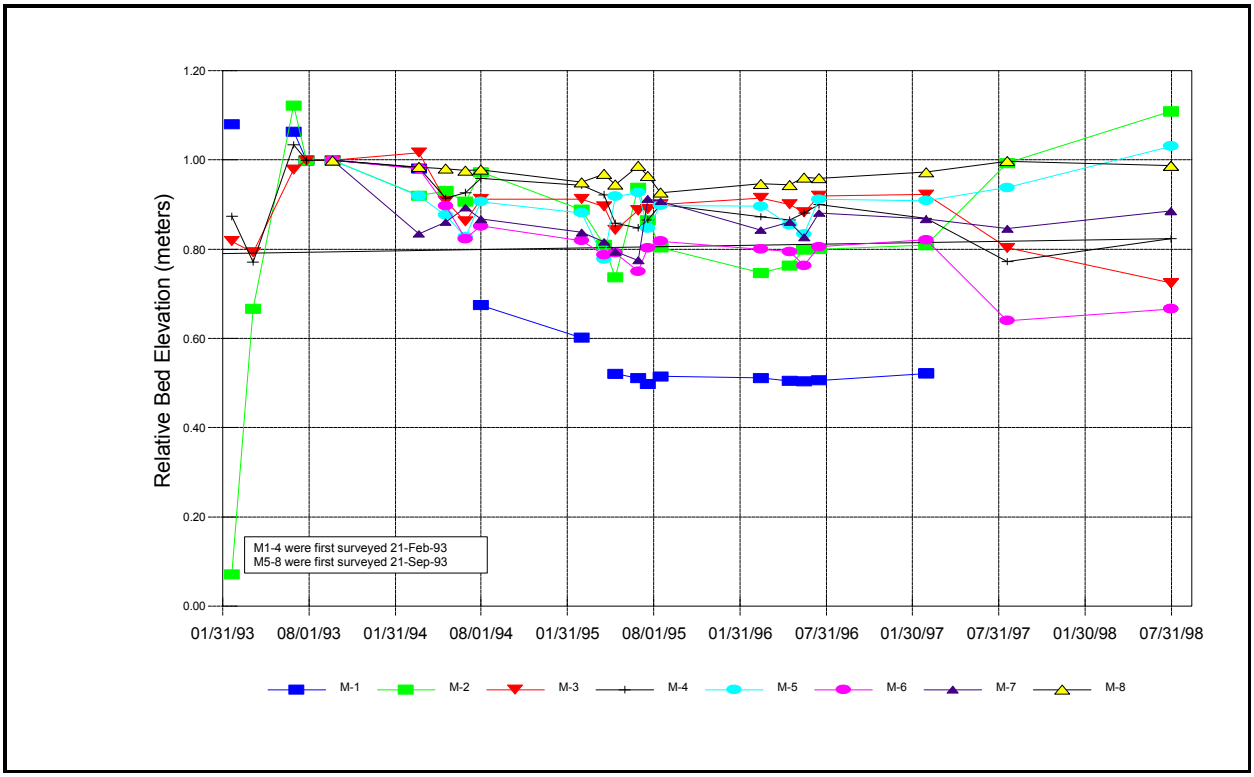

Figure 3.19. Relative bed elevation for all Mixer series transects on the San Juan River (1993-1998).

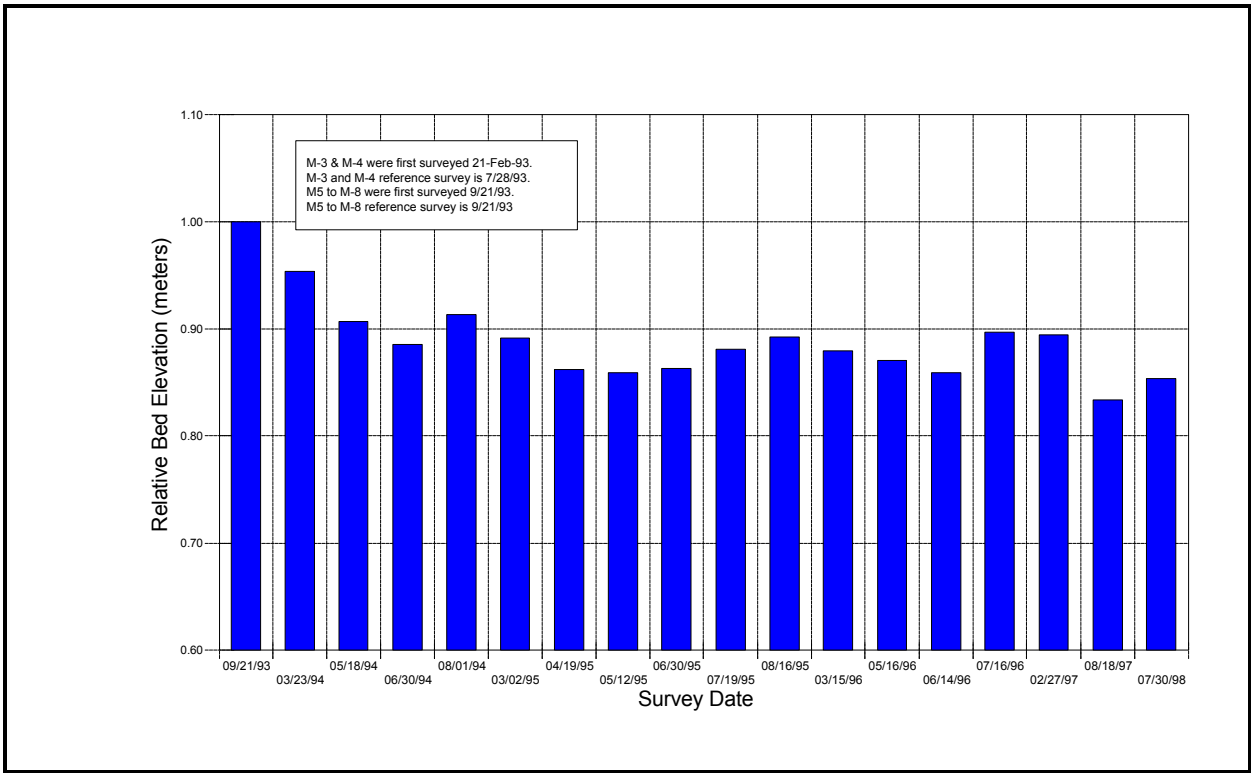

Figure 3.20. Average relative bed elevation for Mixer series transects (M-3 to M-8) on the San Juan River (1993-1998).

Table 3.18. Summary of Mixer series transect changes with time.

Transect	Net Change- m 9/83-8/98	Description of the Pattern of Change
M-01	-0.48	First survey in Feb 93. Total change -0.55 m. Could not survey at high flow, so several missing survey points. Heavy scour in '94 as secondary channel enlarged. Some scour in '95. Stable since. No re-filling between runoff.
M-02	0.11	First survey in Feb 93. 1.04 m total change. Heavy fill in 1993 as this channel was isolated and new channel developed on the right sight of M-01. Stable from '95-97. Filled in '97 and '98. Isolated at low flow.
M-03	-0.28	First survey in Feb 93. -0.09 m total change. Some fill in 1993, scour in '94, stable until '97, scour in '97 and '98.
M-04	-0.18	First survey in Feb 93. -0.05. Filled in '93 and '98. Scoured in '94, '95 and '97.
M-05	0.03	Scoured in '94, scoured and re-filled in '95 and '96, filled in '97 and '98.
M-06	-0.33	Scoured in '94 and '97, scoured and re-filled in '95 and '96, stable in '98
M-07	-0.11	Scoured before runoff in '94, scoured and re-filled in '95 and '96, stable since.
M-08	-0.01	Very stable with some scour in '95 and gradual re-fill since.
MEAN	-0.22	General pattern of scour at peak runoff and refill on descending limb. Greatest net scour in 1994 and 1997. Tend to be erosional between runoff and depositional during runoff, except for 1997.
MEAN w/o M-1&2	-0.15	M-1 is missing several surveys. M-2 filled heavily in 1993 as a new secondary formed north of the transect, isolating it except at high flow.

Table 3.19. Percent cobble substrate for the Mixer series transects on the San Juan River (1993-1998).

Date	Mixer 1	Mixer 2	Mixer 3	Mixer 4	Mixer 5	Mixer 6	Mixer 7	Mixer 8	Average M-3 to M-8
02/21/93	83%	74%	29%	46%					
04/06/93		0%	39%						
06/30/93	94%	23%	73%	90%					
07/28/93	96%	51%	80%	71%					
09/21/93					63%	44%	37%	60%	59%*
03/24/94	83%	26%	70%	69%	49%	29%	34%	54%	51%
05/18/94		28%	75%	89%	26%	36%	41%	49%	53%
06/30/94		36%	75%	64%	43%	23%	39%	64%	51%
08/01/94	89%	37%	73%	70%	51%	17%	39%	65%	52%
03/02/95	87%	27%	62%	65%	52%	33%	37%	66%	53%
04/19/95		32%	65%	74%	54%	39%		67%	50%
05/12/95	75%	68%	74%	68%	52%	37%	52%	61%	57%
06/03/95	83%	29%	82%	66%	51%	46%	59%	64%	61%
07/19/95	92%	34%	79%	73%	57%	38%	41%	68%	59%
08/16/95	93%	35%	82%	75%	51%	36%	43%	41%	55%
03/06/96	94%	32%	75%	73%	61%	39%	46%	66%	60%
05/24/96	93%	46%	73%	76%	54%	50%	44%	66%	60%
06/14/96	94%	34%	75%	75%	53%	46%	40%	58%	58%
07/16/96	91%	50%	80%	69%	54%	36%	44%	64%	58%
02/27/97	87%	27%	72%	75%	48%	38%	43%	51%	55%
08/18/97		13%	81%	41%	60%	55%	40%	64%	57%
07/30/98		28%	66%	44%	39%	46%	45%	65%	51%

* This average includes the July data for M-3 and M-4.

Cross Section Measurement for Debris Field Transects

Figure 3.21 shows the mean bed elevation for each of the debris series transects from September 1993 to August 1998. All data were normalized to use the September 1993 survey as the baseline and the relative elevation of each transect was set to 1.0 meter for that survey.

Figure 3.22 shows the average relative bed elevation for D-1 through D-5 transects. Table 3.20 summarizes the response of each transect. These transects have exhibited more total scour than either the RT or mixer cross-sections and have not stabilized. The pattern of scour during peak runoff and refill on the descending limb is similar to the pattern seen in the mixer, although there is less re-fill for more total net scour.

Table 3.21 presents the cobble percentages during each survey for the debris field series cross-sections. Cobble percentages are generally lower than either the RT or mixer series transects with not significant change with flow or time.

Cross Section Measurement for Clay Hills Transects

Figure 3.23 shows the mean bed elevation for each of the Clay Hills transects from October 1993 to August 1998. All data were normalized to use the October 1993 survey as the baseline and the relative elevation of each transect was set to 1.0 meter for that survey.

Figure 3.24 shows the average relative bed elevation for C-1 and C-2 transects. These transects are located in a canyon reach that is influenced by Lake Powell. There is about 40 ft of sand deposited in the bottom of the canyon in this location, so the river bottom is very mobile. The thalweg is constantly shifting by eroding and depositing sand shoals. Most of the change in the two cross-sections through July 1996 is a result of this erosion and deposition within the cross-sections.

Beginning in 1996, the elevation of the downstream cross-section (C-2) began increasing. C-1 began increasing in 1997. Both are at maximum (approximately 0.65 m higher than the initial surveys) in the fall of 1998. Prior to 1995, Lake Powell levels were sufficiently low to not influence this reach. Even though the lake levels were low, rerouting of the channel at RM 0 placed the channel on a sandstone ledge, preventing erosion upstream. In 1995 lake levels reached a level sufficient to submerge the waterfall that had developed at the ledge, but did not markedly impact channel elevations upstream until 1996. Since that time, the bed elevation has been gradually increasing in response to this backwater effect. A plot of Lake Powell water surface elevation is shown in Figure 3.25. Also shown is the approximate elevation of the waterfall.

Substrate is 100% sand for both of these transects and will remain so regardless of the elevation of the bed. The changes in bed elevation in this reach (below RM 18) are more influenced by Lake Powell than San Juan River discharge.

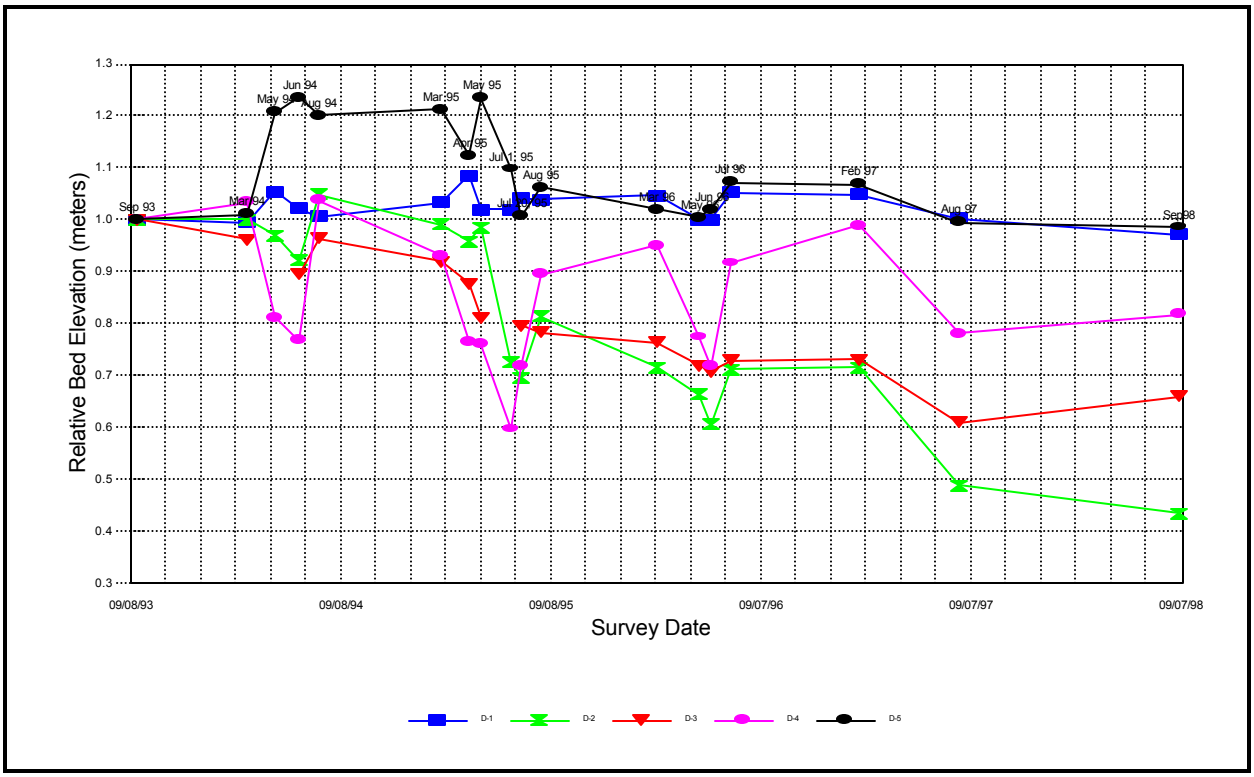

Figure 3.21. Releative bed elevation for all Debris Field series transects on the San Juan River (1993-1998).

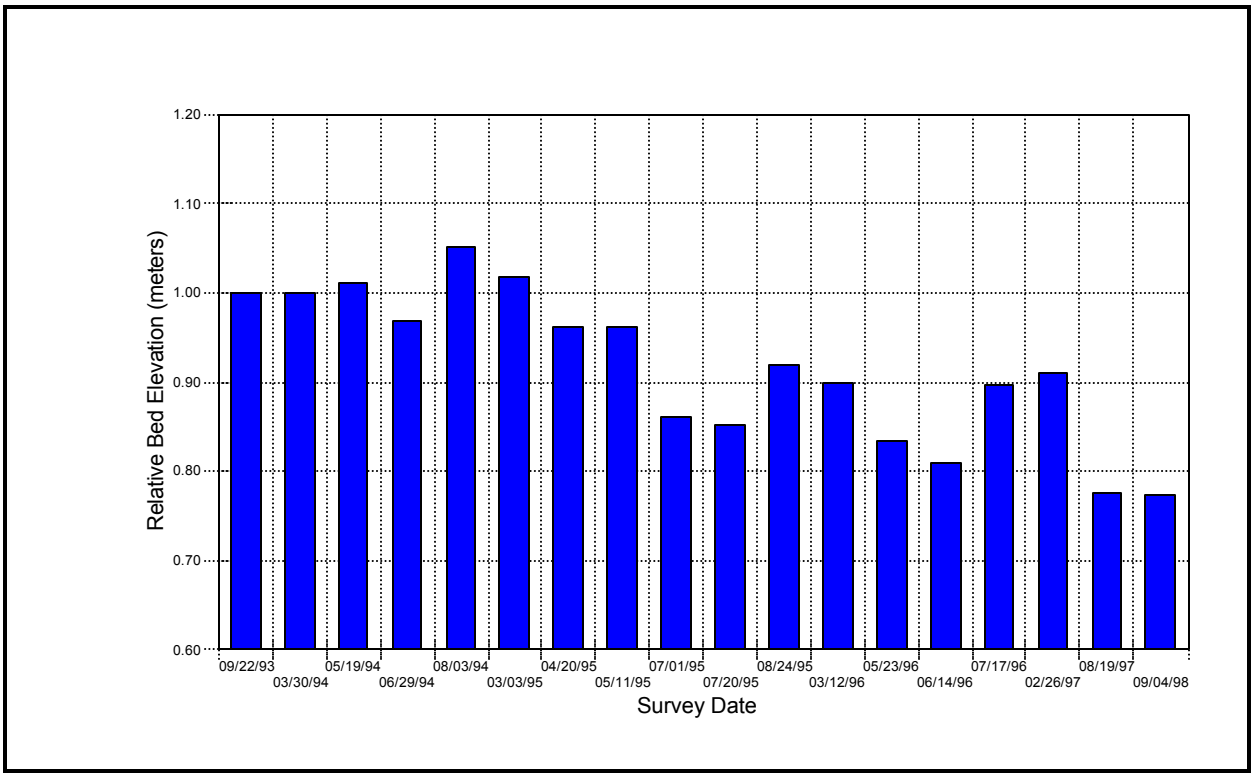

Figure 3.22. Average relative bed elevation for Debris Field series transects on the San Juan River (1993-1998).

Table 3.20. Summary of debris field series transect changes with time.

Transect	Net Change- m 9/83-8/98	Description of the Pattern of Change
D-01	-0.03	Relatively stable, with some deposition until '97, sour in '97 and '98
D-02	-0.57	Heavy scour in '95 and '97, some re-fill on descending limb, net scour each year except '96.
D-03	-0.34	Similar to D-02, except filled slightly in '98.
D-04	-0.18	Heavy scour through peak, large refill on descending limb, little net change until scour in '97.
D-05	-0.01	Large fill in '94, minor fill in '96, heavy scour in '95, small scour in '97, no change in '98
MEAN	-0.23	General pattern of scour at peak runoff and refill on descending limb. Greatest net scour in 1995 and 1997. Tend to be erosional on ascending limb and during peak runoff.

Table 3.21. Percent cobble substrate for the debris field series transects on the San Juan River (1993-1998).

Date	D-1	D-2	D-3	D-4	D-5	Average
09/22/93	34%	22%	16%	16%	19%	21%
03/30/94	28%	20%	14%	9%	21%	19%
05/19/94	36%	38%		22%	51%	29%
06/29/94	21%	25%	13%	4%	34%	19%
08/03/94	34%	24%	5%	4%	30%	19%
03/03/95	24%	29%	9%	5%	17%	17%
04/20/95	25%	29%	13%	8%	28%	20%
05/11/95	21%	29%	8%	9%	42%	22%
07/01/95	22%	15%		23%	43%	21%
07/20/95	30%	10%	43%	7%	21%	22%
08/24/95	25%	11%	43%	7%	8%	19%
03/12/96	25%	12%	40%	3%	40%	24%
05/23/96	27%	18%	43%	2%	26%	23%
06/14/96	27%	14%	44%	3%	12%	20%
07/17/96	26%	15%	48%	1%	28%	24%
02/26/97	21%	9%	34%	6%	28%	20%
08/19/97	33%	14%	29%	14%	17%	21%
09/04/98	37%	26%	31%	13%	23%	26%

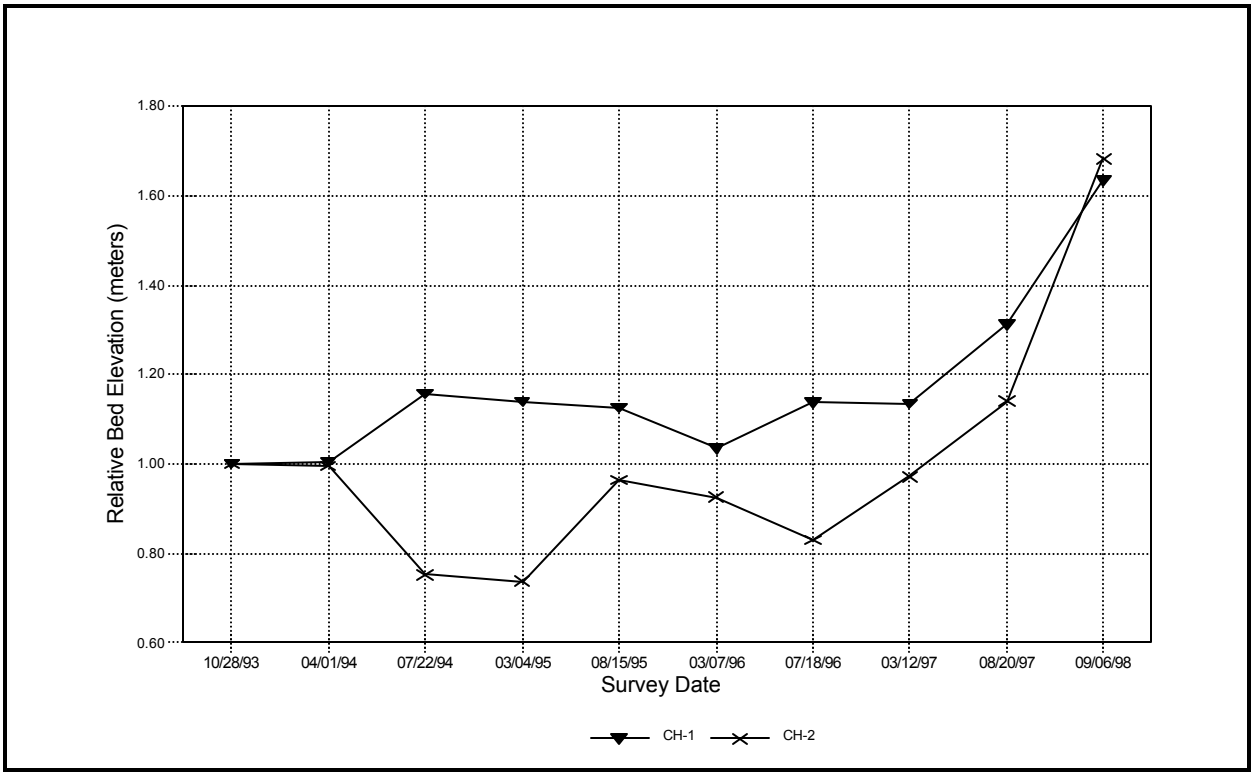

Figure 3.23. Relative bed elevation for the two Clay Hills series transects on the San Juan River (1993-1998).

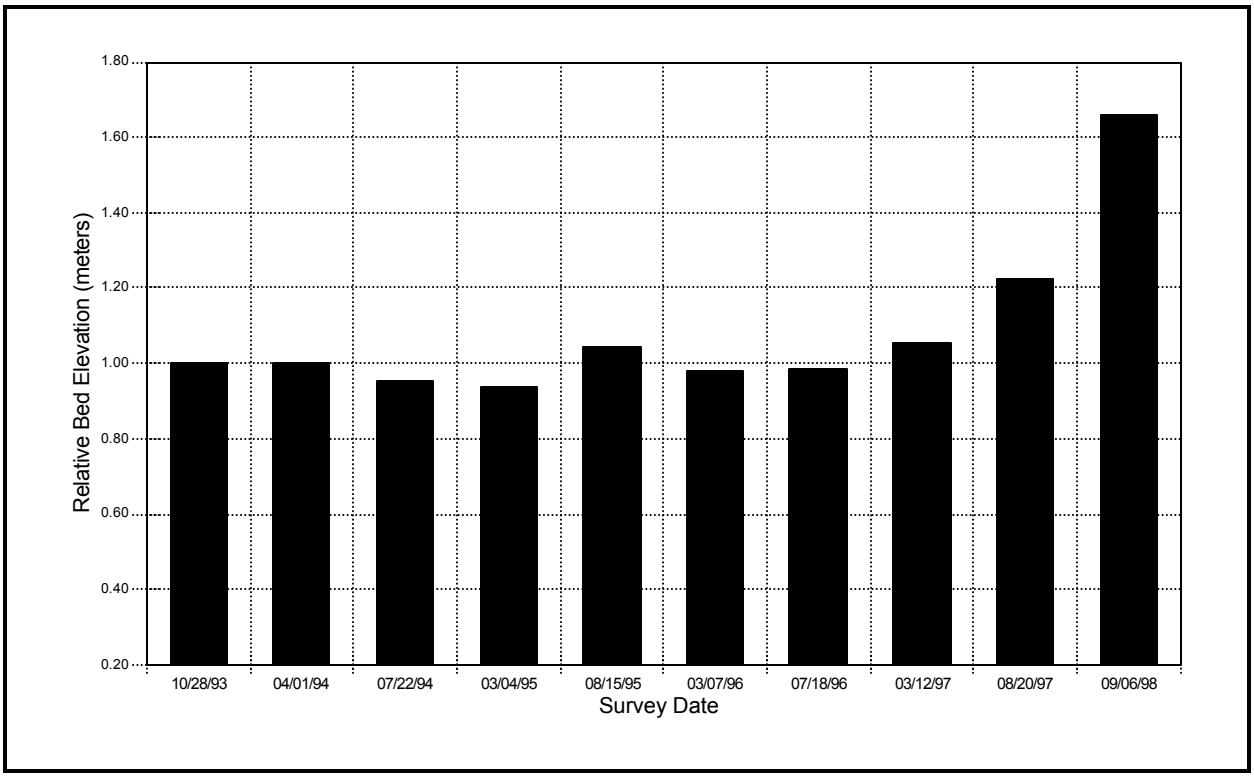

Figure 3.24. Average relative bed elevation for Clay Hills series transects on the San Juan River (1993-1998).

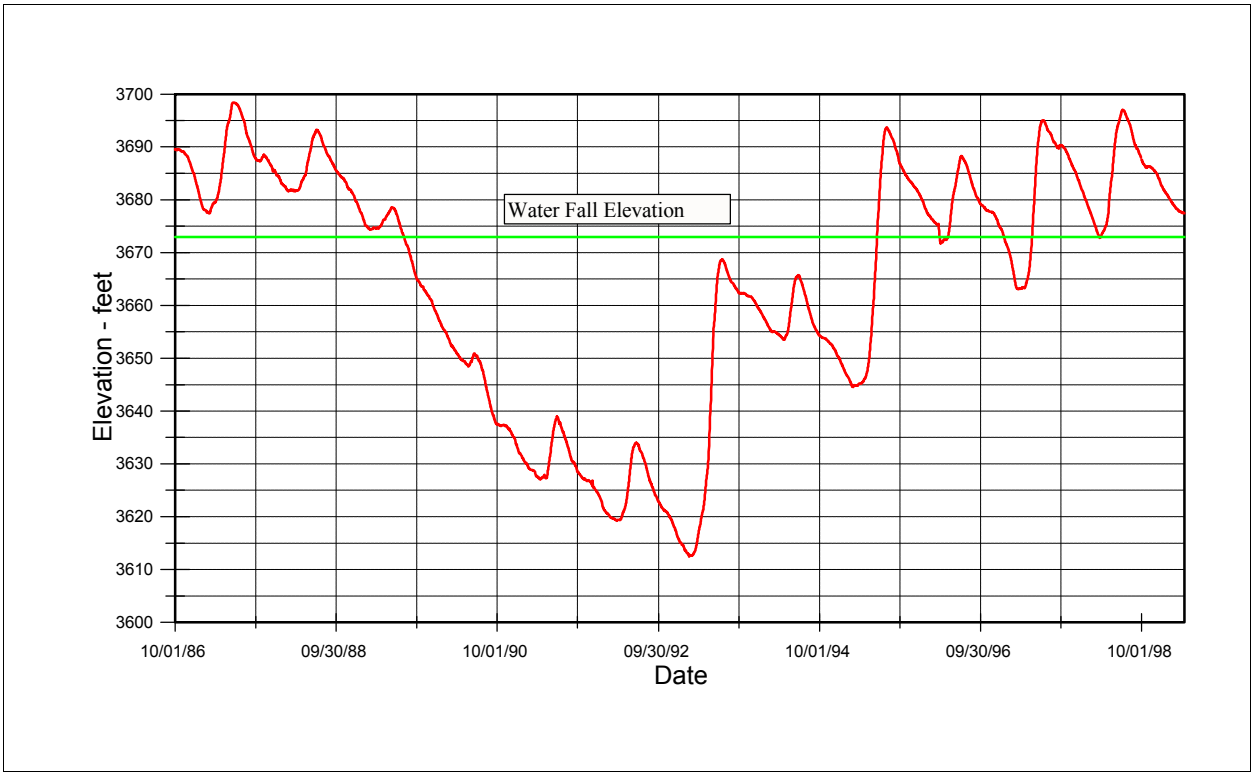

Figure 3.25. Lake Powell water surface elevation (1986-1998).

Channel Response to Flows at USGS Gage Locations

Upon analysis of the data, only the San Juan River at Farmington and San Juan River at Shiprock data could be used. The early records at Bluff were not available, limiting the record to a period too short to be useful. At Archuleta, a portion of the measurements were made by wading and a portion from the cableway. There appears to be a different datum for the two surveys that could not be reconciled, as the elevations between the two methods were consistently different. While there were difficulties in interpreting and adjusting the data from Farmington and Shiprock, the resulting data set used is felt to be sufficiently accurate to allow assessment of the long-term response of the channel at these to locations.

The relative bed elevation at the Farmington gage is shown in Figure 3.26 for the period 1942 - 1996. The baseline elevation of 1.0 m was assigned to the April 1942 data point and all subsequent elevations computed from this baseline. Only April and June elevations are shown, representing pre- and post-runoff. The same information is shown in Figure 3.27 for the Shiprock gage for the period 1943 - 1996. The date of Navajo Dam influence is shown on each plot along with the beginning of the re-operation to mimic a natural hydrograph.

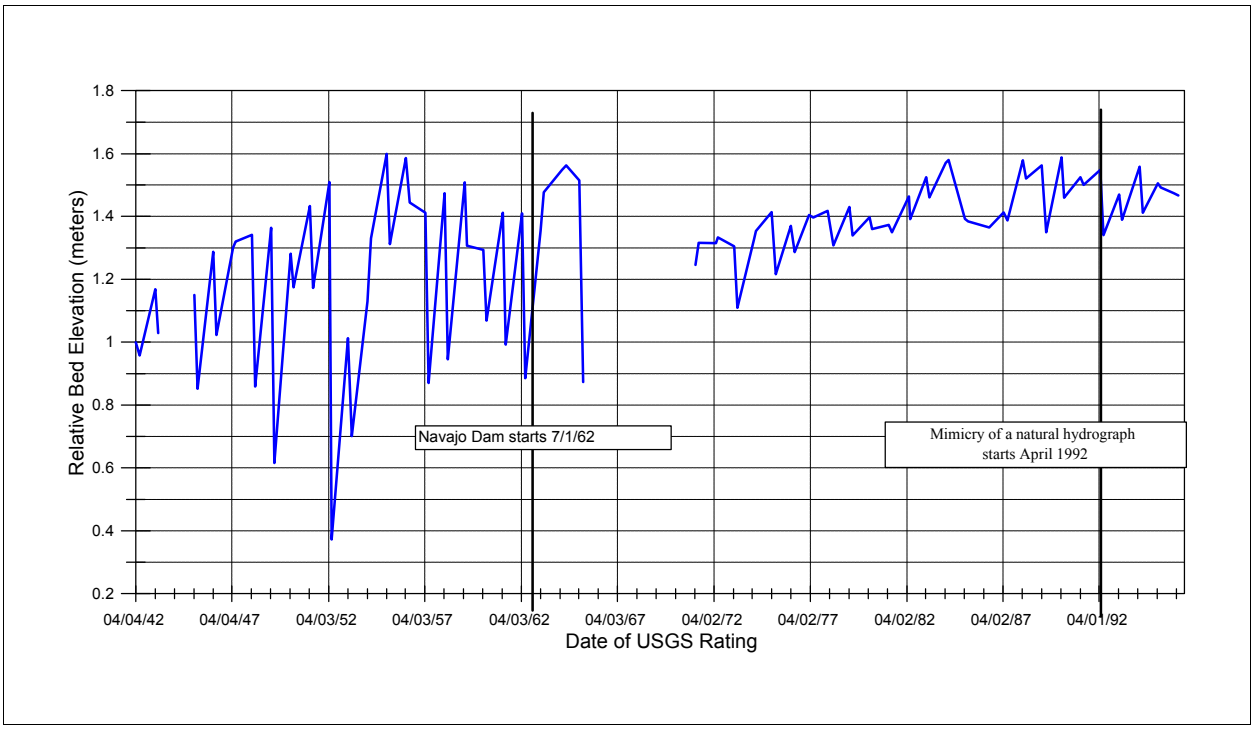

Figure 3.26. Mean relative bed elevation at the San Juan River at Farmington gage (1942-1996).

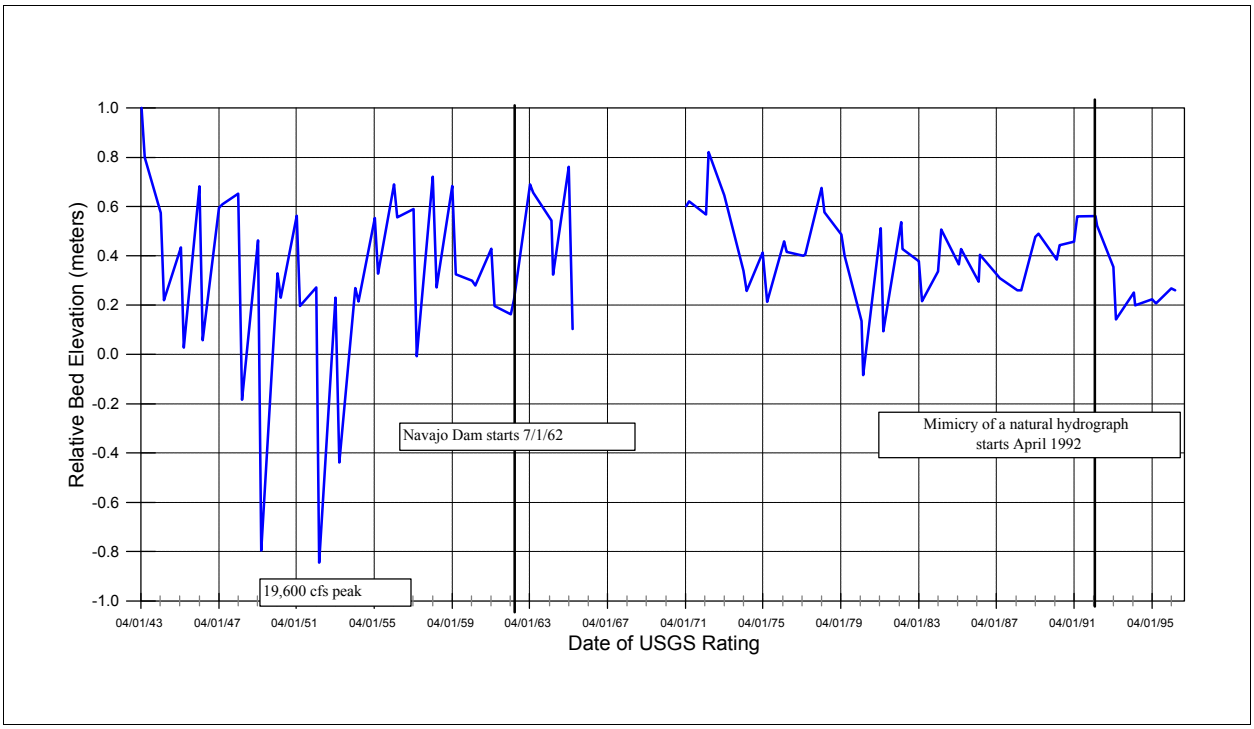

Figure 3.27. Mean relative bed elevation at the San Juan River at Shiprock gage (1943-1996).

Both plots indicate that the extremes in elevation before and after runoff are influenced by the peak magnitude and volume of runoff. As such, there appears to be less variability after closure of Navajo Dam than before, but the difference is more marked for Farmington than Shiprock. There does not appear to be any significant shift of long term scour or deposition due to Navajo Dam influence. Farmington shows a general depositional trend with time, before and after Navajo Dam. Shiprock does not exhibit any statistically significant trend.

There appears to be a minor shift downward in each graph at the beginning of re-operation in 1992, although the trend has not changed after this shift. The shift is more marked for Shiprock than Farmington, reflecting the more dynamic nature of this site. This shift is similar to the results seen at the RT transects. When comparing the amount of shift to the long term patterns, there does not appear to be a concern that any serious channel degrading is occurring. The minimum elevations after re-operation are still above the minimums during the post-dam period and well above the minimums for the pre-dam period.

Substrate Movement at Surveyed Cross-Sections

Both scour and deposition occurred at all cross-sections and during all survey periods, at flows as low as 2,500 cfs, the lowest maximum flow between surveys. In addition, cobble movement (both scour and deposition) occurred at some point in most of these cross-sections at all flows. Table 3.22 summarizes the scour and deposition between survey points for the RT and Mixer cross-sections, including the portion of each that is cobble. Also shown in the table are the hydrographic parameters of the flow recommendation and the linear correlation parameters for each to scour and deposition.

The strongest correlation with total scour and any of the hydrographic conditions is with days above 5,000 cfs ($R^2 = 0.82$, $n = 12$, $p < .01$). There is also a reasonable correlation between peak discharge and days above 2,500 cfs. The correlation improves only slightly when all hydrographic parameters are included.

The correlation between deposition and the hydrographic conditions is not as strong, with days above 8,000 cfs being the best ($R^2 = 0.59$, $n = 12$, $p < .01$). There is significant improvement in the correlation when all parameters are used.

The cobble movement correlations are not as strong, with only three of the parameters significant at the 95% level. Cobble movement (deposition and scour) is most strongly correlated to days above 5,000 cfs, although the correlation is weak. The correlation improves for both scour and deposition when all hydrographic parameters are included in the analysis.

The mixer transects have more variability than the RT transects and the correlations are not as good. In this case, the deposition correlations are better than those for scour for total movement and the opposite for cobble movement. There are no significant correlations for cobble scour, and the cobble deposition relationships are weak.

Table 3.22. Average deposition and scour (total and cobble) at RT and Mixer series transects in the San Juan River (1992-1998) as related to hydrographic conditions.

Period	Total -m^3/m		Cobble - M^3/m		Peak	Days	Days	Days	Days	combined
	Scour	Deposition	Scour	Deposition	cfs	> 10000	> 8000	> 5000	> 2500	
RT cross-sections										
Mar-Jul 92	9.4	7.1	0.3	1.9	8,900	0	3	54	81	
Jul 92 - Feb 93	5.2	6.9	0.8	0.7	3,490	0	0	0	9	
Feb - Jul 93	14.0	5.1	4.0	2.9	10,300	1	16	109	128	
Jul 93 - Mar 94	3.9	8.1	1.4	1.0	4,700	0	0	0	6	
Mar 94 - Aug 94	7.5	2.7	1.1	0.8	10,000	0	13	49	67	
Aug 94 - Mar 95	3.2	6.4	0.6	0.5	2,820	0	0	0	1	
Mar 95 - Aug 95	8.8	2.8	1.8	1.6	12,100	11	27	72	135	
Aug 95 - Mar 96	1.6	6.9	0.6	1.1	2,490	0	0	0	0	
Mar 96 - Jul 96	4.6	3.6	0.9	0.5	3,540	0	0	0	36	
Jul 96 - Feb 97	2.0	7.2	0.4	0.9	2,510	0	0	0	1	
Feb 97 - Aug 97	10.6	2.7	2.3	1.1	11,900	10	29	49	98	
Aug 97 - Aug 98	3.4	8.4	0.9	1.9	8,300	0	2	33	78	
Correlation coefficient - total scour					0.67	0.22	0.55	0.82	0.72	0.84
Significance of f statistic (p) - total scour					<.01	0.12	0.01	<.01	<.01	0.02
Correlation coefficient - total deposition					0.33	0.40	0.59	0.20	0.30	0.83
Significance of f statistic (p) - total deposition					0.05	0.03	<.01	0.14	0.07	0.03
Correlation coefficient - cobble scour					0.36	0.09	0.47	0.58	0.45	0.73
Significance of f statistic (p) - cobble scour					0.04	0.17	0.02	<.01	0.02	0.08
Correlation coefficient - cobble deposition					0.34	0.02	0.12	0.69	0.53	0.89
Significance of f statistic (p) - cobble deposition					0.04	0.70	0.28	<.01	0.01	0.01
Mixer cross-sections										
Feb - Apr 93	8.7	4.4	1.5	0.1	6,720	0	0	25	39	
Apr - Jun 93	19.1	4.8	0.2	3.8	10,300	3	16	67	67	
Jun - Jul 93	3.0	5.8	3.2	1.6	7,360	0	0	9	16	
Jul 93 - Mar 94	2.2	4.5	2.1	1.3	4,700	0	0	0	6	
Mar 94 - May 94	3.7	7.2	3.8	1.5	6,600	0	0	7	14	
May 94 - Jun 94	5.6	7.5	3.4	1.7	10,000	0	13	41	41	
Jun 94 - Aug 94	4.7	2.0	0.2	2.4	5,460	0	0	1	12	
Mar 95 - Aug 95	4.7	6.3	3.2	2.0	12,100	11	27	72	135	
Aug 95 - Mar 96	1.4	2.6	1.5	0.7	2,490	0	0	0	0	
Mar 96 - Jul 96	3.0	1.8	0.8	1.1	3,540	0	0	0	36	
Jul 96 - Feb 97	2.0	2.1	0.7	0.7	2,510	0	0	0	1	
Feb 97 - Aug 97	6.8	10.7	5.0	3.4	11,900	10	29	49	98	
Aug 97 - Jul 98	7.7	4.7	2.3	2.3	8,300	0	2	33	78	
Correlation coefficient - total scour					0.3	0.04	0.15	0.47	0.18	0.71
Significance of *f* statistic (p) - total scour					0.05	0.52	0.2	0.01	0.14	0.07
Correlation coefficient - total deposition					0.63	0.35	0.48	0.33	0.28	0.82
Significance of *f* statistic (p) - total deposition					<.01	0.03	0.01	0.04	0.06	0.01
Correlation coefficient - cobble scour					0.31	0.23	0.24	0.09	0.15	0.66
Significance of *f* statistic (p) - cobble scour					0.05	0.1	0.09	0.33	0.19	0.12
Correlation coefficient - cobble deposition					0.47	0.26	0.41	0.39	0.3	0.51
Significance of *f* statistic (p) - cobble deposition					0.01	0.07	0.02	0.02	0.05	0.31

These relationships are somewhat different than those reported in the Flow Recommendation Report. This table includes the 1998 data and a correction to some of the values for the RT transects. Further, the values reported in the flow recommendation are listed as m^3/m, whereas they are actually ft^3/ft. These changes do not change the conclusions in the flow recommendation report.

Flow Modification Impact on Channel Complexity

Figure 3.28 shows the relationship between the number of islands in Reaches 3 to 5 and discharge during each of the mapping periods. Two regression lines are shown. The longer line represents the full range of discharges encountered. The shorter line includes only flows below 1,200 cfs to represent low flows. It is theorized that channel complexity at low flow would show change first if channel simplification was occurring because of channel scour. As expected, the number of islands increases with increased flow up to about 6,500 cfs as more secondary channels become active. The substantial drop in number of islands between 6,500 and 7,700 cfs indicates overbank flooding at this discharge as inundated islands are flooded and become mapped as flooded vegetation.

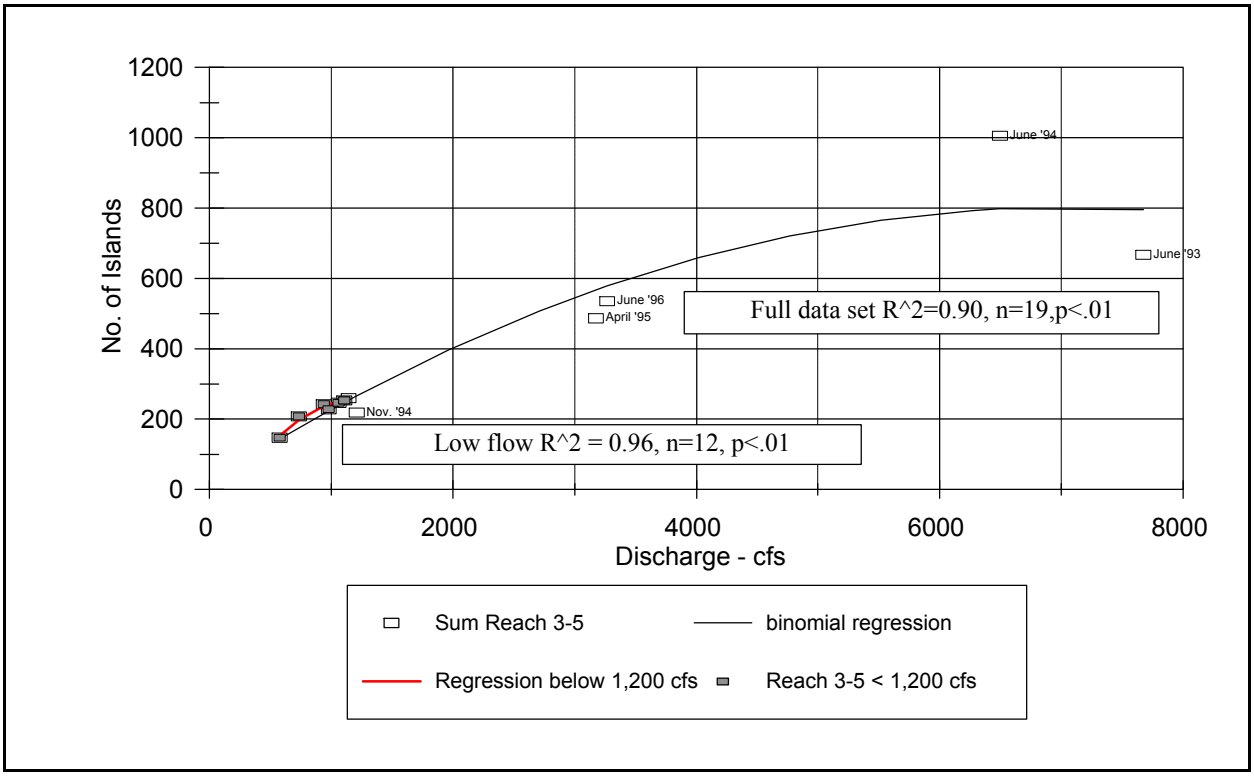

Figure 3.28. Relationship between main channel flow and island count.

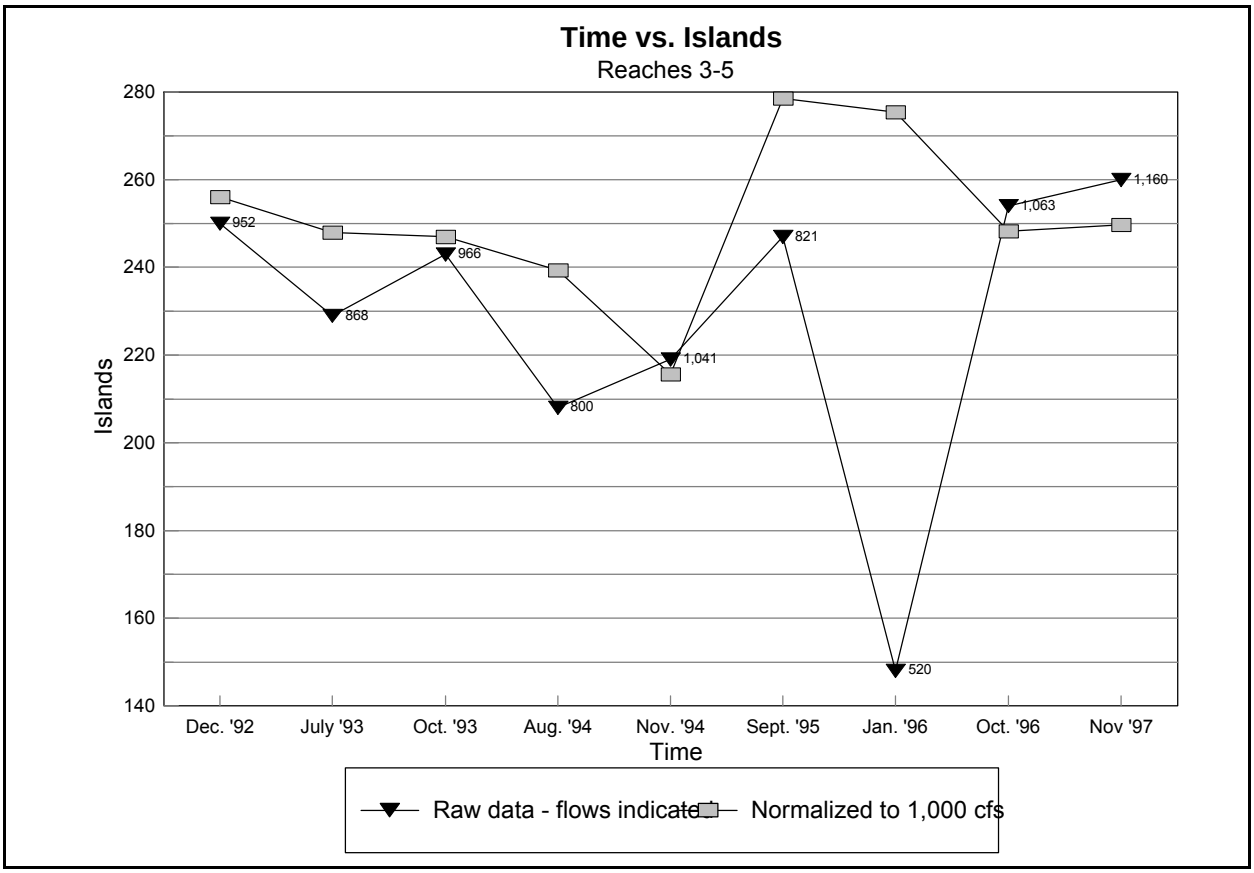

Figure 3.29 Island count in Reaches 3, 4, and 5 at base flow vs. time as a measure of change in channel complexity.

To examine the chronological effect of the flow regime on the number of islands throughout the 7-year research period (a test of channel simplification), the total number of islands in Reaches 3, 4, and 5 was plotted against time as noted by the triangles in Figure 3.29. The first data set plotted represents the actual number of islands at the noted flow for each mapping, with only the mapping runs completed at flows below 1,200 cfs shown. Any variation in island count because of channel simplification for this data set is masked by the change in flow rate during mapping. To determine if a change occurred, the island counts had to be standardized to a common flow. These normalized island counts are represented as squares on the second line. Normalized island counts for each year were computed as the ratio of the island counts predicted by the regression equation (represented by shorter line on Figure 3.28) for a flow of 1,000 cfs, to that ratio predicted at the flow shown in Figure 3.29 times the actual number of islands mapped at the flow shown. The analysis indicates a small reduction in islands through 1994, an increase in 1995, a subsequent decrease in 1996, and a slight increase in 1997 with no net change over the 6-year period. The scour indicated by the decrease in mean channel elevation at the measured cross-sections would indicate an imbalance that could lead to channel simplification (loss of multiple channels and islands). For this short period of record, it appears that there was no significant loss of channel complexity associated with the

channel scour observed, although there appears to have been a short-term loss that was regained during the high-flow condition in 1995.

During 1995, for the first time in the 7-year research period, flows exceeded 10,000 cfs for more than 1 day, achieving a daily peak flow of 12,100 cfs with flows above 10,000 cfs for 11 days at Four Corners. The first increase in islands was exhibited in 1995. The indication from this flow series is that maintaining peak flows near channel capacity (1992 to 1994) may have slightly simplified the channel, while a larger overbank flow (1995) appears to have developed additional channels and islands, reversing the simplification. Some channel complexity may be lost because of summer and fall sediment-laden storm events that tend to berm off small flow-through and secondary channels (August 1994 to November 1994), and runoff events with peaks below 5,000 cfs (1996) may cause loss of channel complexity through the same process. The year 1997 was the only other year with flows above 10,000 cfs and the only other year to exhibit an increase in island count, although the increase is small relative to 1995. This is due in part to large summer sediment inflow between runoff and mapping that refilled small secondary channels in 1997.

Loss of channel complexity is of concern not only as an indicator of channel incision and loss of secondary channels, but because of the potential impact on habitat diversity. Figure 3.30 plots the average Shannon-Weaver habitat diversity index for Reaches 3-5 with non-normalized island count for the flows below 1,200 cfs from 1992 through 1997. The patterns are not the same, but habitat diversity did increase somewhat in 1995 following runoff after a decline in 1994. In general, habitat diversity has not decreased during the period of test flows, corresponding with general trend in island count. However, it appears that habitat diversity is related to processes other than channel complexity. The greatest diversity existed in 1993 after prolonged runoff and again after the high flows in 1997. This change is likely not significant however. Habitat diversity for the number of habitat categories mapped can range from 0 to 1.49 (log of the number of habitats). During the study they ranged from 0.83 to 0.96, a relatively small variation and likely within mapping error.

Habitat diversity was regressed against island count for the three reaches and seven mappings in the data set to determine the existence of a relationship. While there was a positive correlation between island count and habitat diversity it was very weak (R^2= 0.14, p=0.08). By removing the two winter values (December 92 and January 96) the relationship improved (R^2= 0.42, p=0.001), but was still not strong. Obviously, other mechanisms influence habitat diversity as strongly as island count.

While analysis of the trend in island areas seems to indicate that the net effect of the research flows has not been damaging to channel complexity or habitat diversity and that flows above 10,000 cfs are important in maintaining channel complexity, 5 years is a short period of record with which to identify long-term trends. Long-term monitoring will be required to assess the effects of restoration of a more-natural hydrograph on channel complexity.

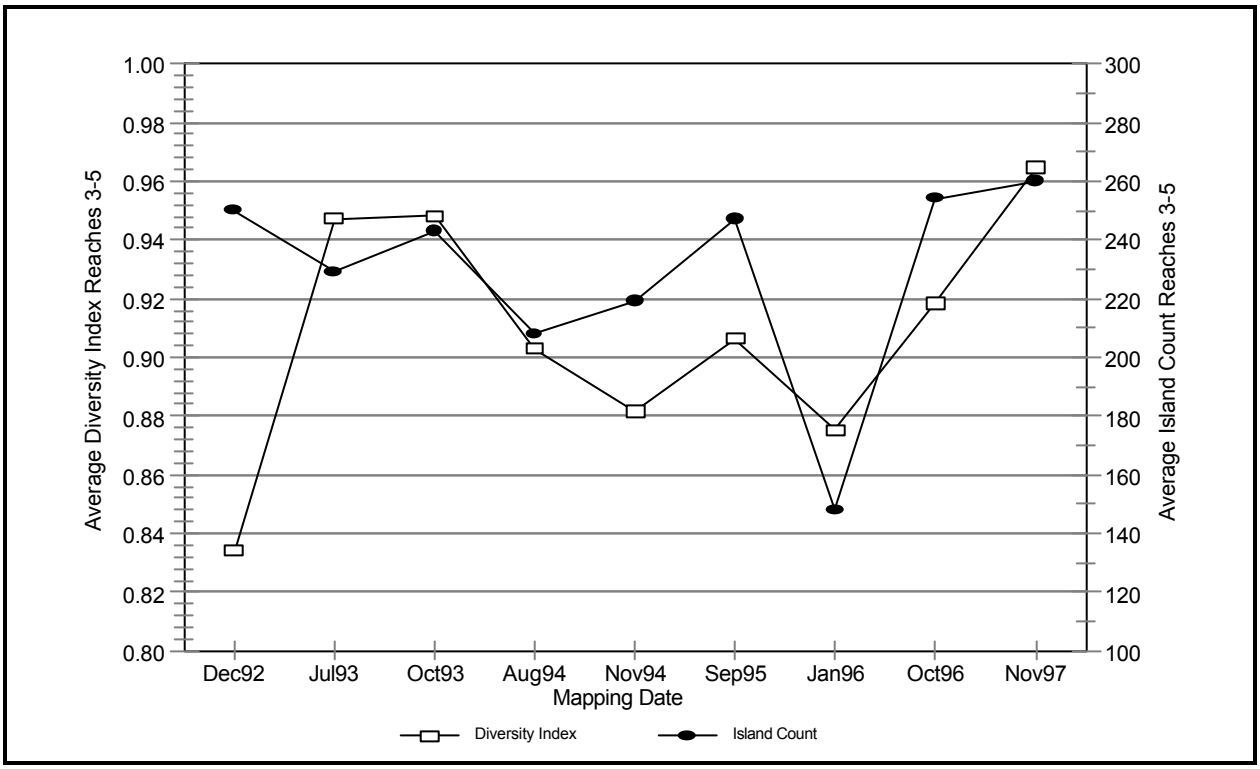

Figure 3.30. Habitat Diversity and Island Count in the San Juan River at flows below 1,2000 cfs, 1992-1997

Bankfull Channel Capacity

A summary of bankfull discharges for the reaches modeled with HEC-RAS is presented in Table 3.23. In the lower three reaches, overbank flow occurred first (indicated by overbank conditions at one transect) at discharges between 7,100 and 7,500 cfs, based on calibrated HEC-RAS modeling. At RM 174, the first transect to show overbank flow occurred at 10,000 cfs. At least two cross-sections in each reach experienced overbank flow between 8,000 and 8,500 cfs for all study reaches except

RM 174, which required 10,500 cfs for overbank flow at two cross-sections. Therefore, bankfull was assessed to be between 7,100 and 10,000 cfs, depending on the study reach. While this discharge is greater than that estimated based on island counts and flooded vegetation for 1993 and 1994, the ranges overlap. If a real difference exists between the beginning and ending of the 7-year research period, it could be partly explained by an increase in channel capacity because of bed scour between 1993 and 1996. However, conclusions based on such a short time period should be considered preliminary, and continued monitoring is necessary to verify an actual change in channel capacity. If channel capacity has increased, the change can be considered relatively insignificant, especially because a concurrent change in channel complexity was not detected. While modeled reaches exhibited initiation of overbank flow at between 7,100 and 10,000 cfs, consistent overbank flow occurred at between 8,000 and 10,500 cfs. The median overbank flow for the 20 cross-sections

Table 3.23. Bankfull discharge from HEC-RAS modeling of four 0.25 mile (mi) reaches in the San Juan River between River Mile (RM) 133 and RM 174.

REACH DESIGNATION	BANKFULL FLOW AT ONE CROSS-SECTION (CFS)	BANKFULL FLOW AT TWO OR MORE CROSS-SECTIONS (CFS)
RM 133	7,500	8,000
RM 167	7,100	8,000
RM 169	7,100	8,500
RM 174	10,000	10,500

modeled was 9,000 cfs. However, the nature of the areas modeled was such that when flows were overbank on more than 25% of the area, any increase in stage (height of water) with increased flow was small. In some areas, the floodplain sloped away from the river channel, allowing the overbank flow to spread out and reenter the channel at a downstream location. In other locations a low, flat floodplain was separated from the river by a short berm, allowing a large increase in flow area for a small change in stage. Based on this information, bankfull discharge for the San Juan River was set at 8,000 cfs (25% of cross-sections overbank) as the value that appeared to fit most of the study area.

The mean bankfull discharge for the RT cross-sections was computed to be 7,300 cfs (range 5,300 to 9,900 cfs) prior to modification of the flows (1992). After 6 years of research flows designed to mimic a natural hydrograph, the mean bankfull discharge was computed to be 8,200 cfs (range 5,800 to 12,600 cfs) for an increase of 12% from pre-research conditions. The 8,000-cfs channel capacity determined from the modeling studies is supported by the results of this analysis and the perceived change in channel capacity over the research period confirmed.

In summary, the bankfull discharge of the San Juan River is about 8,000 cfs and has increased by about 12% since the beginning of the research period. Bankfull flow is considered the practical upper limit for maintenance of cobble transport through low-gradient reaches and is considered in the analysis of cobble bar maintenance in the next section. Flows above 10,000 cfs appear to be important for maintaining channel complexity and floodplain integrity. Continued monitoring will be necessary to verify these values and assess impacts of the restoration of a more-natural hydrograph on channel complexity and capacity.

Cobble Bar Characterization

From the substrate characterization at each cross-section, it is clear that substantial cobble movement has taken place during each of the 6 years measurements have been taken. This qualitative assessment does not allow good predictive capability or characterization of the conditions that exist in suspected spawning locations. The detailed radio tracking completed by Miller Ecological Consultants in the summers of 1993 and 1994 allowed identification of these suspected spawning locations and a characterization of the substrate in these areas. In 1994, the results from these sites

were compared to known spawning areas on the Yampa River and a suspected site on the Colorado River in Grand Junction, Colorado to assess the suitability of substrate for spawning at these locations. Similarity would suggest suitability. However, dis-similarity would not necessarily indicate unsuitability, since it may be possible for successful spawning in substrate with characteristics different than those seen on the Yampa river. The sites did exhibit similar characteristics, except that the cobble size at the Colorado River site was larger than at the other locations. In 1995, the conditions at 13 locations were compared to the Yampa and Colorado data and to previous data at the suspected spawning sites in the San Juan in an attempt to identify other locations for potential spawning. Subsequently, two suspected spawning locations and two potential spawning locations located upstream of the suspected sites have been monitored annually.

Characterization of Bed Material Size in Suspected Spawning Bars

Table 3.24 summarizes the cobble size distribution for each of the bars analyzed in 1995. For comparison purposes, 1994 data from the suspected spawning locations and the Yampa data are included in the table. The average of all bars is very similar to the Yampa site and many of the individual sites are also very similar. In general, the cobble size is not correlated to river mile in the range sampled (76.6 - 173.7) with no increasing or decreasing trend. There is appreciable variability from site-to-site, however.

Table 3.25 shows the same size distribution characteristics for the interstitial sediments sampled from each bar. The distributions are for the material passing a 12.5 mm screen. Again, the variability seen is somewhat random with respect to position on the river and the size does not appear to be correlated to the cobble size. For example, the site with the largest interstitial material has a smaller than average D50 cobble size and the site with the smallest interstitial material has cobble similar in size to the site with the largest interstitial material.

Subsequent surveys were completed from 1996 through 1998 for the two suspected spawning bars and the two potential upstream bars. The results are summarized in Table 3.26. The variation from year-to-year is believed to represent sampling error rather than any response to flows. In 1996, the flows were lower than the other years, so it is unlikely that the bars would have had larger cobble. Sampling error is enhanced in these conditions as the samples are taken under water. Also, the same location on the bar may not be sampled each year due to differences in flow rate and water depth which affect accessability to areas of the bar. Each of these conditions affect the accuracy of the measurement and explain some of the variability in results form year-to-year.

In 1998, the measurement method was changed from ruler measurement of the intermediate cobble dimension to the use of a template with square holes representing 1 cm increments in size. A test of 460 cobbles taken at the same locations and by the same methods used in this study was conducted to compare the results of the two methods. Figure 3.31 compares the size distribution of the same sample from the two methods. There appears to be about a 10% difference in the D_{50} for the 2 methods, with the measured method over-predicting. Figure 3.32 plots the ruler measurement

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Table 3.24. Cobble size distribution for potential spawning sites from 1995 survey.

Date	River Mile	Site	Cobble Diameter Associated with the Indicated "Percent Passive" Size Category mm D84	D75	D50	D25	D16
07/28/95	173.70	173	125	114	72	54	45
07/28/95	172.00	171	120	105	75	53	43
07/27/95	169.00	169A	90	79	60	44	41
07/27/95	168.40	168C	128	109	78	54	51
07/27/95	168.40	168B	118	111	74	58	50
07/27/95	168.40	168A	115	103	78	58	51
07/28/95	163.00	163	123	114	90	65	55
07/28/95	137.70	137B	105	95	70	54	45
07/28/95	137.30	137D	145	138	90	64	58
07/25/95	132.00	132-23	88	75	60	43	36
07/25/95	132.00	132-21	61	52	38	29	26
07/25/95	132.00	132-25	100	92	63	42	36
07/25/95	132.00	132-20	98	83	61	40	35
07/26/95	131.20	132-124	75	63	47	31	24
07/26/95	131.20	131-32	88	63	50	32	21
07/26/95	131.90	131-33	57	53	40	24	21
07/30/95	109.80	109	130	118	80	54	49
07/29/95	88.00	88	104	95	82	61	52
07/29/95	82.95	82A	78	72	61	49	42
07/29/95	82.90	82B	158	139	112	74	65
07/29/95	82.85	82C	90	72	59	46	40
07/29/95	78.00	78	130	114	89	74	71
07/29/95	76.60	76	124	121	101	79	71
	Average		106	95	71	51	45
	Yampa		110	94	76	58	46
	Colorado		125	104	78	49	38
	132-94		100	79	65	52	46
No. of sites exceeding Yampa size			11	13	9	7	10
% of sites exceeding Yampa size			47.8%	56.5%	39.1%	30.4%	43.5%

Table 3.25. Size distribution of interstitial material at selected cobble bars from 1995 survey.

	Cobble Diameter Associated with the Indicated "Percent Passive" Size Category mm				
Site	**D84**	**D75**	**D50**	**D25**	**D16**
173.7	9.34	4.84	2.62	0.92	0.66
172	9.17	4.78	2.11	0.87	0.62
169	10.58	5.29	6.49	2.59	1.15
168.4 C	9.48	4.89	3.07	0.98	0.70
168.4 B	9.71	4.98	3.79	0.93	0.57
168.4 A	10.30	5.19	5.63	1.47	0.98
163	10.13	5.13	5.11	1.21	0.81
137.4	9.96	5.07	4.56	1.11	0.76
137.7	8.03	4.36	1.25	0.59	0.43
132 #21	9.45	4.88	2.98	0.44	0.34
132 #25	10.21	5.16	5.33	0.78	0.40
132 #23	10.10	5.12	4.99	1.03	0.48
132 #20	8.75	4.62	0.77	0.35	0.26
131 #124	9.77	5.00	3.97	0.69	0.40
131 #33	10.11	5.12	5.02	1.18	0.59
131 #32	8.70	4.60	0.63	0.33	0.28
109	9.48	7.78	2.36	0.87	0.55
88	10.57	9.49	6.48	0.87	1.01
82.85 C	9.51	7.82	3.42	1.05	0.58
82.9 B	9.03	7.08	1.59	0.79	0.49
82.95 A	3.53	1.59	1.17	0.75	0.60
78	9.71	4.97	3.77	1.12	0.71
76.6	7.12	4.02	1.31	0.77	0.57
Maximum	10.58	9.49	6.49	2.59	1.15
Minimum	3.53	1.59	0.63	0.33	0.26
Average	9.37	7.61	2.71	0.76	0.46

Table 3.26. Cobble size distribution for two suspected and two potential spawning bars in the San Juan River, 1995-1998.

		Cobble Diameter Associated with the Indicated "Percent Passive" Size Category mm				
Site	**Year**	**D84**	**D75**	**D50**	**D25**	**D16**
M-4 (131.2)	1995	65	54	42	28	21
M-4	1996	108	98	80	66	56
M-4	1997	79	71	52	36	28
M-4	1998	85	70	46	25	19
Average		84	73	55	39	31
M-6 (132)	1995	86	73	51	34	27
M-6	1996	116	106	78	55	46
M-6	1997	99	84	66	49	44
M-6	1998	95	82	59	37	30
Average		99	86	63	44	37
1684	1995	110	102	72	49	46
1684	1996	146	126	84	50	46
1684	1997	105	100	63	43	37
1684	1998	112	99	68	47	36
Average		118	107	72	47	41
1737	1995	n/a	n/a	n/a	n/a	n/a
1737	1996	99	80	48	30	26
1737	1997	126	80	38	22	17
1737	1998	120	103	70	47	39
Average		115	88	52	33	27

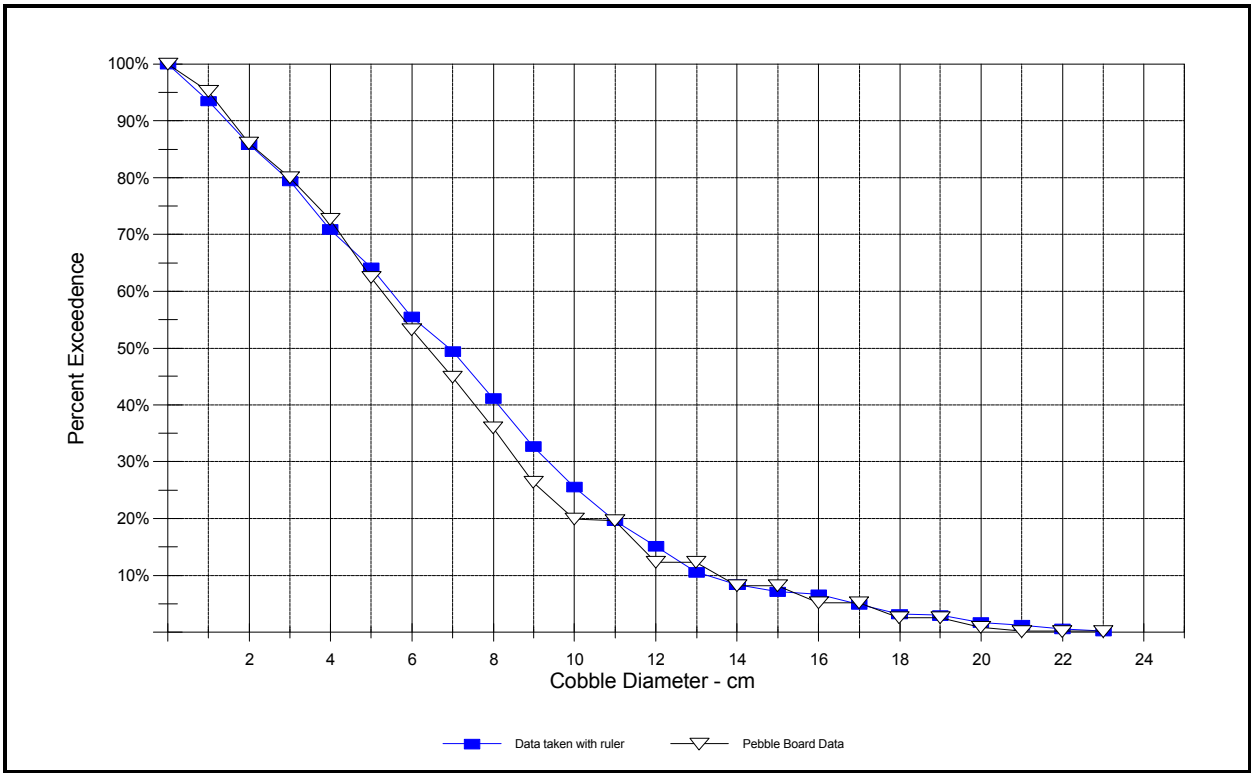


Figure 3.31. Cobble size frequency distribution for ruler and template measured cobble samples.

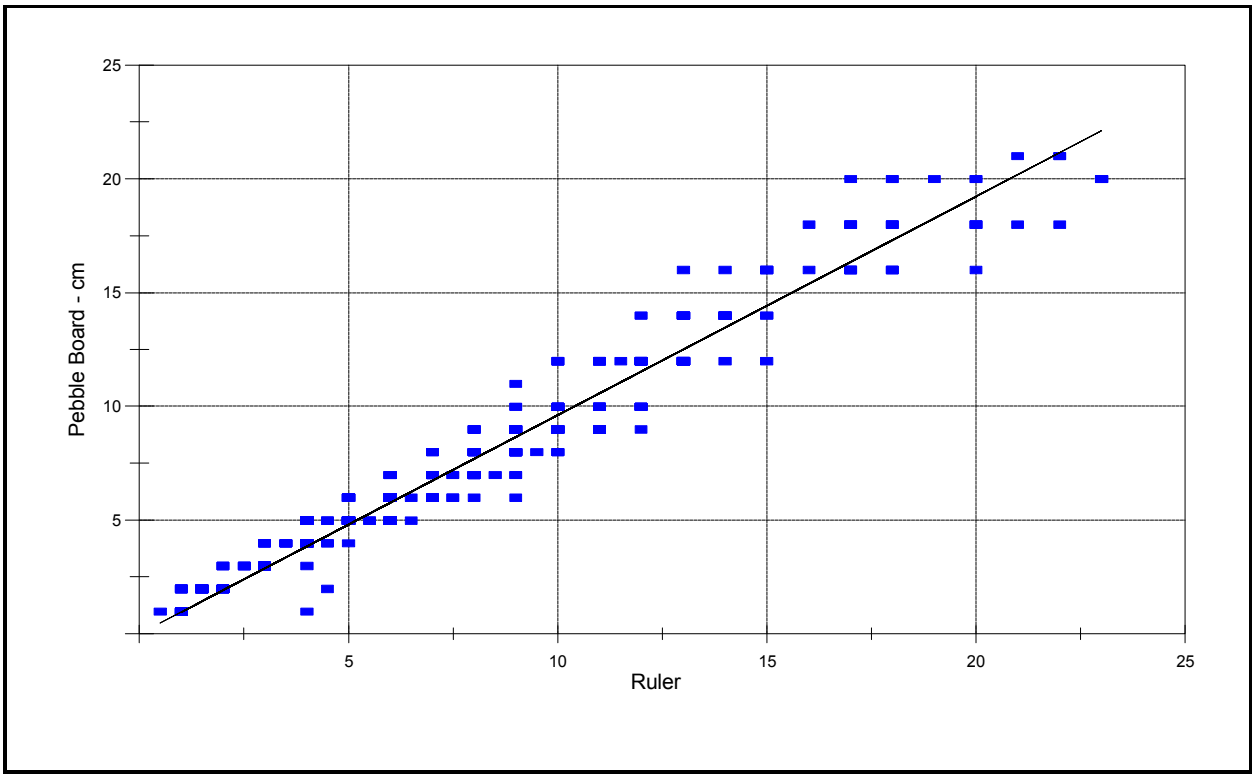


Figure 3.32. Comparison of cobble size measured with ruler and template and the resulting regression line.

on one axis and the template measurement on the other, with a regression line (intercept = 0) also shown. The linear regression indicates that the diameters measured with the template are 96% of those measured with the ruler ($R^2 = .95$, $n = 460$, $p < .01$). No adjustment was made to prior year data, since the 4% difference is easily within measurement error. Standardizing the measurement method will help improve accuracy. Standardized methods and locations and adequate training of the samplers are critical.

Depth of Open Interstitial Space in Cobble Bars

Depths of open interstitial space for each of the bars sampled in 1995 appear in Table 3.27 along with a summary of the cobble and interstitial material. The comparative data from the 1994 sampling is also shown. The data are listed as actual depth in mm and depth expressed as the number of mean cobble diameters. Unfortunately, comparable data are not available from the Yampa spawning bar. Although specific requirements for spawning have not been determined, it is thought that depths less than 1.5 diameters are not likely to be adequate, with 2 diameters or more preferable. Based on this
criteria, sites below RM131.2 exhibit less suitable conditions than the sites above this location, even though the cobble size appears adequate.

Since 1995, open interstitial space has been surveyed at the four locations for which cobble size has been measured. A summary of the results appear in Table 3.28. Low runoff in 1996 and storm events near spawning in 1997 and 1998 have limited the open interstitial space during the after runoff samples. Most severely affected is the potential bar at RM 168.4. The least affected is the potential bar at RM 173.8.

Appendix A contains three-dimensional surface plots of depth of open interstitial space (depth to embeddedness) for these four locations. These plots show a 3-D surface plot of the top of the bar in the vicinity of the sampling with the depth of open interstitial space shown as 3-D "posts" at the location the measurement was taken.

Topographic Changes in Cobble Bars

Topographic surveys completed for three of the bars (173.7, 168.4 and 132) are shown in Appendix A. Figures are included for each bar showing a comparison of the bar topography for all surveys on one figure, the bar topography with open interstitial measurements on another set of drawings and surface plots of the change in the bars between surveys on a third set. The changes are summarized in Table 3.29 for each of the bars.

While the gross change in the bars (average elevation change) is small for all bars (#0.10 m), the pattern of change in response to flow is different among the bars. Only the bar at 132 was surveyed in 1995, showing an increase in bar elevation of 0.09 m. During 1996, RM 173.7 was depositional and the other two were slightly erosional. However the maximum and minimum elevations were reduced for all three bars. Between 1996 and 1997, RM 173.7 was erosional, although the maximum elevation increased. The other two bars were depositional. In 1998 all three bars were depositional.

Table 3.27. Summary of cobble, open interstitial space and interstitial material for potential spawning bars in the San Juan River surveyed in 1995.

River Mile	Site	Cobble Size			Max. Depth of Clean Voids		Interstitial Sediment			Column Velocity		
		D84	D50	D16			D84	D50	D16	Mean	Max.	Min.
		mm	mm	mm	mm	Cobble Dia's.	mm	mm	mm	cm/sec	cm/sec	cm/sec
173.70		125	72	45	170	2.4	9.3	2.6	0.7	75	90	60
172.00		120	75	43	210	2.8	9.2	2.1	0.6	86	105	58
169.00		90	60	41	170	2.8	10.6	6.5	1.2	105	138	70
168.40		110	70	46	225	3.2	10.1	4.8	0.8	83	140	60
166.60	**San Juan Power Plant Diversion Dam**											
163.70	**Four Corners Power Plant Diversion Dam**											
163.00		123	90	55	200	2.2	10.1	5.1	0.8	111	138	90
158.80	**Hogback Diversion Dam**											
142.00	**Cudei Diversion Dam**											
137.70		105	70	45	230	3.3	10.0	4.6	0.8	75	90	60
137.30		145	90	58	150	1.7	8.0	1.2	0.4	82	90	75
132.00	Main Bar	95	58	32	240	4.1	9.5	3.0	0.3	100	128	67
131.20	Red Wash	75	47	24	130	2.8	9.8	4.0	0.4	58	110	22
131.20	Main	63	41	21	130	3.1	9.4	2.8	0.4	66	95	32
109.80		130	80	49	105	1.3	9.5	2.4	0.6	74	80	67
88.00		104	82	53	90	1.1	10.6	6.5	1.0	63	68	58
82.95	C	78	61	42	115	1.9	9.5	3.4	0.6	77	90	65
82.90	B	158	112	65	85	0.8	9.0	1.6	0.5	77	90	70
82.85	A	90	59	40	80	1.4	3.5	1.2	0.6	113	130	90
78.00		130	89	71	115	1.3	9.7	3.8	0.7	68	82	45
76.60		124	101	71	100	1.0	7.1	1.3	0.6	72	90	55
Average		106	71	45	150	2.1	9.4	2.7	0.5	81	103	61
Yampa Tertiary		110	76	46								
132	94 Bar	100	65	46	450	6.9						
131	94 RW	62	35	21	120	3.4						
131	94 Main	80	45	25	170	3.8						
131	93 RW				120							
132	93 Bar				120							

Table 3.28. Summary of depth of open interstitial space in cobble bars.

DEPTH EXCEEDENCE	1993	1994	1995	1996	1997[1]	1998[6]
	Areal extent exceeding stated depth of open interstitial space - m^2					
RM 173.7(potential spawning bar), cobble D50 = 5 cm						
1 x D_{50}	n/a	n/a	362[2]	2204 / 3437[3]	1356	3499
1.5 x $D5_{50}$	n/a	n/a	342[2]	1512 / 1868[3]	571	1913
2.0 x D_{50}	n/a	n/a	321[2]	907 / 822[3]	214	656
RM 168.4 (potential spawning bar), cobble D50 = 6 cm						
1 x D_{50}	n/a	n/a	495[7]	566/857	374	2238
1.5 x $D5_{50}$	n/a	n/a	262[7]	170/171	94	767
2.0 x D_{50}	n/a	n/a	111[7]	57/86	94	64
RM 132 (main spawning bar), cobble D50 = 6 cm						
1 x D_{50}	64[4]	126[4]	853	712	688 (367)[5]	309
1.5 x D_{50}	10[4]	63[4]	500	522	276(67)[5]	148
2.0 x D_{50}	2[4]	29[4]	317	308	172(33)[5]	40
RM 131 (lower red wash spawning bar), cobble D50 = 5 cm						
1 x D_{50}	n/a	466	222	66	157	123
1.5 x D_{50}	n/a	106	100	66	105	46
2.0 x D_{50}	n/a	29	47	33	66	15

[1] A large storm event occurred between July 29 and August 14, peaking twice in the 6,000 cfs range. This storm was just prior to survey in 1997, which appears to have partially filled some open interstitial space with sediment.
[2] The area surveyed was limited to chute channels (362 m^2) compared to full bar (8,000 m^2) in 1996 and 1997.
[3] The first value is pre-runoff, the second post-runoff
[4] The area surveyed was about 10% that of later years, but was concentrated in the cleanest areas.
[5] First value is estimated based on a 20% subset survey taken in July prior to the storm event. Value in parenthesis was taken just after the storm event.
[6] A sediment laden storm occurred between July 27 and Aug 5 (Peak 2500 cfs), just prior to Survey
[7] The area surveyed was limited to chute channels (774 m^2) compared to full bar (9,000, 11,300, 7,800 m^2) in 1996,1997, 1998, respectively).

Table 3.29. Summary of changes in three cobble bars in the San Juan River surveyed between 1995 and 1998. (needs to be converted to metric).

Survey Date	Average Elev. (M)	Change in Elev. (ft)	Max Elev. (ft)	Min Elev. (ft)	Ac-ft SJ@ Farmington	Max cfs
Bar at RM 173.7						
04/02/96	100.00		94.8	89.0		
07/08/96	100.12	0.12	94.5	89.5	327,207	3550
08/22/97	99.78	-0.34	95.0	87.8	1,708,389	12,400
08/10/98	99.88	0.10	94.8	87.6	1,322,083	7,580
Bar at RM 168.4						
04/03/96	100.00		95.15	91.46		
07/09/96	99.97	-0.03	95.12	90.10	326,000	3,550
08/22/97	100.05	0.08	95.11	91.60	1,705,000	12,400
07/29/98	100.19	0.14	95.49	91.35	1,360,000	7,580
Bar at RM 132						
03/08/95	100.00		94.26	88.30		
07/25/95	100.28	0.28	94.49	89.19	1,478,000	11,700
03/13/96	100.25	-0.03	94.09	88.73	478,000	2,550
7/10/96	100.20	-0.05	93.66	88.59	355,000	3,550
8/21/97	100.55	0.35	93.56	87.79	1,700,000	12,400
8/11/98	100.68	0.13	94.07	88.79	1,330,000	7,580

Examination of topographic surface plots in Appendix A point out more significant differences than the gross changes would suggest. The shape of the bar at RM 173.7 shows only minor change, most of which is concentrated around the chute channel. This is also the location of the deepest open interstitial space. The bar at RM 168.4 demonstrates more broadly distributed, but small change, although a small chute channel is beginning to develop through the bar. The bar at RM 132 is more dynamic. The changes in certain locations of the bar have been large and the shape and size of the chute channel have both changed substantially over the survey period.

From the detailed surveys of these bars, and data collected at other suspected spawning sites that have since been lost due to channel change, it is obvious that any given spawning bar will only have utility for a finite period of time. For example, the bar in the Red Wash secondary channel at RM 131.2 where Miller (2000) documented Colorado pikeminnow in spawning behavior in 1994 was created in 1993 and isolated again by 1996. As the characteristics of a bar change and the features required for spawning lost, other bars develop. For the period of this survey (1995 - 1998), the three bars surveyed have maintained conditions thought to be necessary for spawning and will likely continue for some time. Among these, it appears that the upstream bars are more stable than the RM 132 bar and will likely persist longer. The dynamic nature of the bars is expected and necessary to maintain areas of open interstitial space.

Cobble Bar Survey Summary

Based the analyses in this section, it appears that sites with suitability equal to those used by Colorado pikeminnow exist upstream of the suspected sites(geomorphological and habitat suitability does not necessarily equate to use, but indicates potential). If these upstream sites could be used for spawning, the backwater habitat available downstream from spawning would increase in area by 33-43% and in number by 30-35%. In addition, the distance between spawning site and Lake Powell would be increased by up to 31% or 45 miles.

Cobble Transport Analysis

The range of values for three predicted conditions of cobble movement (initiation of motion, average motion, full motion) appears in Table 3.30 for the modeled reaches. The flows at which the three conditions are met in each modeling reach are shown in Table 3.31.

Table 3.30. Boundary shear stress conditions at various flow rates for four modeled reaches.

CFS	RM 133.0		RM 167.0		RM 169.0		RM 173.7	
D_{50} - cm	*5.00*		*6.00*		*6.00*		*4.00*	
Required for beginning motion (J^*_c= 0.02 - 0.03)	**0.34 - 0.51**		**0.41 - 0.61**		**0.41 - 0.61**		**0.27 - 0.41**	
Required for average motion (J^*_c= 0.03 - 0.045)	***0.51 - 0.76***		***0.61 - 0.91***		***0.61 - 0.91***		***0.41 - 0.61***	
Required for full motion (J^*_c= 0.45 - 0.06)	***0.76 - 1.01***		***0.91 - 1.22***		***0.91 - 1.22***		***0.61 - 0.77***	
			Boundary Shear Stress					
1,000		0.07		0.12		0.07		0.11
2,000		0.12		0.17		0.17		0.17
3,000		0.18		0.24		0.25		0.23
4,000		0.24		0.30		0.31	**0.28**	0.28
5,000		0.29		0.35		0.36	**0.34**	0.34
6,000	**0.34**	0.34		0.40	**0.42**	0.42	**0.38**	**0.38**
7,000	**0.41**	0.41	**0.48**	0.48	**0.46**	0.46	***0.44***	**0.44**
8,000	**0.47**	0.47	**0.53**	0.53	**0.51**	0.51	***0.48***	**0.48**
9,000	***0.52***	**0.52**	**0.58**	0.58	**0.56**	0.56	***0.53***	**0.53**
10,000	***0.59***	**0.59**	***0.65***	**0.65**	***0.61***	**0.61**	***0.57***	**0.57**
11,000	***0.63***	**0.63**	***0.71***	**0.71**	***0.66***	**0.66**	***0.61***	***0.61***
12,000	***0.67***	**0.67**	***0.78***	**0.78**	***0.71***	**0.71**	***0.65***	***0.65***

Note: **Bold = beginning motion**
Bold italics = average motion
Shadowed cells = full motion

Table 3.31. Flows required to meet critical shear stress conditions for cobble transport.

Modeling Reach	133	167	169	173.7
Minimum Channel Capacity - cfs	7,500	7,100	7,100	10,000
Average Channel Capacity - cfs	8,000	8,000	8,500	10,500
Cobble D_{50} - cm	5.0	6.0	6.0	4.0
Minimum flow for beginning motion - cfs	6-8,000	4-6,000	4-9,000	3-7,000
Ave flow for beginning motion - cfs	6-9,000	7-10,000	6-10,000	4-7,000
Minimum flow for ave. motion - cfs	8-12,000	6-10,000	9->12,000	7-10,000
Ave flow for ave. motion - cfs	9->12,000	10->12,000	10->12,000	7-11,000

Note: Flows above bankfull are not modeled accurately because of the inability to accurately assess the roughness of the overbank condition or define the flow channel without large amounts of additional data and the ability to calibrate the model at these higher flows. Therefore, values above bankfull presented in the table are qualitative only.

According to these calculations, all of the modeled reaches have boundary shear stresses in the range necessary for incipient motion for the average of all cross-sections at or below bankfull flow. Only one reach attained the condition (J^*_{c50} = 0.030 to 0.045) that the literature discussed in the **METHODS** section would suggest is necessary for measurable transport on average, although in all but one reach some transects were predicted to reach the condition below bankfull flow. The comparison of pre- and post-runoff surveys of the upstream cobble bar at RM 173.7 shows an increase in mean bar elevation during the 1996 runoff period and a subsequent decrease in average elevation during the 1997 runoff period. This would suggest that cobble was transported to the bar at a flow of less than 4,000 cfs (1996) and eroded from the bar during the higher flows in 1997. The bar at RM 168.4 was stable in 1996 but aggraded slightly in 1997. Given the morphological nature of the changes in the examined cobble bars, any noted cobble transport could have resulted from local scour and deposition rather than from immigration or emigration of material, but the change in the bars could have resulted from upstream transport based on the assumption of the low end of required J^*_{c50}. Based on these findings, the conditions for cobble transport in these reaches range from marginal to plausible at or below bankfull discharge, depending on the reach. However, adequate conditions exist for marginal transport only if the smaller J^*_{c50} values are applicable.

Three possible conditions found in the San Juan River supply some possible explanations for predicted transport to be somewhat less than anticipated. First, cobble diameter measurements erred on the large side; second, incipient and average motion begin at lower dimensionless shear stress values (low end of the range) in the San Juan River; and third, cobble is not adequately transported through lower gradient reaches of the system.

While the first condition is verified by the accuracy of measurement versus the diameter found using the template, samples taken in 1998 actually suggest that the mean cobble diameter may be a bit

larger than the earlier measurements show. It is still possible that the samples have an inherent bias to larger particles , especially due to the underwater nature of the sampling. However, it appears that this is not a valid explanation for predicted transport appearing less than anticipated based on field observation.

The second condition may be because cobble shape and the presence of sand in the system influence cobble transport. If the sand acts as a lubricant, then transport could begin at lower average values. The typical process of bar formation observed in the San Juan River consists of erosion of an upstream bar under high-gradient conditions across the bar and subsequent deposition on a bar located downstream. In addition, boundary shear stress may vary locally with varying substrate, depth, and velocity. As such, cobbles in a high-gradient reach may experience an adequate boundary shear stress for saltation or entrainment. The abundance of sand in the San Juan River may facilitate continued transport once a cobble is dislodged from the bed. This condition would tend to support using the lower end of the J^*_{c50} values.

The third condition is that cobble becomes locally available and transported from shoreline sources or that bar erosion allows short-distance movement, even though system shear stress is not adequate to move cobble through long, low-gradient reaches from upstream sources. In such a case, cobble transport is adequate in the short-term to locally maintain currently active cobble bars, and long-term sediment balance is met by continuous upstream erosion (head cutting) and subsequent downstream deposition to the extent that the higher gradient locations move through low-gradient reaches. This phenomenon, along with the formation of new secondary channels and resulting rapid, short-term transport, has been observed locally in the San Juan River. Further, local imbalance has caused deposition and subsequent change in main or secondary channel location. Such activities maintain sediment balance in the system over the long term, but may cause local imbalance.

Since the empirical data indicate cobble movement, even at low flows, and show that cobble movement generally increases with increased flow magnitude and duration, it is quite possible that some combination of the last two conditions exist in the San Juan River. Cobble bars will continue to be monitored for changes with varying flow conditions.

The model studies indicate that flows in the neighborhood of channel capacity (8,000 cfs) are necessary to transport cobble of sufficient size and quantity to build bars. While effective flow, in terms of total sediment transport and channel maintenance, is typically lower than bankfull flow (Andrews 1980, Pitlick and Van Steeter 1998), the bankfull flow recommendation is for cobble transport and bar formation, and it is needed less frequently than typical effective flows. Sediment transport theory, as applied to four modeling reaches, does not support a recommendation less than bankfull for the required cobble transport, and flows above bankfull provide very little additional shear stress for the volume of water required because of large overbank flow. Therefore, bankfull flow is the recommended flow magnitude to support cobble transport in the San Juan River.

Low Velocity Habitat Creation and Maintenance

Cobble/Sand Bar Monitoring

D-1: The results of 5 surveys of the bar located downstream of transect D-1 at RM 88 are summarized in Table 3.32. Three-dimensional surface plots of the survey areas are shown in Appendix B. The bar complex was subdivided to define points that would be in the backwater area separately from the remainder of the bar. Both minimum and maximum elevations are shown for the entire bar and for the backwater area and average elevations are shown for the entire area surveyed.

By comparing the various average and maximum elevations for the backwater area and the entire survey area, a definite pattern emerges. The backwater area filled somewhat during the summer after runoff and scoured over winter, while the bar remained about constant in elevation and shape. During spring runoff in 1995, the bar was scoured, losing about 0.6 m in maximum elevation and 0.15 m in average elevation. The upper end of the bar was eroded away on the main channel side and the lower end of the bar is nearly gone.

Based on this series of surveys, the bar appeared to be in an erosional state during the 1995 runoff (peak discharge 329 m^3/sec (11,600 cfs) at Four Corners), losing substantial area and elevation. The backwater area accumulated some sediment during the summer low-flow period and was cleaned some during the winter flow period, with little change during peak runoff. During the August 14 and October 12, 1995 surveys, no backwater existed at 41 m^3/sec (1,450 cfs) and 25.5 m^3/sec (900 cfs), respectively.

Table 3.32. D-1 Bar Survey Summary.

Date of Survey	Backwater Area Only		Entire Cobble Bar		
	Max Elev	Min Elev	Max Elev	Min Elev	Ave Elev
August 24, 1994	94.5	91.4	96.6	91.4	93.40
October 7, 1994	94.3	92.0	96.7	92.0	93.45
March 5, 1995	94.3	91.5	96.6	91.5	93.32
August 14, 1995	93.2	91.2	94.7	90.9	92.83
October 12, 1995	93.2	91.3	94.7	90.8	92.89
March 11, 1996	93.1	91.3	94.6	90.8	92.59
July 19, 1996	93.8	91.4	94.6	90.9	92.68
October 8, 1996	94.3	91.2	94.7	90.9	92.79

By 1996, the bar that formed the backwater is nearly eroded away. The backwater is essentially gone by October 1996. Surveys were terminated at the end of 1996.

D-4: The results of 5 surveys of the bar located at transect D-4 (RM 86.4) are summarized in Table 3.33 Three-dimensional surface plots of the survey areas are shown Appendix B. The bar complex was subdivided as described above. At this location, the minimum elevation of the backwater area increased during the summer of 1994, decreased during the winter, changed very little in depth during the spring runoff in 1995 but increased in extent and then decreased again during the summer of 1995. The maximum elevation of the entire bar changed very little, with a slight increase shown during spring runoff and a decrease shown in summer 1995. It is apparent that the bar is being eroded during spring runoff on the main channel side. Even though the maximum elevation increased during spring runoff, the bulk of the bar controlling the backwater did not change in elevation relative to the post runoff condition in 1994, although the shape changed considerably. Backwater conditions exist at flows above about 900 cfs and becomes a flow-through at flows above about 1,500 cfs. Below 900 cfs, the berm that forms at the lower end of the backwater isolates water in the backwater area from the main channel. The berm appears to develop during the summer and is eroded during spring runoff.

This bar is also erosional on its main channel margin and relatively stable along the top. The higher flows during 1995 did not increase the elevation of the top of the bar, but did cause additional erosion on the margin. The 1996 flows induced further margin erosion. If the trend continues, the backwater will be lost. Surveys were terminated at the end of 1996.

Table 3.33. D-4 Bar Survey Summary.

Date of Survey	Backwater Area Only		Entire Cobble Bar		
	Max Elev	Min Elev	Max Elev	Min Elev	Ave Elev
August 24, 1994	94.4	93.3	98.2	92.8	95.54
October 7, 1994	94.7	93.9	98.3	93.4	95.85
March 5, 1995	95.0	93.5	98.2	91.8	95.74
August 14, 1995	94.6	93.3	98.4	92.2	95.41
October 12, 1995	94.2	92.5	98.0	91.8	95.47
March 11, 1996	94.6	93.1	98.4	92.3	95.34
July 19, 1996	95.2	93.2	97.3	92.5	95.42
October 8, 1996	95.3	93.9	98.2	92	95.58

CH-2: The results of 5 surveys of the bar located at transect CH-2 (RM4) are summarized in Table 3.34. Three-dimensional surface plots of the survey areas are shown in Appendix B. The bar complex was subdivided as described above. This is a very dynamic site with both deposition and scour occurring continually along the margins of the thalweg and over the entire area at higher flows. The values in Table 3.34 are not as instructive as for the other two bars due to the dynamic nature of this site. However, by inspection of the data for the entire bar, it is evident that the higher flows during 1995 runoff (both volume and magnitude) did not increase the elevation of the bar. If fact, the maximum elevation of the bar decreased by 0.2 ft during this time and actually increased during 1995 summer flow to return to the maximum elevation recorded in 1994. On average, the elevation of the entire area surveyed dropped by 0.06 ft during spring runoff and increased by 0.32 ft during the summer of 1995. The minimum elevation of the bar occurred at the end of the 1995 runoff, demonstrating scour of nearly 3.0 ft. However, this is at a location on the margin of the thalweg that occurred as the thalweg shifted.

During the period of August 25, 1994 to October 12, 1995, the thalweg shifted from river left at the lower end to river right and then back to river left. At the upper end it shifted from river right to river left. The large but shallow backwater that existed in 1994 disappeared in 1995. After runoff in 1995 no backwaters existed in this reach at flows above 25.5 m^3/sec (900 cfs). In fact, at flows of 38 m^3/sec (1,350 cfs), nearly the entire area is under water.

Table 3.34. CH-2 Bar Survey Summary.

Date of Survey	Backwater Area Only		Entire Sand Bar		
	Max Elev	Min Elev	Max Elev	Min Elev	Ave Elev
August 25, 1994	93.0	91.5	94.4	90.3	92.18
October 6, 1994	94.0	91.3	94.3	90.4	92.24
March 4, 1995	93.2	90.0	94.1	89.9	92.23
August 15, 1995	93.3	92.6	94.1	87.1	92.31
October 13, 1995	93.8	92.8	94.4	90.1	92.66
March 8, 1996	93.6	91.7	94.2	90.8	92.55
July 18, 1996	94.1	90.6	94.1	89.3	92.30
October 9, 1996	94.4	89.4	94.7	89.4	92.60
March 12, 1997			94.6		92.41
August 20, 1997			95.5		93.11
September 9, 1998			96.7		95.10

This trend of continuous local change in bar shape but no change in average or maximum bar elevation continued until 1997. From March 1997 until September 1998, the average elevation of the bar increased by 0.76 m and the maximum elevation increased by 0.61 m, similar to the change in the C-2 transect discussed earlier. This change is in response to the rising Lake Powell surface elevation.

Summary: Between 1994 and 1996, none of the bar heights responded to differences in runoff. It appears that the bars at D-1 and D-4, and their associated backwaters, formed as alluvial material deposited during earlier times eroded away, exposing a more resistant cobble bar with a backwater behind the bar. At flows in the range of 283 to 340 m^3/sec (10,000 to 12,000 cfs) the bars are eroding. At 100 m^3/sec (3,540 cfs) there was no obvious erosion. They may erode over a larger range of flows, but flows higher than 12,000 or between 10,000 and 3,540 cfs have not been tested. These are not permanently maintained features, but are representative of the many transitory backwaters in the system.

The conditions at CH-2 are much different. The sands forming the bars at this location are deposited in response to the gradient change created by Lake Powell backwater. In 1995 a backwater condition (elevated Lake Powell water surface created higher water surface elevation at a given flow in this reach) existed, yet the bar did not build in elevation during spring runoff. However, this backwater condition did not occur until the end of runoff, with no effect this far up river. In 1996, the water surface elevation again dropped. The lack of average elevation change would indicate that sediment transport was about in balance (no scour or deposition) at this site through 1996. Beginning in 1997, in response to lake elevations, the bar began to rise and continued through 1998, in response to Lake Powell water surface elevations.

Maintenance of Secondary Channel Associated Backwaters

Based on six measurements over a range of discharges, a relationship was developed to predict secondary channel discharge as a function of main channel flow. The relationships developed for each channel had an r^2 of 0.99 (p=0.002). The plots of the mean depth of the backwaters and the main and secondary channel hydrographs are shown in Figure 3.33. Suspended sediment concentration was measured about twice weekly during this time to provide data for later modeling.

HEC-6 was used to model sediment transport in the two secondary channels so that predictions could be made for other conditions. Survey data from May 13 and 19, 1997, were used for channel morphology in the model. Manning's *n* was determined using HEC-RAS, by varying Manning's *n* until the modeled water surfaces matched the surveyed water surfaces. This resulted in a Manning's *n* of 0.023 for Sand Island and 0.027 for Montezuma Creek. These *n* values are on the low end of the range for typical, natural channels, but they are consistent with the predominantly smooth-bottomed, relatively straight secondaries being modeled. Between May 13 and August 9, 1997 (the runoff period modeled), eight of the ten total surveys were completed in each secondary. To calibrate HEC-6, the hydrographs in Figure 3.33, with their accompanying sediment load, were routed through the channels. Parameters were adjusted until the modeled volumetric change in

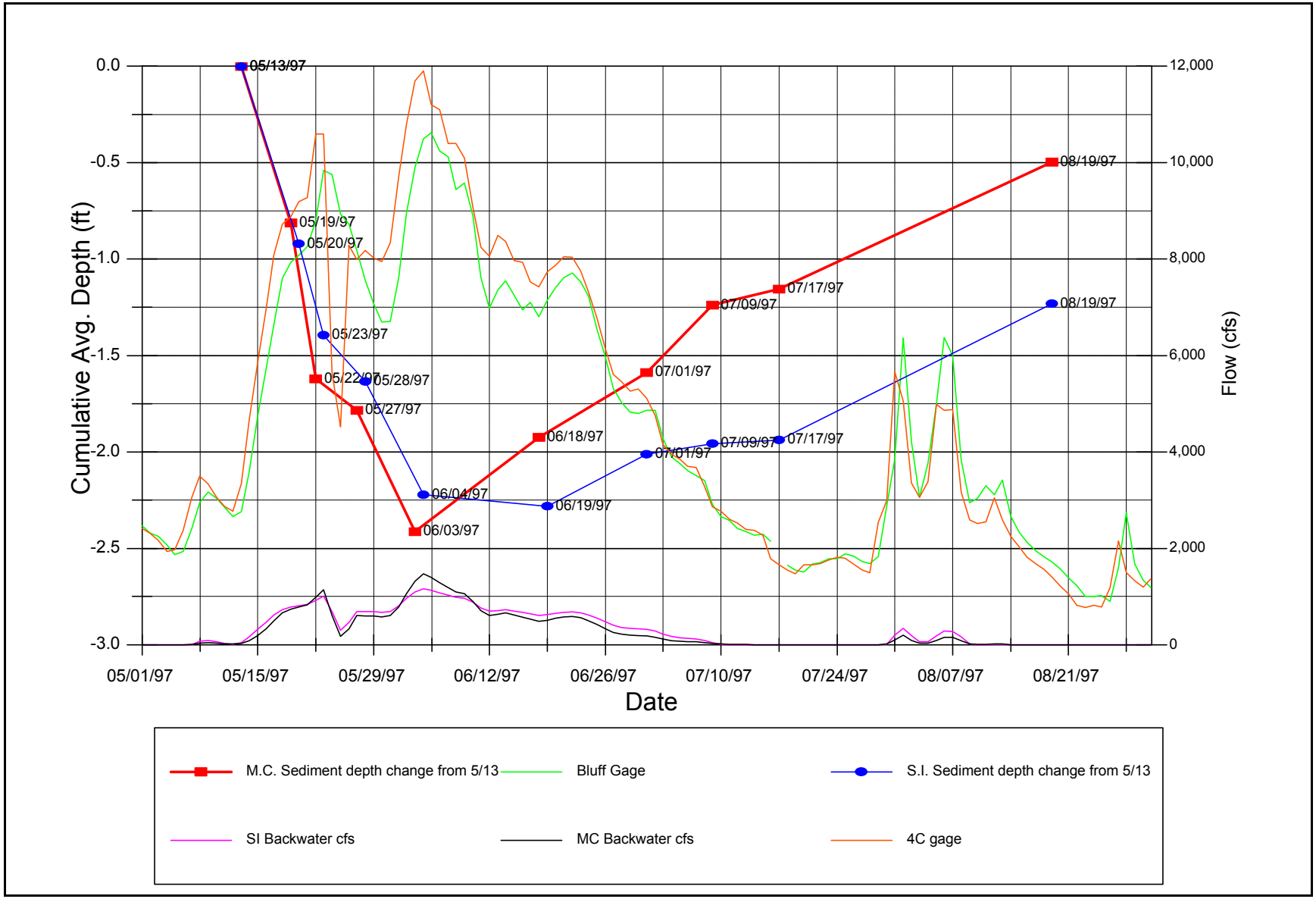
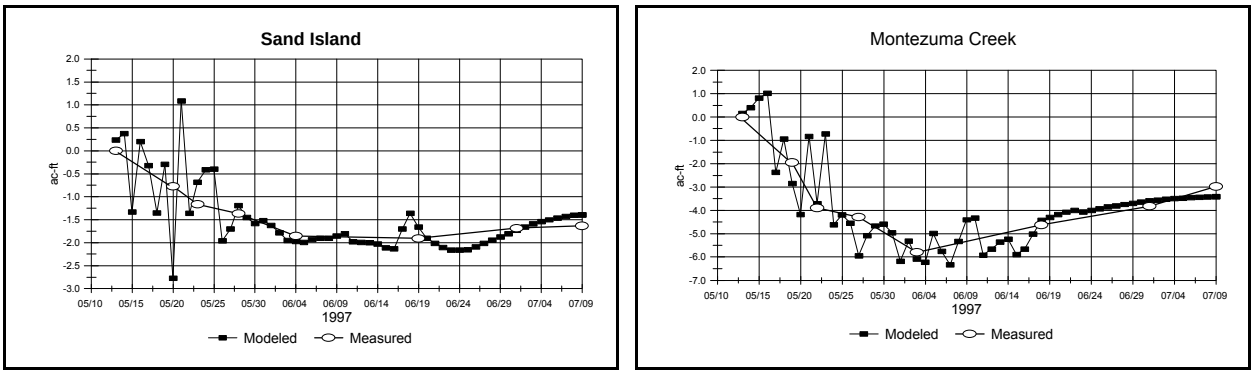


Figure 3.33. Flow and backwater depths for 1997 runoff for the Montezuma Creek and Sand Island sites.

sediment load matched as closely as possible the measured volumetric change in sediment load. The parameter adjusted was the size distribution of inflowing suspended sediment. For Sand Island, there was one sediment size distribution for the entire time period, which was 50% very fine sand and 50% fine sand. For Montezuma Creek, the starting sediment size distribution was 71% very fine sand and 29% fine sand, which changed to 99% medium sand and 1% coarse sand on May 25, 1997. Suspended sediment size fractionation was completed to determine composition of sand and silt, not for a range of fine substrate sizes, so some calibration was necessary. Figure 3.34 shows the measured and modeled results for the two backwaters.

For these secondary channels, the HEC-6 results for sediment inflow and outflow were extremely sensitive to even small changes in the sediment size distribution. For example, starting Montezuma Creek with 75% very fine sand and 25% fine sand instead of 71% very fine sand and 29% fine sand gave the results shown in Figure 3.35. Furthermore, the scatter in the fit in the early part of the runoff period indicated sensitivity to sediment concentration as well as particle size. The scatter about the mean was because of changes in sediment concentration at the break points. Further, one dimensional modeling of these complex processes limits the robustness of the analysis. Therefore, without a more-detailed particle size distribution and daily sediment concentration, projecting these results for other flow and sediment conditions is qualitative, at best.

Using the calibrated parameters, model runs were completed for 1993 and 1995 with sediment concentrations collected during those years at about 10-day to 2-week intervals. During both years, backwaters were well maintained by flows after runoff. At the end of the runoff in 1993, sediment concentration was at its lowest point of the 2 years. The model was also operated for 5 years of simulated hydrographs from river operations model output to represent five different hydrograph scenarios and four sediment concentrations. The sediment concentration patterns used represented a low-sediment concentration year similar to 1993 at Shiprock and Montezuma Creek, representing upstream and downstream differences, and a relatively high concentration pattern. These patterns were chosen to demonstrate the differences in years and reflect the normal upstream-to-downstream gain in sediment. The concentrations used are shown in Table 3.35. Disregarding storm peaks, they represent the range of expected concentrations during spring runoff in the San Juan River. The results of the modeling runs are summarized in Table 3.36. Results are shown only for Montezuma Creek. Sand Island results are similar, except the volume of removed sediment is less because the backwater was smaller. Maintenance was characterized as excellent, good, fair, or poor. Because results of the two low and two high sediment concentrations were similar, a qualitative evaluation was indicated for the two main categories only, not for the upstream or downstream conditions. In nearly all cases, the backwater was maintained at maximum depth during the runoff period, usually by peak flow conditions, and then partial refilling occurred on the descending limb. While flushing usually began at flows lower than 5,000 cfs, it became more effective at higher flows; therefore, 5,000 cfs is used as the threshold condition for effective flushing. While duration required for cleaning varies depending on the shape of the hydrograph and suspended sediment load, 3 weeks at flows above 5,000 cfs is set as the minimum condition for full cleaning as an average condition, assuming that the flow follows a typical increasing and decreasing pattern to allow for flows above 5,000 cfs for the cleaning period.



.**Figure 3.34. HEC-6 calibration results for Sand Island and Montezuma Creek.**

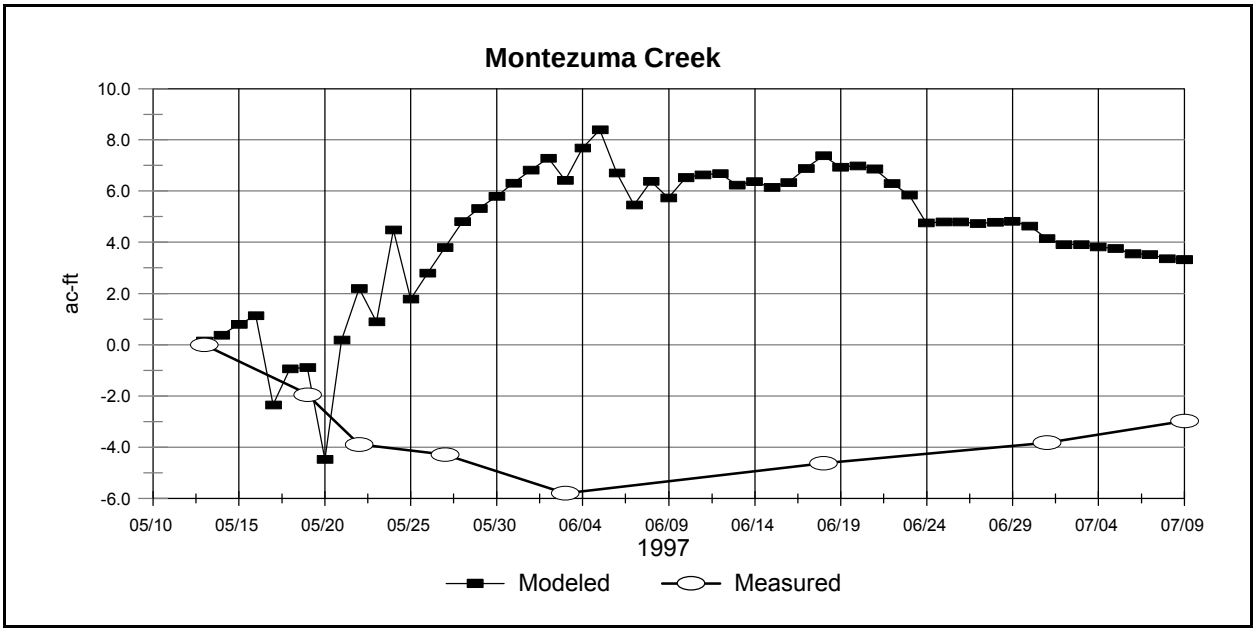


Figure 3.35. Modeling results with small change in grain size to demonstrate sensitivity.

From the empirical survey data and modeled results, several preliminary conclusions can be made: (1) main channel flows above 4,000 cfs initiate flushing, but effective flushing occurs at about 5,000 cfs, (2) if flows do not exceed 5,000 cfs, more time is required for adequate flushing, (3) shorter descending limb duration results in less refilling and better maintained backwaters after runoff, (4) short duration, steep ascending limbs to relatively high peaks (approximately 9,000 to 10,000 cfs), combined with steep descending limbs, maximize backwater maintenance for the volume of water required compared with more-extended runoff with lower peaks.

Table 3.35. Sediment concentrations (parts per million (ppm)) used in HEC-6 simulations.

	Low		High	
	Upstream	Downstream	Upstream	Downstream
	190	300	550	800
May 17 - May 31 - ppm	275	415	750	1,050
May 31 - June 10 - ppm	170	450	1,050	1,300
June 10 - June 20 - ppm	110	170	400	460
June 20 - June 27 - ppm	70	130	150	200
June 27 - July 31 - ppm	20	30	150	100

Table 3.36. Summary of HEC-6 modeling results for Montezuma Creek site.

	1997	1995	1993	1976	1970	1960	1937	1930
Nose - weeks	4	0	10	0	0	0	6	0
Ascending limb - weeks	4	10	4	5	2	4	2	4
Descending limb - weeks	4	5	4	2	6	1	6	4
Peak flow - cfs	11,900	12,000	10,000	8,900	8,800	9,500	9,200	10,000
Begin cleaning flow - cfs	4,500	4,000	4,000	3,800	3,800	3,900	4,600	4,000
Weeks to maximum cleaning	3	5	10	2	2	2	3	2.5
Results - low concentration	n/a	n/a	n/a	good	good	excell.	good	good
Results - high concentration	n/a	n/a	n/a	poor	poor	excell.	fair	poor
Results - actual concentration	good	good	good	n/a	n/a	n/a	n/a	n/a
Sediment concentration	mod.	low	low	n/a	n/a	n/a	n/a	n/a

It is important to note that location in the system may influence the effectiveness of backwater-maintenance flows. The backwaters measured and modeled in this discussion are located in Reach 3 and are subject to heavy sediment inflow. Backwaters higher in the system may clean faster because they receive less sediment inflow. In 1998, two additional backwaters will be modeled in Reach 5 to assess any difference in site locale. Also, additional calibration data will be collected to refine the modeling process. As with other flow recommendations, additional monitoring is required, and future modification may be warranted.

Channel Morphology Response Summary

During the 7-year research flow period, channel cross-section surveys indicated a slight increase in channel depth and channel capacity in response to the increase in spring runoff volume and magnitude, regaining some of the cross-sectional area lost after closure of Navajo Dam. Bankfull capacity in Reaches 3 to 6 (below Farmington, New Mexico) may have increased by as much as

12%. Most of this change occurred by 1995, with relative stability since that time. Most of this increase in channel capacity is a result of removal of sand from the streambed. Relatively little net cobble loss (about 10% of the total loss) has occurred. There has been no appreciable change in channel complexity as measured by the number of islands present at base flow as a result of the research flows, although channel complexity did increase after flows exceeded 10,000 cfs for 11 days in 1995.

At some locations, cobble transport occurs at flows as low as 2,500 cfs. Cobble movement to and from cross-sections generally increased with increased flows, but movement is not highly correlated to any single hydrologic parameter. A combination of hydrologic conditions, including peak flow magnitude and days above 10,000, 8,000, 5,000, and 2,500 cfs, explains about 70% of the variation in scour and deposition of cobble at the cross-sections, although the correlation is not statistically significant at the 95% level because of the limited degrees of freedom.

Bankfull channel capacity below Farmington is about 8,000 cfs, with some overbank flows as lows as 7,100 cfs. Cobble transport modeling in the San Juan River only marginally supports observed cobble transport, but given the approximations in modeling and potential measurement error, there is not large disagreement between observed and modeled conditions. Based on the combination of the modeling results and measurement of cobble movement, flows above 8,000 cfs for a minimum of 8 days are likely necessary for reconstruction or replacement of cobble bars in the system. Flows of about 2,500 cfs for 10 days or more are adequate to develop clean cobble for spawning and should be provided regularly (at least once every two years). Bars erode slowly, so flows above 8,000 cfs are needed less regularly than the smaller reshaping flows. For channel maintenance purposes, flows should exceed 8,000 cfs for 8 days with an average frequency of 1 year in 3 years. Periodic flows above 10,000 cfs are helpful in maintaining channel complexity, providing new cobble sources for subsequent bar construction, and maintaining floodplain integrity. Frequency of these flows is less critical than that of maintenance flows, and a lower frequency is desirable if it will allow greater effectiveness of high flows. A duration of 5 days with an average recurrence frequency of 1 year in 5 years is suggested by the empirical data and is consistent with mimicry of a natural hydrograph when considering the historical loss of channel capacity. Periods of high flow following low-flow years are important to the maintenance of the geomorphology of the system.

Kondolf and Wilcock (1996) suggested that providing channel maintenance flows of magnitudes that transport both sand and gravel may not achieve the objective of reducing the sand content of the bed and may result in loss of coarse sediment from the system. Analysis of the data for the San Juan River does not indicate either condition as a problem with the flows recommended. Percent cobble substrate has increased with time, cobble is abundant in the system, the cobble bars surveyed do not appear to be degrading, and open interstitial space is consistently maintained. Transport conditions necessary to remove fine sediment from the system occur for much longer durations and at greater frequency than those required to transport cobble. Supplying cobble mobilization flows 1 year in 3 years is only a slight increase from post-dam conditions, a period that indicated a slight loss of channel capacity. While it is not likely that the concern suggested by Kondolf and Wilcock (1996) is a problem in the San Juan River, continued monitoring will be required to identify if a problem occurs and to adjust flow recommendations accordingly.

Backwaters in the San Juan River typically flush at flows above 4,000 to 5,000 cfs. When limited flow is available, the most-effective hydrograph scenario is one of a rapid ascending limb to a relatively high magnitude peak, followed by a rapid descending limb. For full flushing of backwaters, flows should be maintained above 5,000 cfs for 3 weeks or more, assuming a relatively natural hydrograph with a peak of 1.5 to 2.5 times this level. If flows are maintained at or near 5,000 cfs, substantially longer times are needed for flushing. While backwaters are not totally lost when flushing flows are inadequate, they are diminished in size and quality. Frequency of achieving flushing conditions will be influenced by the level of sediment accumulation in the prior years and the availability of water to achieve peak flows above 5,000 cfs for 3 weeks. Peaks between about 3,000 and 4,000 cfs may actually increase the filling of backwaters during runoff and should be avoided if possible.

While the flow conditions discussed here are based upon the response of the geomorphology, they form the basis of natural hydrograph mimicry, a condition that is desirable in restoration of habitat for native fishes (see discussion in Chapter 1). Application of the rates, durations, and frequencies represented here provides for a hydrograph shape and annual variability that is similar to natural conditions.

Suspended Sediment Sampling

Sampling Results

The suspended sediment concentrations at Farmington, Shiprock, Four Corners and Montezuma Creek sampling sites are plotted against discharge on Figures 3.36 through 3.39, respectively, for the 1992-1998 sampling period. Utilizing this full data set for each of these gages demonstrates the poor correlation between suspended sediment concentration and discharge for the San Juan River. These data were also plotted with the 1963-1980 daily data for the San Juan River near Bluff (located at Mexican Hat) in Figure 3.40 (no spot samples included).

Variability and range of sediment concentration from these data sets are similar to the historic data, although the average is in the low side of the historic range. Since the sampling design was to avoid storm events, the shift to the low side of the historic data is expected. When including the spot data that includes storm influenced concentrations, the ranges more closely match. The data do not suggest a shift in sediment concentration since 1980.

In an attempt to develop a sediment-discharge rating curve for the San Juan River, to assess the sediment transport capacity, an attempt was made to filter out any storm influenced data from the full data set. In filtering these samples, any sample that was considered to be influenced by a storm event in the previous 10 days was removed. The results for Four Corners and Montezuma Creek appear in Figures 3.41 and 3.42, showing the relationships for pre-peak and post-peak conditions. Even with this filtering, no statistically significant relationship exists, although there is an apparent difference between ascending and descending limbs of the hydrograph. To demonstrate the storm influence on sediment concentration, the Four Corners data were plotted together with the

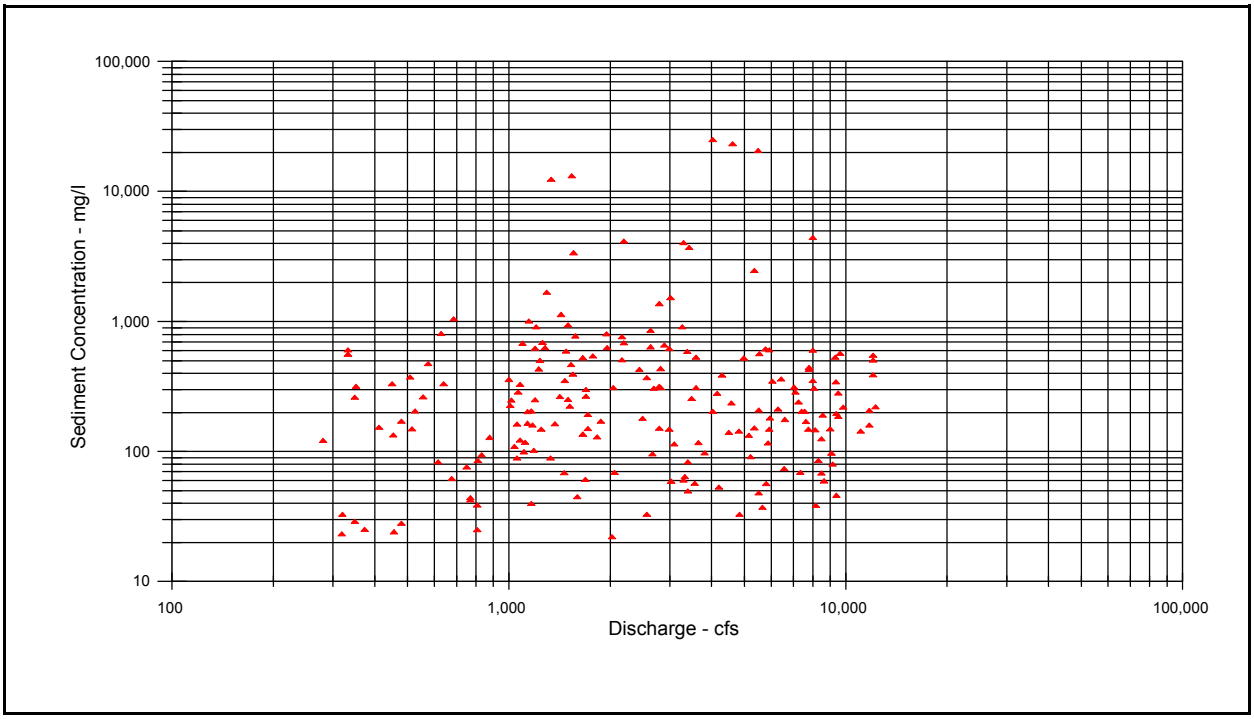


Figure 3.36. Suspended sediment vs flow for the San Juan River at Farmington, 1992-1998.

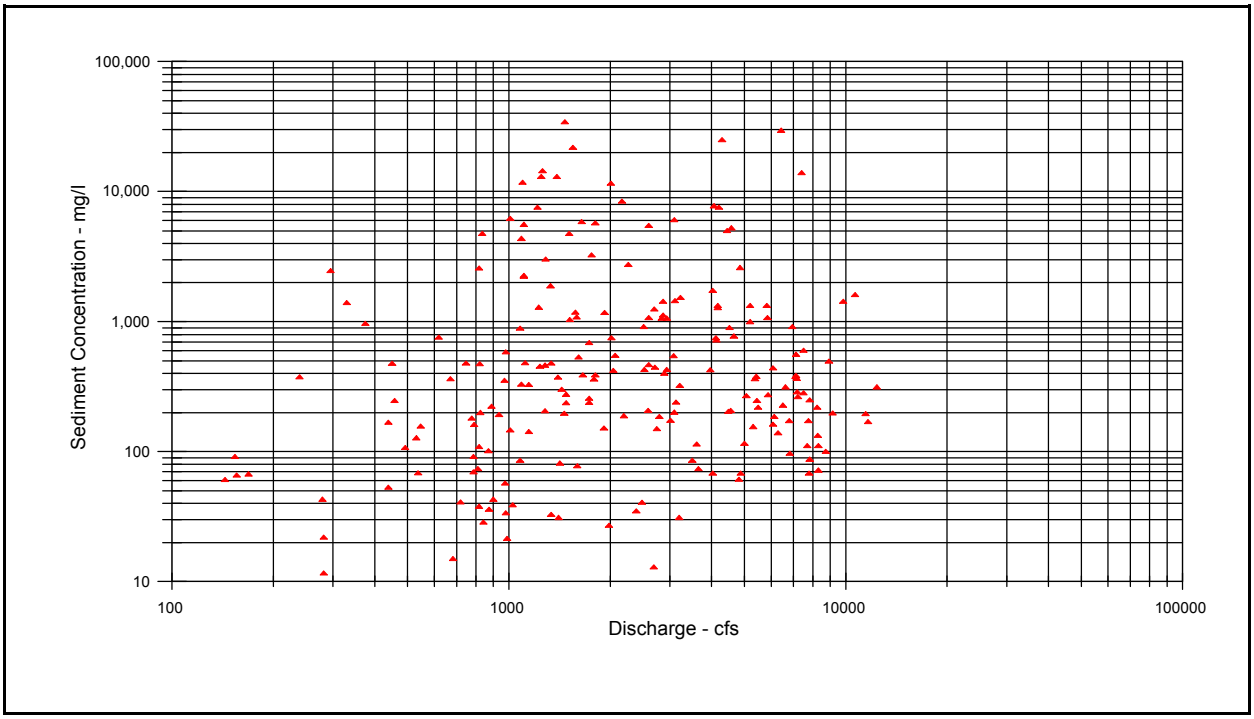


Figure 3.37. Suspended sediment vs flow for the San Juan River at Shiprock, 1992-1998.

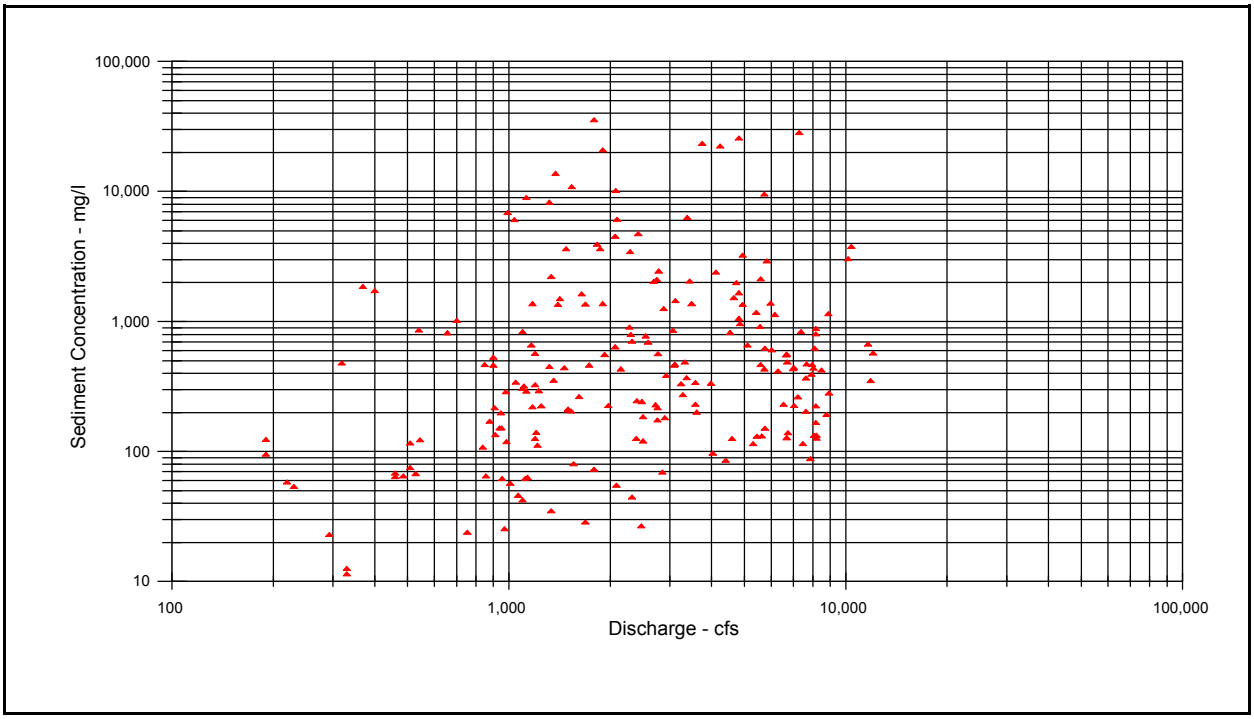


Figure 3.38. Suspended sediment vs flow for the San Juan River at Four Corners, 1992-1998.

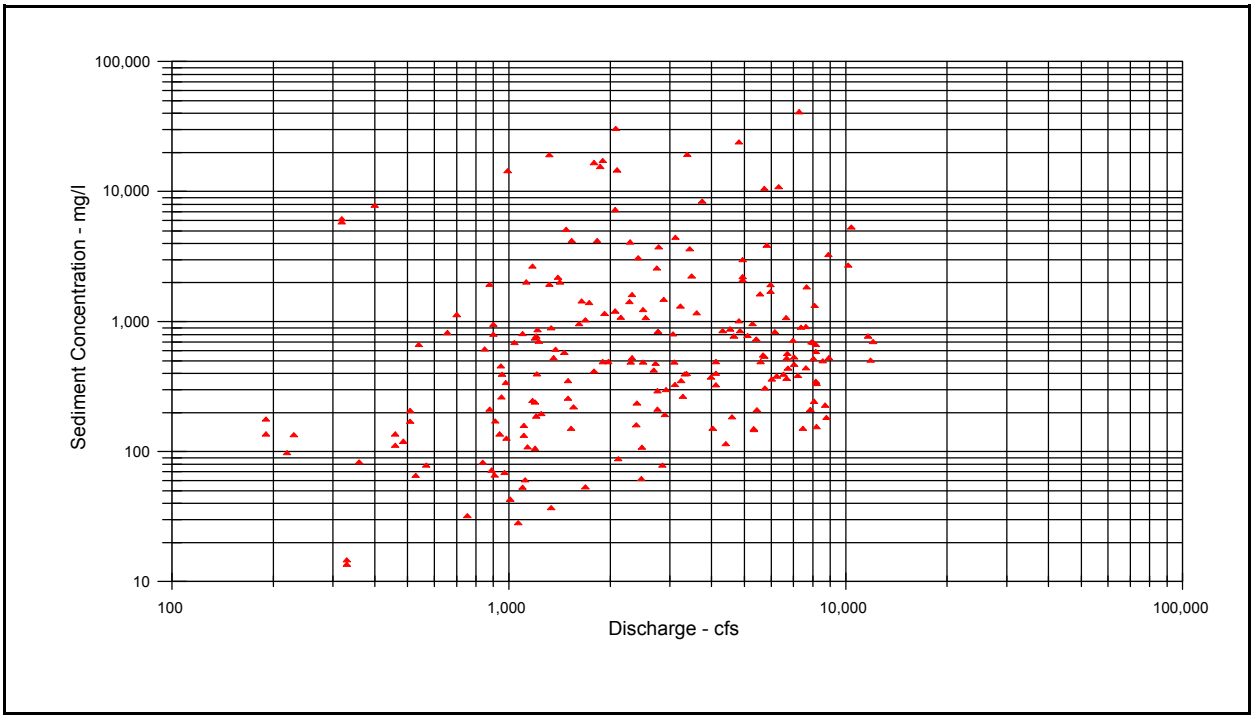


Figure 3.39. Suspended sediment vs flow for the San Juan River at Montezuma Creek, 1992-1998.

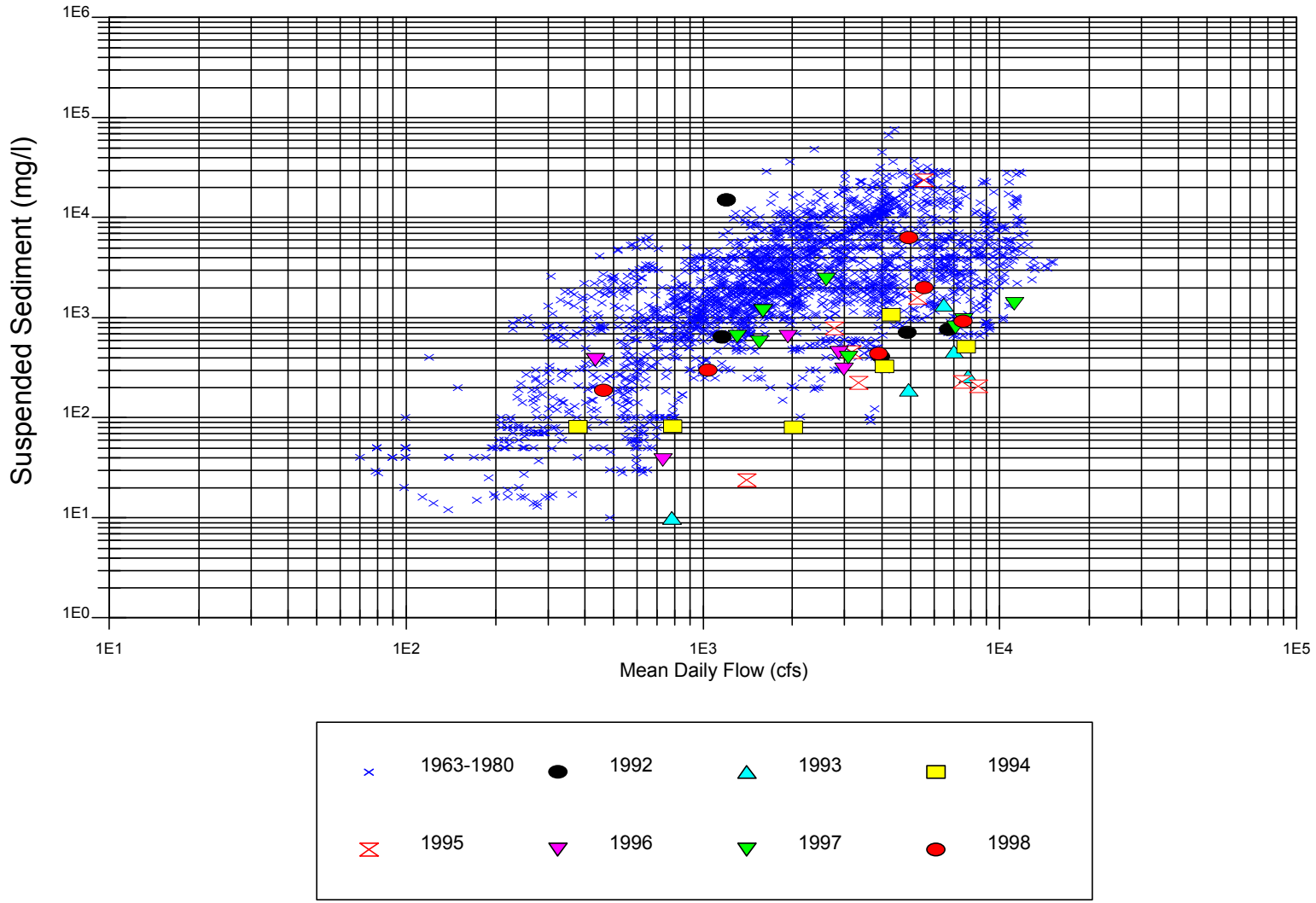


Figure 3.40. Suspended sediment vs flow for the San Juan River at Bluff, 1960-1983 compared to 1992-1998.

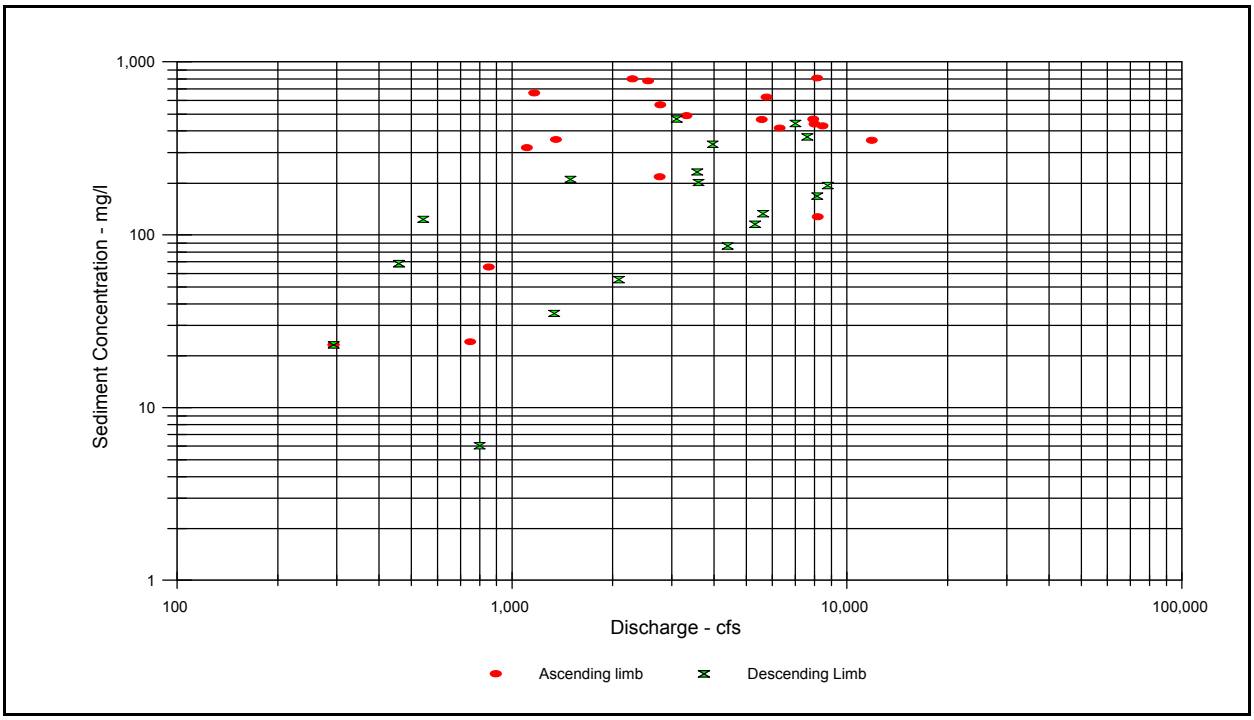


Figure 3.41. Suspended sediment vs flow for the San Juan River at Four Corners, 1992-1998, for non-storm influenced samples.

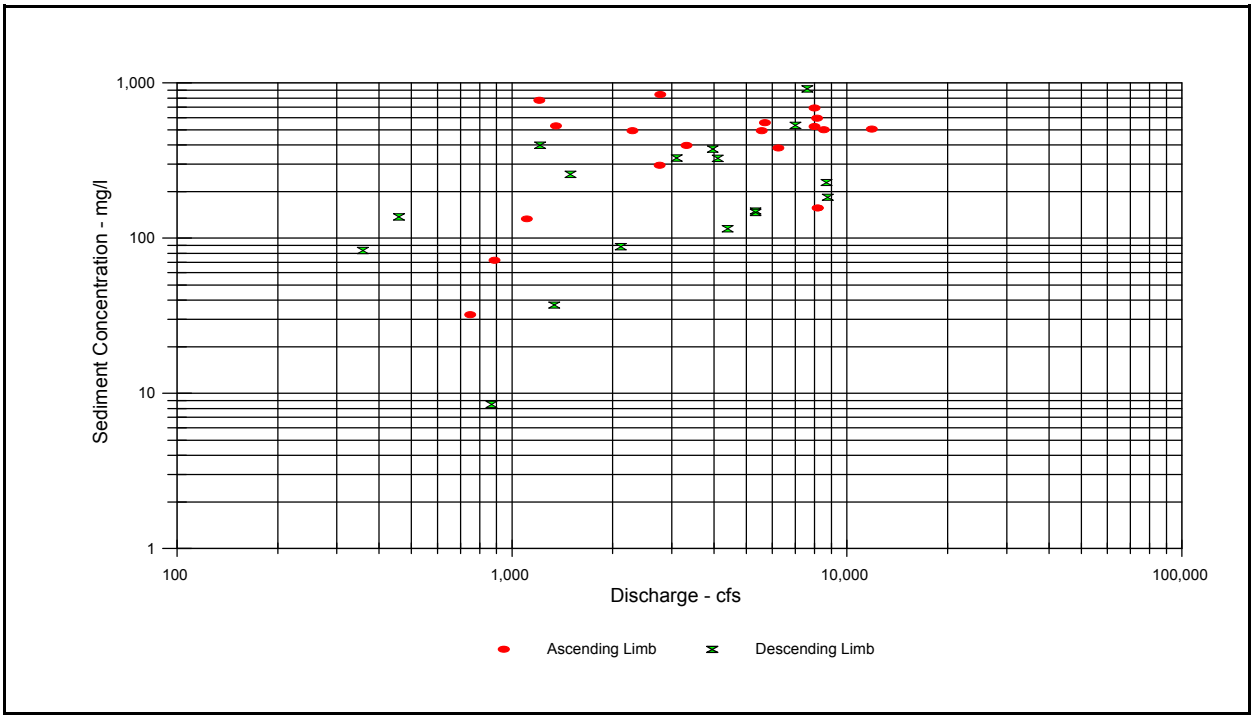


Figure 3.42. Suspended sediment vs flow for the San Juan River at Montezuma Creek 1992-1998, for non-storm influenced samples.

hydrograph in Figure 3.43. The storm event influence can be seen by the extreme elevation in sediment concentration during increases in flow. In some cases, a very small increase in flow resulted in a large increase in sediment concentration due to the high concentration of tributary inflow. During one sampling trip, the sediment concentration in Chinle Wash was over 13% with a flow of 170 cfs. That one tributary increased the sediment concentration in the San Juan River below that point by 3700 ppm.

Due to the myriad of inflow points and the impracticality of measuring all the inflow concentrations on a sufficiently high frequency to allow computing mass balance, it was not possible to compare sediment transport to change in cross-section. The data collected have been used in fine sediment transport analysis for prediction of backwater flushing requirements.

DISCUSSION

Historic Analysis of Fluvial Morphology

Typically, we think of a desire to restore a river to its "natural" function through such activities as habitat restoration and mimicry of a natural hydrograph. In the case of the San Juan River, determining what this "natural" function was is difficult. No quantitative data and little qualitative data are available prior to the early part of the 20th century, yet the impact of man in the basin was strongly felt by then. The condition of the river in the 1930's when our earliest quantitative data are available is likely not the condition to which we would desire restoration. The lower portion of the river, including the canyon, was heavily sediment laden. There was no stability to the channel and most of the cobble was probably buried in 0.3 to 2.0 meters of sand.

By the early 1950's when the next aerial photography was available, not only had there been a significant shift in suspended sediment load in the system, allowing the channel to scour the sand from the system and form a more defined channel, but invasion of tamarask had begun, with substantial establishment by this period. The smaller, stabler channel was quite different than the 1930's channel. The larger, stabler islands likely led to more stability in the complex habitats typically associated with islands and the secondary channel system became more developed, especially in the lower three reaches. This was likely a positive development, although the depletion of water in the summer for irrigation led to extremely low flows in these reaches which was likely detrimental.

By the time Navajo dam was constructed in the early 1960's, the channel had stabilized even more, although the mean bankfull channel width was about the same as a decade earlier. With stabilization came a loss of channel complexity with fewer and smaller islands. The loss of bankfull islands is somewhat perplexing. It is possible that vegetation encroached into the shallower secondary channels during this drier than normal period. At high flows there would have been flooding, but possibly inadequate stream power to remove the tamarask, resulting in a simpler bankfull channel. On the aerial photos, the vegetated secondaries would not have been included in the bankfull channel area.

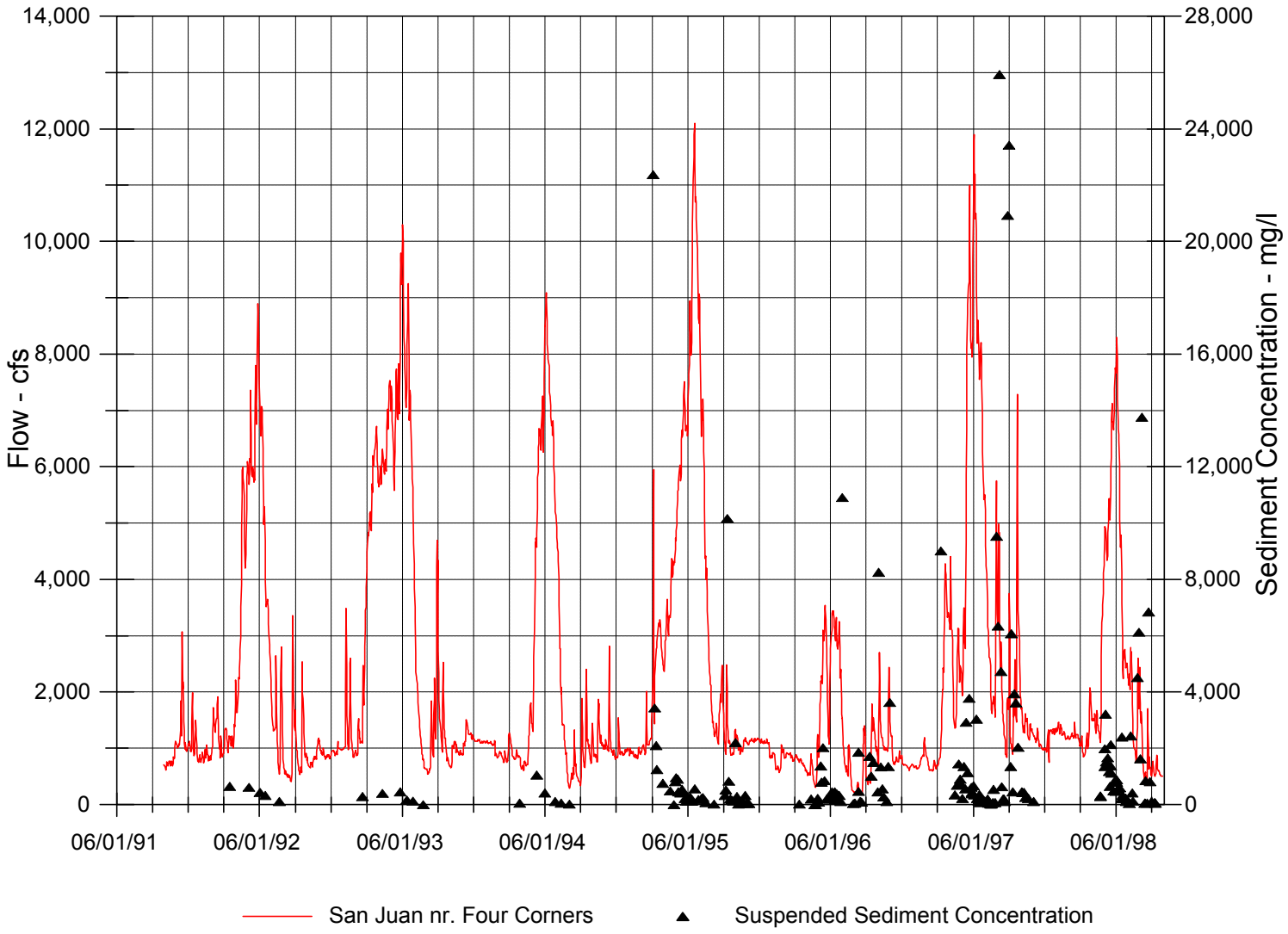


Figure 3.43. Daily flow and spot suspended sediment concentration for the San Juan River at Four Corners, 1994-1998.

Between the early 1960's and 1988, the channel became much smaller, but in the process, gained significant island area and island count. Since the bankfull channel area lost is almost equal to the island area gained, it appears that previous sand and cobble bars became vegetated during this period of reduced spring peak flows. The channel is much more stable and is now heavily armored with Russian Olive along most of its course. The loss of bankfull channel capacity, estimated at between 15% and 30%, now requires less flow for channel maintenance and out-of-bank conditions occur at reduced flows.

The effect of introducing higher spring flows into this channel has resulted in a small increase in channel capacity, with channel complexity remaining relatively constant. The higher flows dislodge Russian olive trees along the banks, adding debris piles and habitat complexity.

Since no habitat mapping was completed prior to this research period, the actual change in aquatic habitat is not known. Nor is it known which of the channel conditions would be best for the endangered and other native fish.

Geomorphological Characterization

The eight geomorphological reaches identified allow analysis of system response to changed in hydrology to be analyzed on a finer resolution than considering the entire river. Further, sub-reaches are identified that can be utilized across all research studies to the extent that the boundaries are useful. The sub-reach definitions are based on characteristics that are distinct in terms of geomorphology and habitat, rather than arbitrary, or non-quantitative. To better relate the data presented in the analysis above to the conditions in the field, the following narrative descriptions are provided:

Reach 1: (RM 0 to 16, Lake Powell confluence to near Slickhorn Canyon) has been heavily influenced by the backwater effect and fluctuating reservoir levels of Lake Powell. Fine sediment has been deposited to a depth of about 40 ft in the lowest end of the reach since the reservoir first filled in 1980. This deposition of suspended sediment into the delta-like environment of the river/reservoir transition has created the lowest-gradient reach in the river. This reach is canyon bound with an active sand bottom. The thalweg meanders in the sand bottom, alternately creating scour (deep runs to sand shoals) and deposition (sandbars) along the thalweg at all discharges. At low flow (below 1,000 cubic feet per second (cfs)), backwaters form in mainchannel sandbars. At flows above 1,000 cfs, backwaters form in tributary mouths and invaginations in the canyon walls, and mainchannel backwaters are lost as the low sandbars are inundated. While this reach has the highest abundance (surface area per RM) of backwaters among the reaches studied, the backwaters are highly unpredictable and ephemeral due to the shifting thalweg, changing river flow, and fluctuating reservoir elevations that vary seasonally and annually.

Reach 2: (RM 17 to 67, near Slickhorn Canyon to confluence with Chinle Creek) is also canyon bound but is located above the influence of Lake Powell. The gradient in this reach is higher than in either adjacent reach and the fourth highest in the system. The channel is primarily bedrock confined and is influenced by debris fans at ephemeral tributary mouths. Riffle-type habitat

dominates, and the major rapids in the San Juan River occur in this reach. Due to the steeper gradient, narrow canyon bottom, and low sinuosity, backwater habitats are small and scarce in this reach. Low-velocity habitats are primarily created as sand deposits in eddies below debris fans. While sandbar-associated backwaters are found, they are often associated with either debris fan/eddy complexes or eddy deposits below shoreline colluvium. Some oil development exists within an isolated area of floodplain in this reach, near the town of Mexican Hat, Utah.

Reach 3: (RM 68 to 105, Chinle Creek to Aneth, Utah) is characterized by higher sinuosity, lower gradient (second lowest), broad floodplain, multi-threaded channel, high island count, and high percentage of sand substrate. This reach has the second highest density of backwater habitats after spring peak flows, but is extremely vulnerable to change during summer and fall storm events, after which this reach may have the second lowest density of backwaters. As a result, this reach has been deemed the most highly responsive reach to extreme discharge events. While cobble is present in this reach, it is frequently mixed with sand. Areas of clean cobble are usually small and ephemeral. The active channel results in a large number of organic debris piles at lower flow created by dislodged Russian olive trees.

Reach 4: (RM 107 to 130, Aneth, Utah, to below the "Mixer") is a transitional reach between the upper cobble-dominated reaches and the lower sand-dominated reaches. It has the most bedrock contact of any reach. Sinuosity is moderate compared to other reaches, as is gradient. Island area is higher than in Reach 3 but lower than in Reach 5, and the valley is narrower than in either adjacent reach. Total water surface area is somewhat less at all flows than in the adjacent reaches. River banks are more stable in this reach than in Reach 3, and about the same as in Reaches 5 and 6. Backwaters in this reach are subject to perturbation from summer and fall storm events, but Reach 4 is not considered as responsive as Reach 3. Backwater habitat abundance is low overall in this reach (third lowest among reaches) and there is little clean cobble. Perturbation of secondary channels due to summer and fall storm discharges is a problem in this reach. One perennial tributary, the Mancos River, enters the San Juan River in this reach.

Reach 5: (RM 131 to 154, the "Mixer" to just below Hogback Diversion) is predominantly multi-threaded with the largest total wetted area (TWA) and largest secondary channel area of any of the reaches. Secondary channels tend to be longer and more stable than in Reach 3 but fewer in number overall. Riparian vegetation is more dense in this reach than in lower reaches but less dense than upper reaches. Cobble and gravel are more common in channel banks than sand, and clean cobble areas are more abundant than in lower reaches. Channel gradient in Reach 5 is steeper than in all lower reaches but flatter than Reaches 6 and 7. This is the lowermost reach where adjacent irrigated lands and irrigation return flow influence riparian vegetation and bank stability, and contribute to groundwater accretion. The river valley is broadest in this reach. One perennial tributary, Chaco Wash, enters the San Juan River in this reach. This is the lowermost reach containing a diversion dam (Cudei). This reach is much less subject to perturbation of backwaters and spawning bars during summer and fall storm events than the lower reaches, especially in the upper portion of the reach.

Reach 6: (RM 155 to 180, below Hogback Diversion to confluence with the Animas River) is predominately a single channel, with 50 percent fewer secondary channels than Reaches 3, 4, or 5. Cobble and gravel substrates dominate, and cobble bars with clean interstitial space are more abundant in this reach than in any other. Irrigated land adjoins the river for the full length of this reach, often on both sides of the river. There are four diversion dams that may impede fish passage in this reach (Figure 2.1). Backwater habitat is low in abundance in this reach, with only Reach 2 having less. Gradient is the second steepest of all reaches, although about 10 percent of the elevation change occurs at the diversion dams, making the effective slope about the same as that in Reach 5. Two tributaries enter in this reach: the LaPlata River which carries little water to the San Juan River except during runoff, and the Animas River which is the largest tributary to the San Juan River in the study area. A third tributary, the Ojo Amarillo, is naturally ephemeral but is effectively perennial at present due to irrigation return flow. Irrigation return flow influences riparian vegetation and groundwater accretion in this reach. The channel has been altered by dike construction in several areas to control lateral channel movement and overbank flow.

Reach 7: (RM 181 to 213, Animas River confluence to between Blanco and Archuleta, New Mexico) is similar to Reach 6 in terms of channel morphology, with about the same secondary channel count, TWA, and valley width. Irrigated land adjoins most of this reach on both sides of the river, and groundwater accretion contributes to an increase in grass understory. The river channel is very stable in this reach. The reduction in magnitude of peak flows with the construction of Navajo Dam caused a reduction in overall shear stress and a reduced ability to move large-grained embedded cobble. In addition, much of the river bank has been stabilized and/or diked to control lateral movement of the channel and overbank flow. While the dominant substrate type is cobble, armoring has occurred that, coupled with the bank armoring and grass understory, limits availability of new cobble sources within this reach. Water temperature in this reach is influenced by the hypolimnetic release from Navajo Dam and is colder during the summer and warmer in the winter than the natural river. Sediment load is also reduced due to the sediment-trapping influence of the dam and limited tributary influence resulting in relatively clear water compared to downstream reaches.

Reach 8: (RM 213 to 224) is the most directly influenced by Navajo Dam, which is situated at its uppermost end (RM 224). This reach is predominantly a single channel, with only four to eight secondary channels, depending on the flow. This reach has the lowest number and TWA of secondary channels of any reach above the lower canyon (Reaches 1 and 2). The valley narrows in this reach, with less irrigation influence and less artificial stabilization of the channel. Cobble is the dominant substrate type, and because lateral channel movement is less confined in this reach, some loose, clean cobble sources are available from channel banks. In the upper end of the reach just below the dam, the channel has been heavily modified by excavation of material used in dam construction, thus also modifying gradient and channel morphology. In addition, the upper 6.2 mi of this reach above Gubernador Canyon are essentially sediment free, resulting in the clearest water of any reach. Because of Navajo Dam, this area experiences much colder summer and warmer winter temperatures. These cool, clear water conditions have allowed development of an intensively managed blue-ribbon trout fishery to the exclusion of the native species in the uppermost portion of the reach.

River Geometry Analysis

The response of the river to the test flows is best seen in the response in the cross-sections established for this study. The model developed for scour as a function of the previous year's deposition and the total volume of flow during the runoff period is significant and describes 95% of the variability in scour at the RT transects, considering the average change for all cross-sections. The data and the model both indicate that the river is approaching a new dynamic equilibrium, with a 7 - 10% increase in channel cross-sectional area. While not all cross-sections respond the same, the deviations from this model are explained by the conditions at the individual transects.

The mixer and debris field transects are more variable, as would be expected from their locations. However, these transects also show a general trend of scour with time.

To put this change in perspective in the long term, channel response at USGS gage locations were examined. At both the Farmington and Shiprock gages, the historic changes have been greater than anything measured at the transects. During the test flow period, the Shiprock gage shows a trend similar to the study transects, with an initial scour and then relative stability. The Farmington gage did not show any change in trend due to the restored flows. This gage has been in a general trend of deposition since 1942 and that trend is continuing, with a large gravel bar building down from the bridge that is just upstream of the gage. In the case of both gages, the variation in average bed elevation from year to year is less after the dam. However, the dam does not appear to have influenced the general trend at either gage.

Along with the change in bed elevation has come an increase in the percent of cobble substrate with the higher flows. This is especially true following runoff. Much of the exposed cobble is again covered with sand during the non-runoff period, only to be exposed again during runoff. The increase in cobble substrate could lead to increased primary productivity in the system with time.

The relatively strong (r^2 = 82%) correlation between scour and days with flow above 5,000 cfs indicates the ability of these flows to move sediment from the main channel. Other correlations are not strong or are not significant.

The analysis of cobble movement vs flowrate, indicates that some cobble moves, especially in the higher gradient areas over bars, at 2,500 cfs or less. Since no measurements were taken in periods when the flow did not exceed 2,500 cfs, it has been assumed that 2,500 cfs is the threshold for moving cobble to provide open interstitial space on existing bars. It is likely that some cobble moves at flows lower than 2,500 cfs on many bars, but the data are not available to verify that hypothesis. While the 2,500 cfs may be considered a conservative (high) estimate of the required flow, the amount of cobble movement below 2,500 cfs would likely diminish the available clean cobble for spawning. Since this is not a particularly difficult flow to achieve, sufficient cobble movement to provide suitable spawning occurs nearly every year.

The trend of cumulative scour at the cross-sections suggests the potential for channel simplification as secondary channels are isolated at lower flows. Analysis of the trend in island count at low flow through 1994 suggested that some simplification was occurring. In 1995, this trend reversed, with an increase in islands in response to out-of-bank flows. Since the island count has seen no net change over the test period, channel simplification is not likely to occur with mimicry of the natural hydrograph, as long as periodic out-of-bank flows occur. Since this conclusion is based on a short period of record, continued monitoring is recommended to verify that the channel is not being simplified.

The scour that has occurred has resulted in an increase in bankfull channel capacity of about 12% over the research period to an average flow of about 8,000 cfs. Since the bankfull channel area is still much less than during pre-dam conditions, the historic bankfull capacity was likely greater than 8,000 cfs, although now measurements have been made to quantify the historic bankfull discharge.

Cobble Bar Characterization

Characterization of cobble bars in the San Juan River indicates that there are multiple locations that have characteristics similar to the Yampa spawning bar in terms of cobble size distribution, suggesting that they are suitable for spawning as well. Cobble bar sampling from RM 76 to RM 173 indicated that the size of cobble does not change with distance down river in the bars sampled. Since the channel gradient and discharge do not change appreciably in the area studied, the consistency of cobble size is not surprising.

Also not surprising is the finding that the bars increase in the depth of open interstitial space with distance up-river. The finding coincides with the geomorphological characterization and habitat mapping that indicate an increase in abundance of sand substrate with distance downstream..

While the area of bars that contain appreciable depth of open interstitial space changes from year-to-year in response to cleaning and subsequent filling by sediment laden storm events, in all years surveyed, areas of open interstitial space in excess of two mean cobble diameters existed. The area diminished in years of low runoff or in situations of storm events occurring before the survey was completed, but was always present.

Based on an assumption that open interstitial depth of 2 mean cobble diameters is adequate for spawning, it appears that in all survey years suitable gravels in locations that exhibit the physical characteristics associated with spawning in 1994 were available for locations above RM 131. Conditions below RM 131 are less suitable, but not proven to be inadequate.

Flows to Support Cobble Transport

Based on the results of the studies conducted to date, it is concluded that sufficient local cobble movement exists to provide some clean cobble for spawning with flows of 2,500 cfs or higher for a duration of at least 10 days prior to spawning. The threshold flow of 2,500 cfs is determined from

data in Table 3.22 indicating cobble movement at flows at or below 2,500 cfs. The 10-day duration is based on qualitative assessment of the data in Table 3.22, coupled with field observation of bar reshaping. Duration of flows at about 2,500 cfs for as little as 1 day indicate cobble movement, but there were extended periods at marginally lower flows, as these conditions typically occurred between the summer and following spring measurements. The March to July 1996 period demonstrated substantial cobble movement with 36 days above 2,500 cfs, and March to May 1994 indicated large cobble movement in the Mixer with 14 days above 2,500 cfs, although flows exceeded 5,000 cfs for this period. While no data precisely indicate the minimum required duration, the 10-day duration was selected as the minimum threshold because it falls within the results summarized above and is considered reasonable based on field observation. Longer durations at somewhat lower flows may serve the same function as indicated by the pre-runoff conditions in 1996, but there is insufficient information to conclude threshold conditions lower than 2,500 cfs.

The bankfull flow of 8,000 cfs was selected as the flow required for cobble transport and bar building based on model results of the four research reaches reported in Table 3.31, and flow calculations at the RT cross-sections; it is qualitatively supported by the decrease in island area and count at flows somewhere between 6,500 and 7,700 cfs (Figure 3.29). Examination of the cobble movement data reported in Table 3.22 suggests an 8-day duration as appropriate for the minimum duration necessary for bar-building cobble transport. This minimum duration is based on the channel cross-section data indicating measurable cobble movement with as few as 3 days at 8,000 cfs and substantial cobble movement after 13 days. The two durations were averaged to arrive at the recommended value. The flow/duration criteria were analyzed for adequacy of channel maintenance by examining historical conditions since the closure of Navajo Dam. During this time period, cross-section surveys indicated a narrowing and deepening of the channel, especially in the higher reaches (5 and 6), with a recurrence frequency of about 1 year in 4 years for flows of 8,000 cfs for 8 days. Since some channel capacity was lost under these conditions, an increase in the average frequency of bankfull flows is needed to prevent further lost capacity and possibly assist in restoring some of the capacity already lost. An average recurrence frequency of 1 year in 3 years (33%) will increase the frequency of conditions necessary for maintenance of channel capacity. Therefore, 8,000 cfs for 8 days with an average recurrence frequency of 1 year in 3 years are the conditions recommended for cobble bar construction and channel maintenance. From a sediment-transport and channel-maintenance standpoint, the full range of flows from 2,500 cfs through 10,000 cfs plays an important role. Mimicking a natural hydrograph that includes flows in this range is necessary. Just providing the conditions required at 8,000 cfs would be inadequate and could lead to channel simplification and armoring over time. Because of the short period of study, monitoring should continue to verify these relationships.

Flows above 10,000 cfs are recommended periodically for maintaining channel complexity and floodplain integrity. The response of islands to flows shown in Figure 3.29 indicates that flows less than 10,000 cfs (1992 to 1994) may result in channel simplification with time unless combined with higher flows that develop new secondary channels and islands through overbank flow (1995). Examination of the flow record indicates a duration of 6 days at Bluff and 11 days at Four Corners, with a resulting increase in islands above pre-research period levels providing conditions that were more than adequate for maintenance of channel complexity. High flows are the most-altered portion

of the natural hydrograph in the San Juan River. Historically, these flows have played a major role in floodplain development. While all the mechanisms of importance have not been identified and quantified during the research period, the general paradigm of natural flow mimicry would not be met without restoration of these higher flows to some degree. Therefore, a conservative threshold requirement of 5 days at or above 10,000 cfs was selected for purposes of natural flow mimicry and maintenance of channel complexity.

The cobble bar maintenance flow (2,500 cfs) should occur at a frequency sufficient to ensure long-term reproductive success of the species of interest. The cobble bar construction flow (8,000 cfs) is needed less frequently if bars are maintained (cleaned and reworked) on a regular interval. Data suggest that the bars can be reworked to provide clean cobble for several years without the necessity of reconstruction or replacement. Channel maintenance requirements indicate an average recurrence of 1 year in 3 years for flows above 8,000 cfs. The 10,000-cfs flow condition is not required as frequently. Historically, it had been 8 years between the occurrence of these conditions (1987 and 1995). Looking at the potential for channel complexity deterioration indicated in Figure 3.29, the required average recurrence frequency for maintenance of channel complexity and floodplain integrity was determined to be 5 years. During the pre-dam period, the 10,000-cfs flow conditions were met 39% of the time (4 years in 10, vs. 2 years in 10 in this recommendation). The reduction in channel capacity that has occurred since the closure of Navajo Dam allows a lower frequency of achieving these conditions. Given the short duration of the studies upon which these recommendations are based, future refinement of the recommendations will likely be necessary, thus requiring an adaptive management approach.

Low Velocity Habitat Maintenance - Measurement of Change in Sand/Cobble Bars

During the course of the research period, no relationship was developed between spring runoff conditions and bedform structural change influencing backwater formation. Studies of bar change did not indicate a relationship between bar height and peak runoff magnitude or volume for the range of flows tested, likely because most peak flows were at or above bankfull where stage and shear stress change little with change in flow. Further, a large percentage of backwaters are associated with secondary channel or tributary mouths. Therefore, the structural studies concentrated on backwater cleaning processes.

Detailed monitoring and modeling of fine sediment transport in two secondary channel associated backwaters indicated flows must be in the 4,000 - 5,000 cfs range to initiate cleaning. Further, flushing is improved by longer durations and higher magnitudes of spring flows. Both backwaters begin to refill with sediment on the descending limb of the hydrograph. Modeling indicated that steeper descending limbs tended to limit the amount of deposition. Summer storm events can fill in these backwaters during heavily perturbating (multiple sediment laden storm events in one season) years. Modeling is very sensitive to sediment concentration and grain size distribution, making it difficult to accurately predict performance in a non-calibration year. So far, each year analyzed has required a separate calibration, with low accuracy of predicted results. For accurate modeling, at

least daily sediment concentration and size distribution would be required. It also may be that sediment transport through the secondary channel forming the backwater has less course material that would result from the bedload in the main channel due to the elevated nature of the inlets of most of these secondary channels. Calibration shows that finer sediment size than measured in the main channel is required to achieve a match with measured channel conditions. For modeling to be effective, more intense sediment concentration data would be needed and possibly a more robust model. The conclusions here are based most strongly on the monitoring data and response to flows rather than the modeling results.

Suspended Sediment Analysis

In any study of fluvial morphology it is desirable to be able to measure sediment inflow and outflow to determine the sediment balance. While this is possible for non-storm influenced periods in the San Juan, it is not practical to measure all the inflows required in the San Juan River due to the numerous inflows. The sediment data collected did indicate that the concentrations measured fall within the range of historic sampling, although averages were on the low side of the historic mean This could represent a shift to lower sediment concentrations, or indicate a sampling bias as the non-runoff period was not sampled.

Sufficient analyses have been completed to now that the system is heavily perturbated by summer and fall storm runoff events, where measured tributary inflow concentrations of total suspended solids (tss) have been as great as 130,000 ppm (13%). These heavy sediment contributions lead to reduced backwater habitat quality and require more frequent flushing to maintain system health.

CONCLUSIONS

History of Fluvial Morphology

- There has been substantial change in the geomorphology of the San Juan River since the early 1930's.
- Much of this change is associated with change in suspended sediment load and in the riparian vegetation community and density.
- A portion of the change, especially in the reduction of channel capacity, has occurred as a result of the modified hydrology as a result of the operation of Navajo Dam
- Data do not exist to determine if the habitat conditions for the fish are better or worse today than at other times in history for the habitat range that is presently available. Given the change in available range, it is clear that there has been a significant overall reduction in available habitat.

Change in Channel Morphology with Test Flows

- Test flows since 1991 have further modified the geomorphology net scour in the system resulting in an increase in channel capacity of about 12%.
- This scour seems to be stabilizing to a new dynamic equilibrium condition, although it is too soon to assure that this is the case.
- The amount of scour is less than the normal range of scour and subsequent deposition that has been observed at USGS gages over the past 50+ years, indicating that there will not be catastrophic change in the channel as a result of continued mimicry of a natural hydrograph.
- Flows at 2,500 cfs or greater transport sufficient cobble on the higher gradient portions of bars to develop clean locations for spawning. A duration of 10 days is adequate, with frequencies sufficient to support regular spawning required.
- Flows greater than 5,000 cfs are associated with scour at the cross-sections measured, with the amount of scour being moderately correlated to days above 5,000 cfs. It is assessed that flows of 5,000 cfs or more for 21 days are adequate to clean backwaters and these conditions should exist at least every other year, on average.
- Bankfull channel capacity is estimated to average about 8,000 cfs between Farmington and Bluff, representing an increase of about 12% during the research period

Cobble Bar Characterization

- Cobble bars exist in the system that appear to have conditions suitable for spawning. The conditions are better above RM 131 than below and are comparable to conditions on the Yampa spawning bar.
- There appears to be ability to transport cobble through low gradient reaches of the system to maintain a sediment balance, although this transport likely occurs at a low rate on average, with local, periodic high rates of transport for short distances.

Low Velocity Habitat Creation and Maintenance

- Surveys of two main channel sand/gravel bars associated with backwaters indicate that the bars were erosional in nature and that high flows created scour along the margin and eventual loss of the backwaters.
- Increased flows did not increase the height of the bars, which did not change appreciably over the course of the study period. This finding is counter to findings in the Green River. Since most peak flows were at or above bankfull, the actual stage did not change markedly from year to year, explaining the reason for the limit on bar height.
- Bar height in Reach 1 did increase, but in response to Lake Powell elevation rather than stage during runoff. Geomorphology of the river in Reach 1 appears to as influenced by lake level as discharge.
- Maintenance of backwaters occurring at the mouths of isolated secondary channels is related to flows above 5,000 cfs, the approximate threshold flow for initiation of flushing of these backwaters.

- These backwaters tend to scour through runoff and refill on the descending limb and during subsequent sediment laden storm events. Steeper descending limbs and longer peak runoff favor cleaner backwaters.

Suspended Sediment Analysis

- Suspended sediment concentration appears to be similar to historic conditions and is typically higher during summer storm events than during spring runoff. Summer storms of small magnitude can generate high sediment concentrations when they originate in small, unprotected watersheds in the lower portion of the basin.
- It was not possible to compute a sediment balance for the study area due to the many small tributaries that contribute large volumes of sediment during short duration storm events.

CHAPTER 4: HABITAT STUDIES

The quantity of aquatic habitat utilized by upper trophic levels is an important factor that must be considered regarding the recovery of endangered fishes in the San Juan River. In the following section of this report, the spatial and temporal distribution of habitats are described in detail. Factors which regulate the formation and persistence of these habitats are also discussed in the context of various hydrologic conditions.

INTRODUCTION

The distribution and abundance of habitat types commonly found in riverine systems are modified by both the magnitude-duration of spring runoff and the amount of base flows during the summer/fall period. The intent of this investigation was to evaluate aquatic habitat in the San Juan River with the specific objective to:

> ***Characterize the distribution and abundance of habitat in the San Juan River and measure the response of habitat to experimental flows.***

During certain times of the year, the rare fishes in the San Juan River utilize specific habitat types. It is therefore important to understand the mechanisms of formation of these habitat types (i.e. backwaters) as well as the factors which regulate their quantity during the critical periods that these habitats are needed by the target species.

METHODS

From 1992 to 1997, aquatic habitat in the San Juan River was mapped thirteen times. Table 4.1 describes the mapping periods, flow ranges and river miles mapped as part of this study. Although mapping occurred over the entire 224 miles from Lake Powell to Navajo Dam, the most intensively mapped reaches were between RM 154 and RM 2 (Reaches 1 to 5). Table 4.2 describes the 36 specific habitats mapped, along with the eight general categories used to group the habitats for statistical analysis.

Mapping occurred in the field using hard copies of aerial videography as base maps. While floating down the river, habitats were drawn as polygons and identified using unique codes. Upon returning to the laboratory, maps were entered into a GIS system for analysis. Processing the data in GIS produced coded polygons (habitats) by which the surface areas were computed and sorted individually. The data was then retrieved and analyzed by cross tabulation (summarized by habitat type by river mile).

Table 4.1. The Hydrologic Characteristics of Each Mapping Run by Geomorphic Reach

		GEOMORPHIC REACH							
MAPPING DATE	**FLOW CATEGORY**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Nov. 16-20, 1992 Dec, 1-5, 1993	low	NM	NM	949	849	952	878	NM	NM
June 4-10, 1993	high	NM	7781	7781	8279	6971	7437	NM	NM
July 19-23, 1993	medium	1078	1078	1078	1010	868	1308	NM	NM
Oct. 28-Nov. 3, 1993	medium	992	992	933	899	931	945	NM	NM
June 13-28, 1994	high	5780	5790	5790	7235	6490	7100	3730	3740
Aug. 19-24, 1994	low	578	626	642	792	845	605	633	633
Nov. 15-18, 1994	medium	1383	1397	1335	1129	1041	1045	NM	NM
Apr. 11-16, 1995	medium	3055	3215	3300	3045	3300	3135	2550	2550
Sept. 4-7, 1995 Oct. 4-16, 1995	medium	1430	1205	1029	1080	961	1265	815	796
Jan. 22-26, 1996	low	589	584	582	639	524	608	252	252
June 4-10, 1996	medium	3230	3210	3105	3440	3230	3445	NM	NM
Oct. 23-26, 1996	medium	1130	1123	1125	1010	1060	1225	NM	NM
Nov. 17-Dec. 2, 1997	medium	1168	1134	1137	1155	931	905	NM	NM

NM=not mapped

Table 4.2. The Detailed Habitat Types and the Eight General Categories on the San Juan River

HABITAT CATEGORY	HABITAT TYPE
Low Velocity	pool debris pool rootwad pool eddy edge pool riffle eddy
Run	shoal/run run scour run shore run undercut run run/riffle
Riffle	riffle shore riffle riffle chute shoal/ riffle chute rapid
Backwater	backwater backwater pool embayment
Shoal	sand shoal cobble shoal
Slackwater	slackwater pocket water
Vegetation Associated	overhanging vegetation inundated vegetation
Other	isolated pool cobble bar rootwad pile abandoned channel (dry) sand bar tributary island irrigation return boulders

RESULTS

The thirty-six habitat types were mapped thirteen times on a river-wide basis. In order to demonstrate the major differences in habitat quantity, the data were summarized first by river mile for major habitats. These data for a high (greater than 7000 cfs), medium (3000 cfs), and low (less than 700 cfs) flow mapping run can be seen in Figures 4.1 and 4.2. Figure 4.1 clearly shows that run habitats dominate the total surface area of habitats. On a broad scale, the canyon reaches (Reaches 1 and 2) had comparable total wetted areas when compared to the upper river reaches (Reaches 6, 7, and 8). However, the middle geomorphic reaches (Reaches 3, 4, and 5) had significantly greater total available habitat areas (Figure 4.3). In addition, the total wetted areas (TWA) for these reaches had significant linear relationships with flow, with TWA increasing as flow increased.

On a river-wide basis (Reaches 1-6), inspection of the habitat types presented in Figures 4.1 and 4.2 shows that both runs and inundated vegetation increase dramatically from low to high flow mapping runs (Figure 4.4). This is verified by plotting the density of run and inundated vegetation habitats (m^2 from Reaches 1 through 6). As can be seen in Figure 4.5, both habitats have positive linear or curve linear relationships with flow. Shoal and riffle habitats have the opposite trend with increasing surface areas with decreasing flows. Shoals show a strongly decreasing pattern even through the highest flow mapped (Figure 4.6). Riffles had a similar decreasing pattern except they increased slightly at higher flow (greater than 7,000 cfs).

Low velocity habitat types had two component habitats that responded differently to increasing flows (Figure 4.7). Pool habitats decreased significantly with flow, while eddies had a significant linear increase (r^2=0.90). Slackwaters, although changing locations in the river with flows, did not change in magnitude and did not have a relationship with flow (Figure 4.8).

Backwaters, which are an extremely rare habitat type when expressed as surface area, are critical for the rare and native fishes in the San Juan River. Their distribution and magnitude was found to be highly variable. Their relationship with flow varied by geomorphic reach, as well as the location within the channel. For example, in Reaches 1 and 2, backwaters were found to be associated with main channel sandbars or side canyon mouths, both of which had different relationships with flow (Figure 4.9). In the non-canyon reaches where there are multiple channels, Reaches 3, 4 and 5 have very complex relationships with flow (Figure 4.10). These relationships, although having the same basic form, vary by reach. In these three reaches, at very low flows, backwater surface areas decrease. At flows between 700-1000 cfs, the areas are at a maximum. With increasing flows, these backwaters decrease in area, reaching minimum values when flows were between 2000 and 3000 cfs, depending upon the reach. At flows greater than 3500 cfs, backwater area again increases. It is believed that these relationships reflect the gain and/or loss of main channel bar, and secondary channel associated backwaters as flows increase.

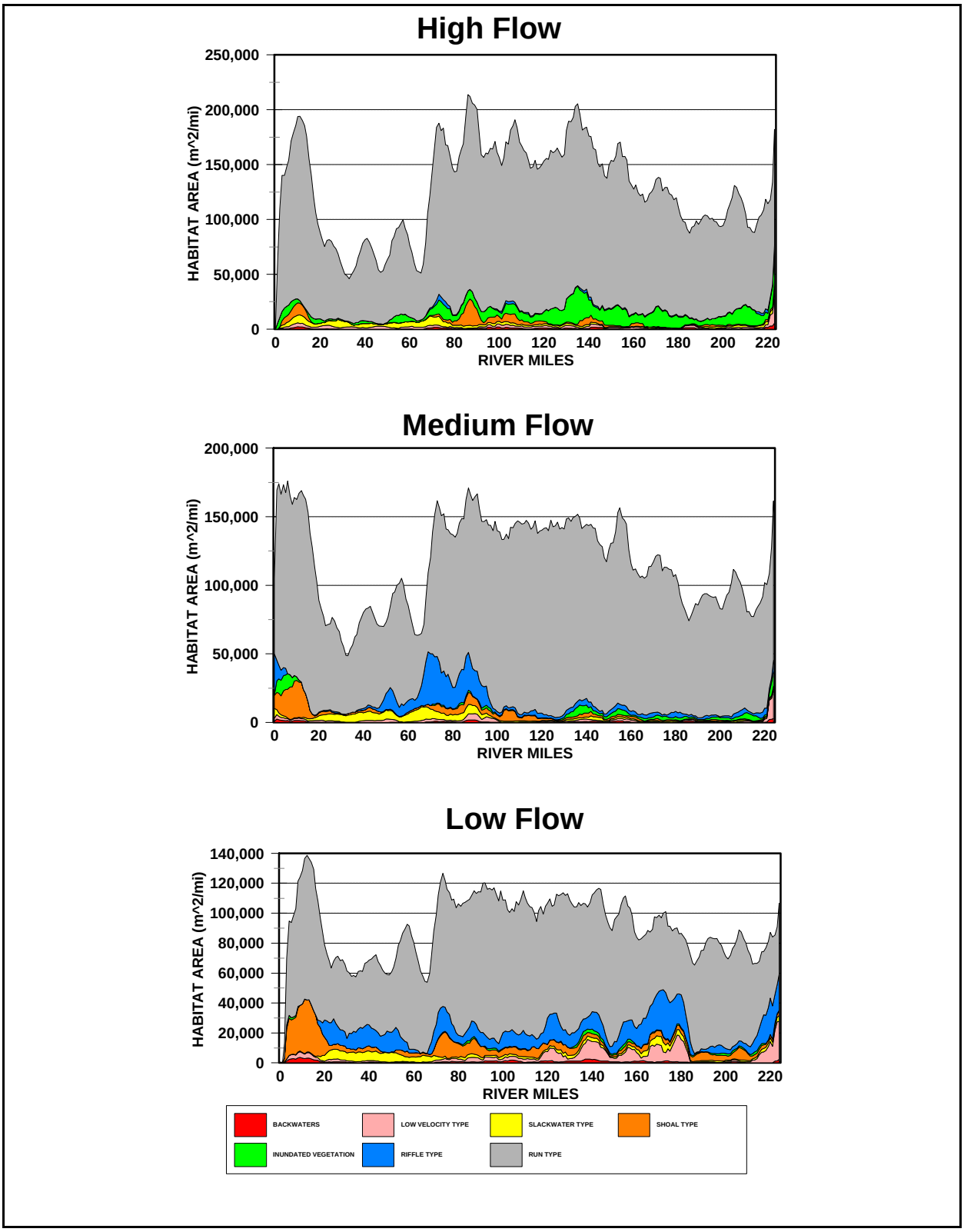


Figure 4.1. The Spatial Distribution of the Seven Major Habitat Types (Excluding "Other") in the San Juan River for Three Flow Regimes

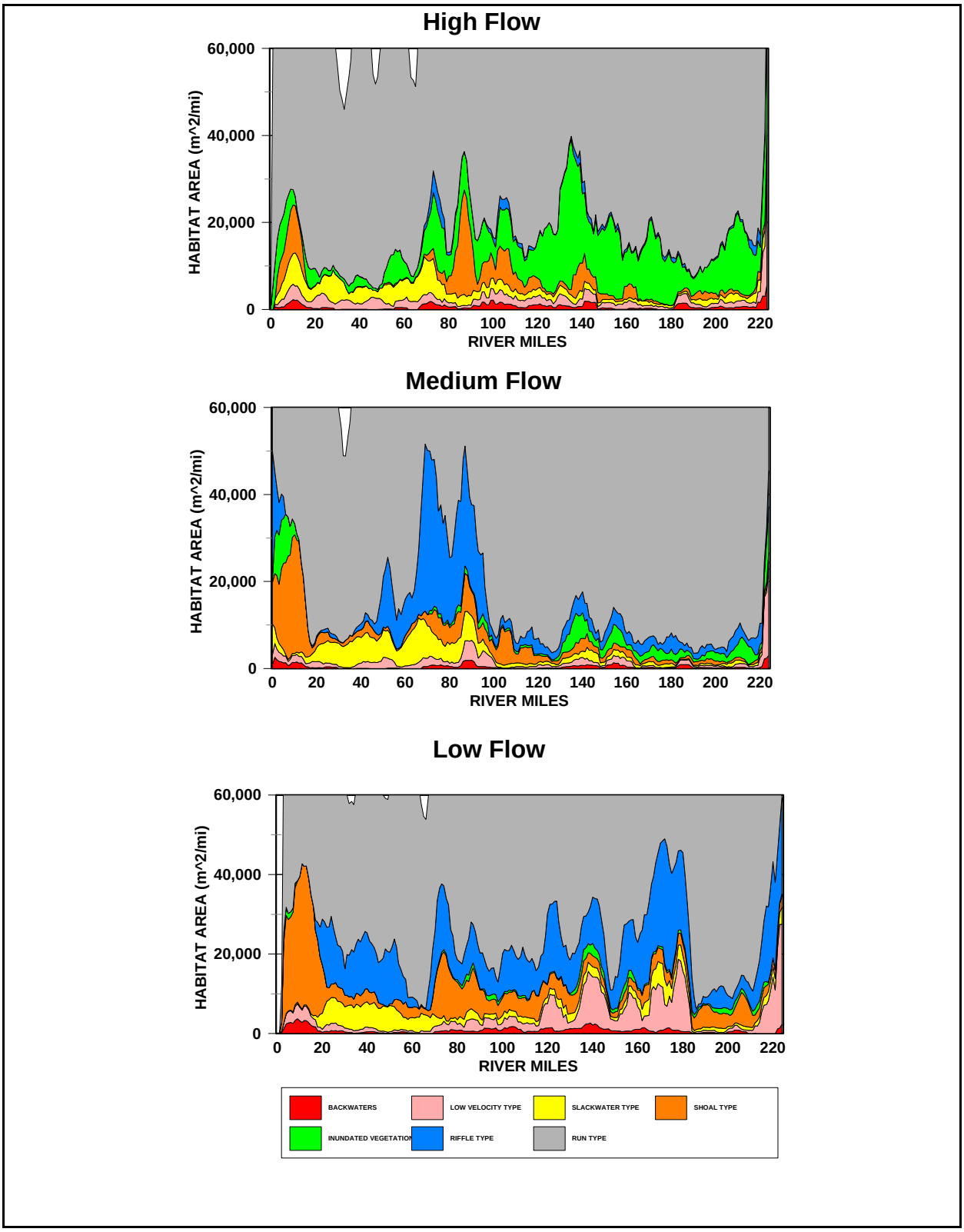


Figure 4.2. The Spatial Distribution of Seven Habitat Categories in the San Juan River with Expanded Scales to Allow Viewing Minor Categories

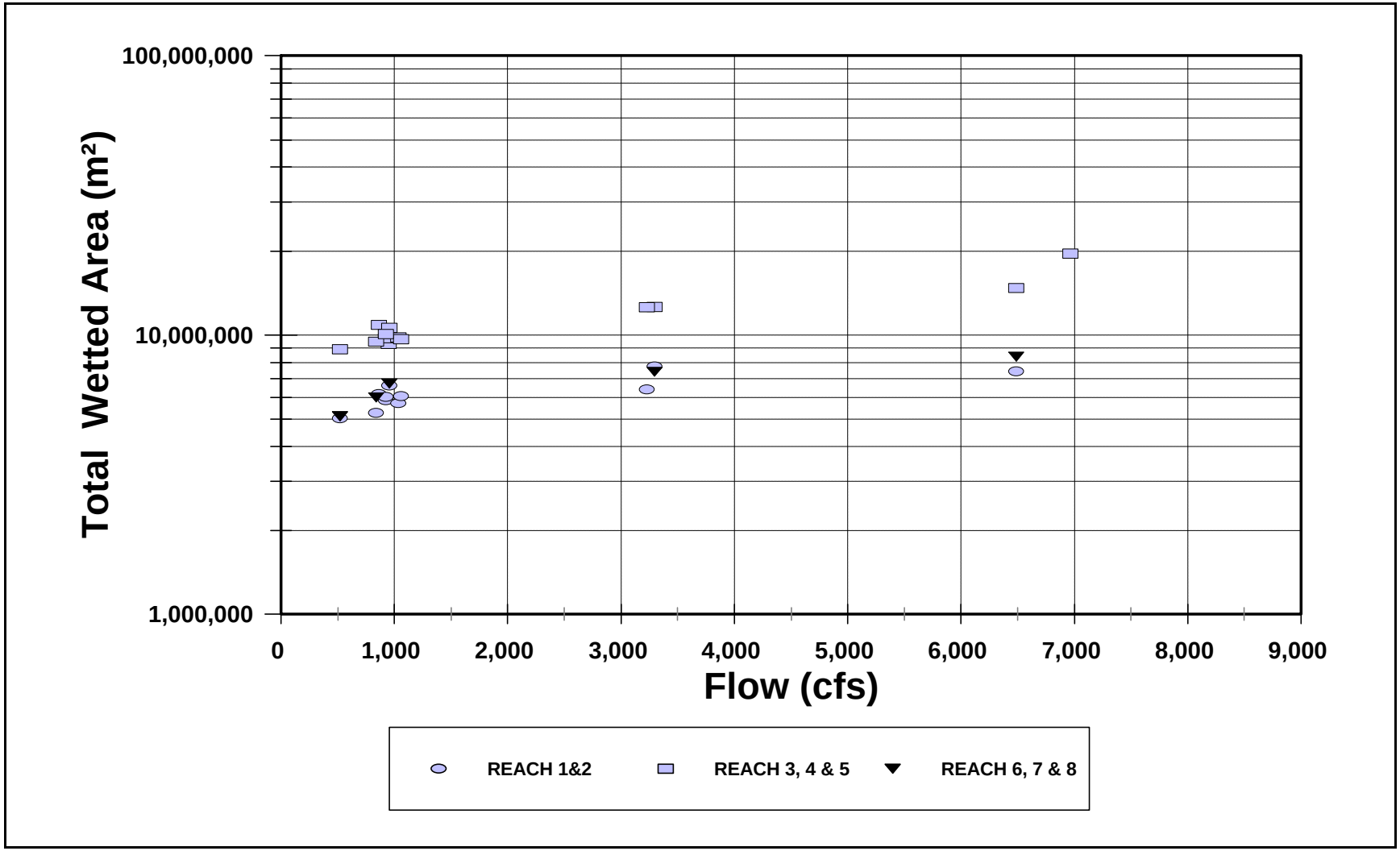


Figure 4.3. The Total Wetted Area vs. Flow Relationships for the Three Combinations of Geomorphic Reaches

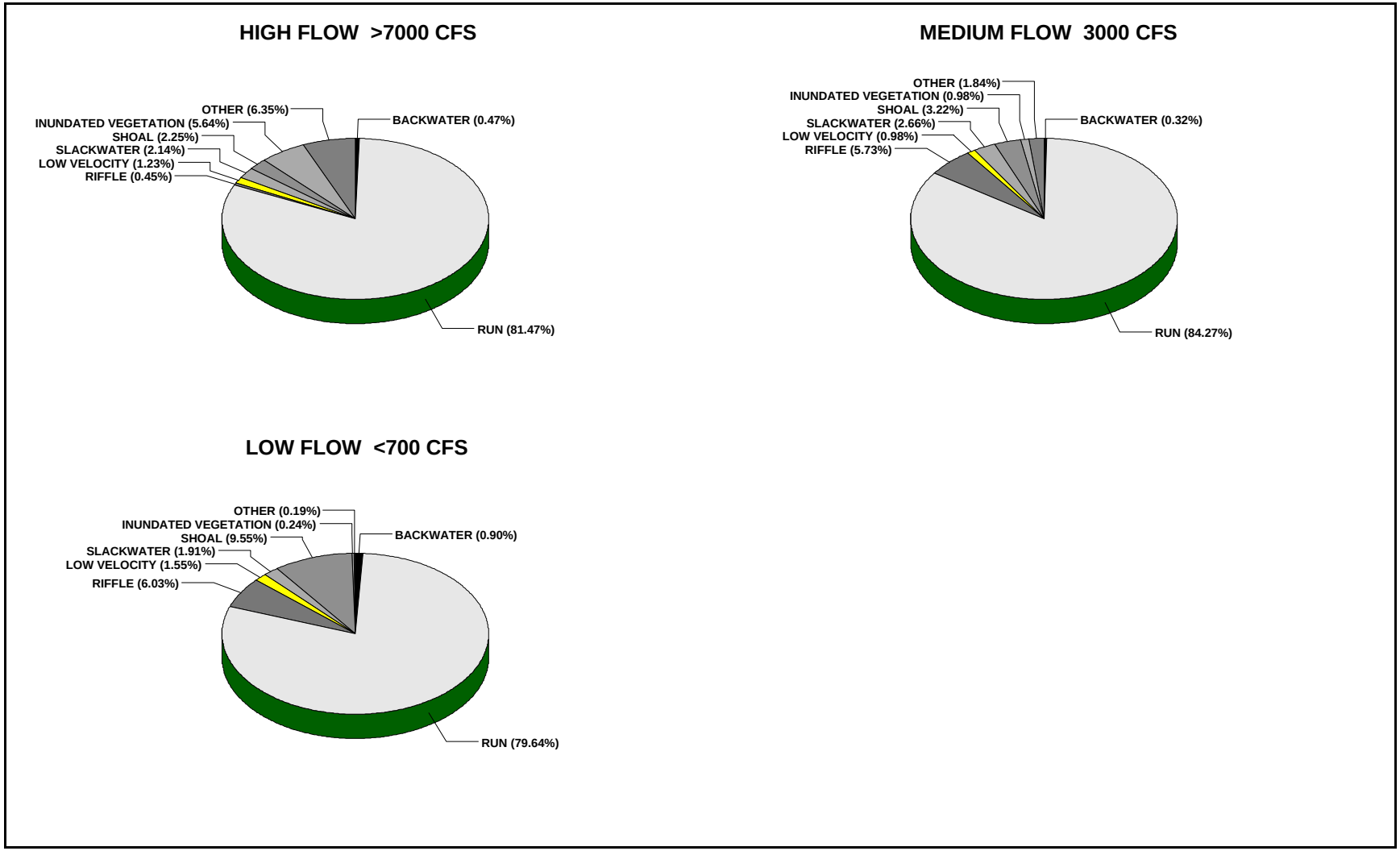


Figure 4.4. A Summary of the Major Habitat Categories as a Percent of Total Wetted Area for a High, Medium and Low Flow Period

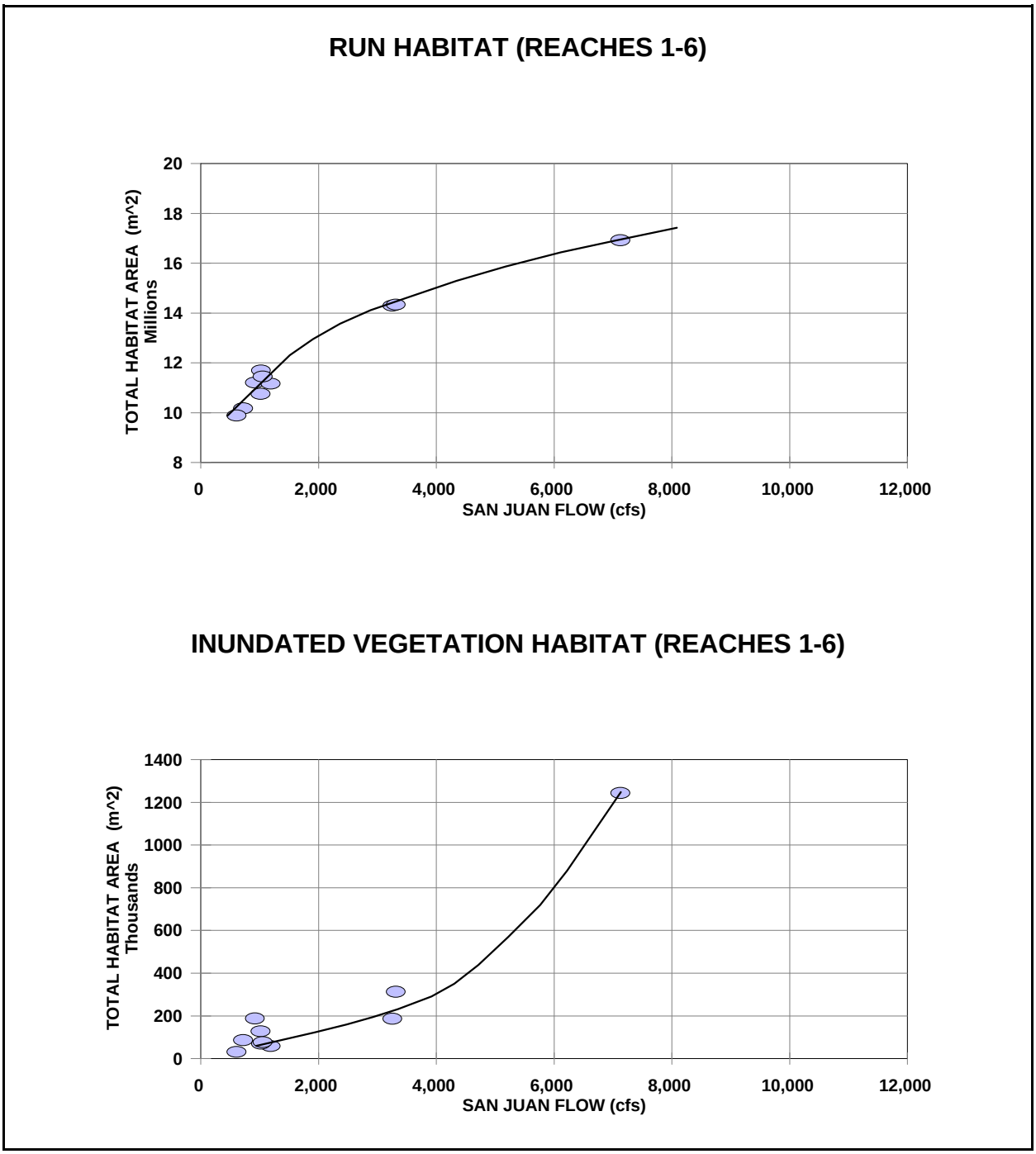


Figure 4.5 **The Comparison Between Habitat Area (M2) and Mapping Flow for the Sum of Reaches 1 Through 6 in the San Juan River for Runs (above) and Inundated Vegetation (below)**

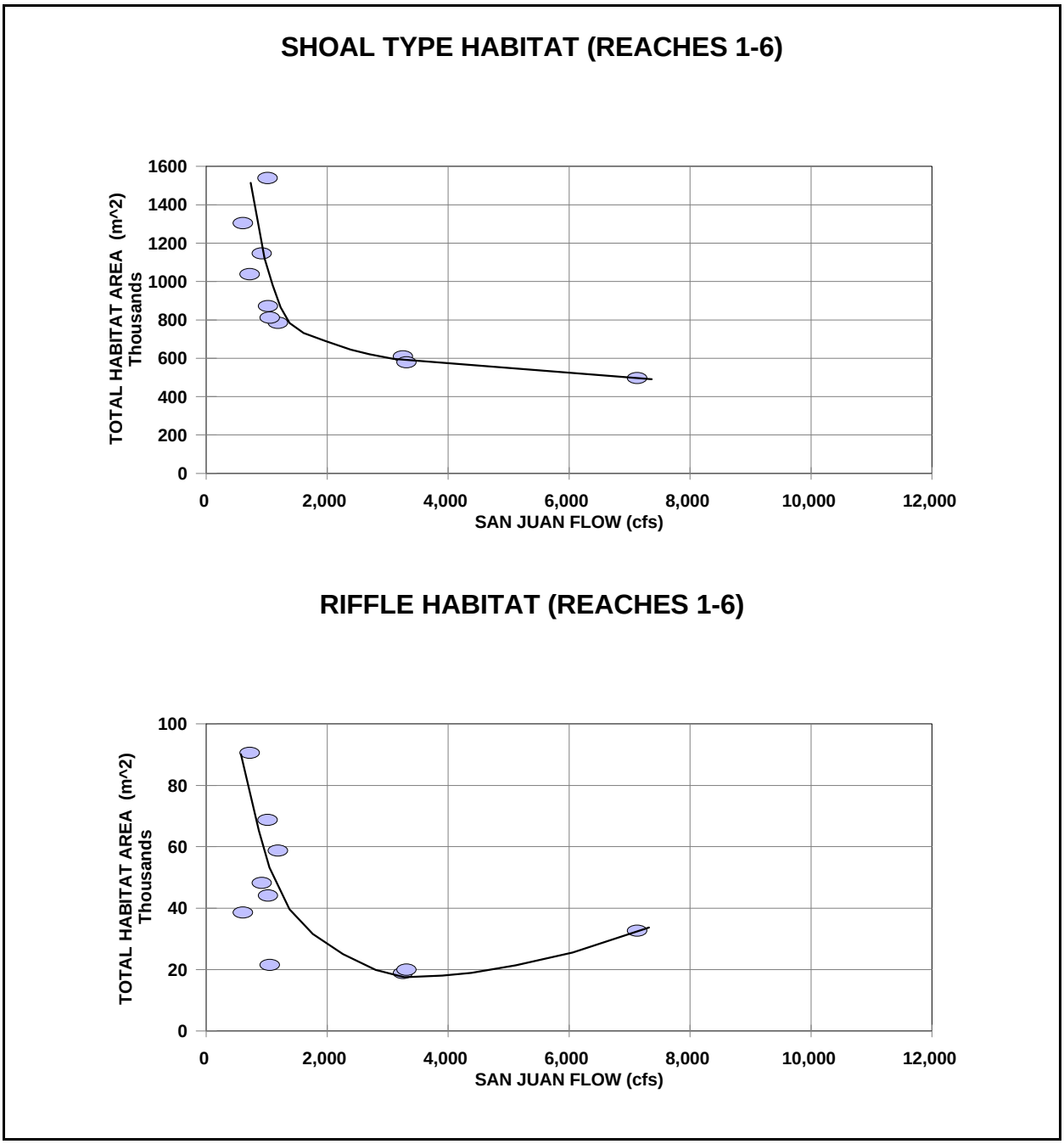


Figure 4.6. The Comparison Between Habitat Area (m2) and Mapping Flow for the Sum of Reaches 1 Through 6 in the San Juan River for Shoal Types (above) and Riffles (below)

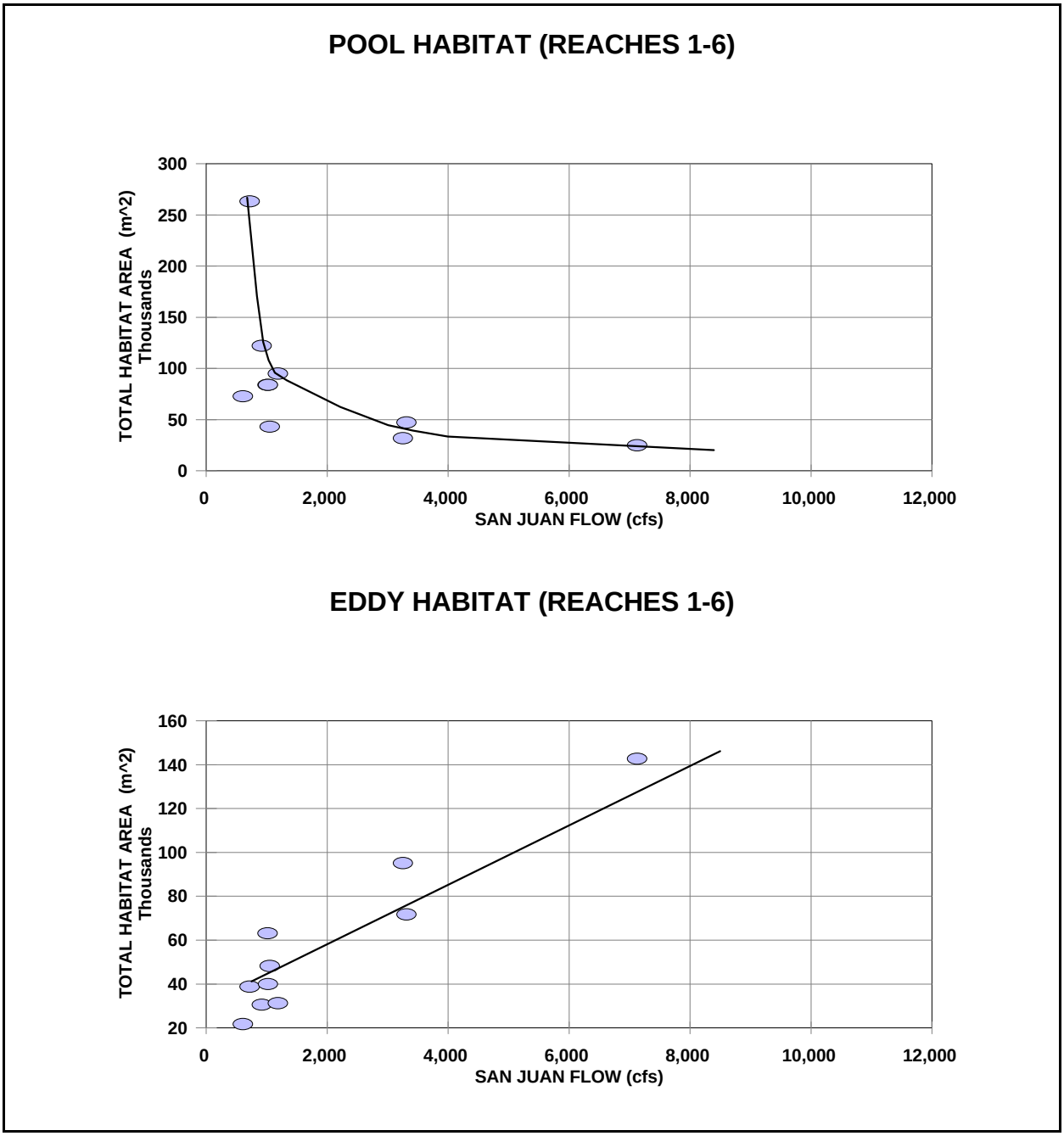


Figure 4.7. The Comparison Between Habitat Area (m2) and Mapping Flow for the Sum of Reaches 1 Through 6 in the San Juan River for Pools (above) and Eddies (below)

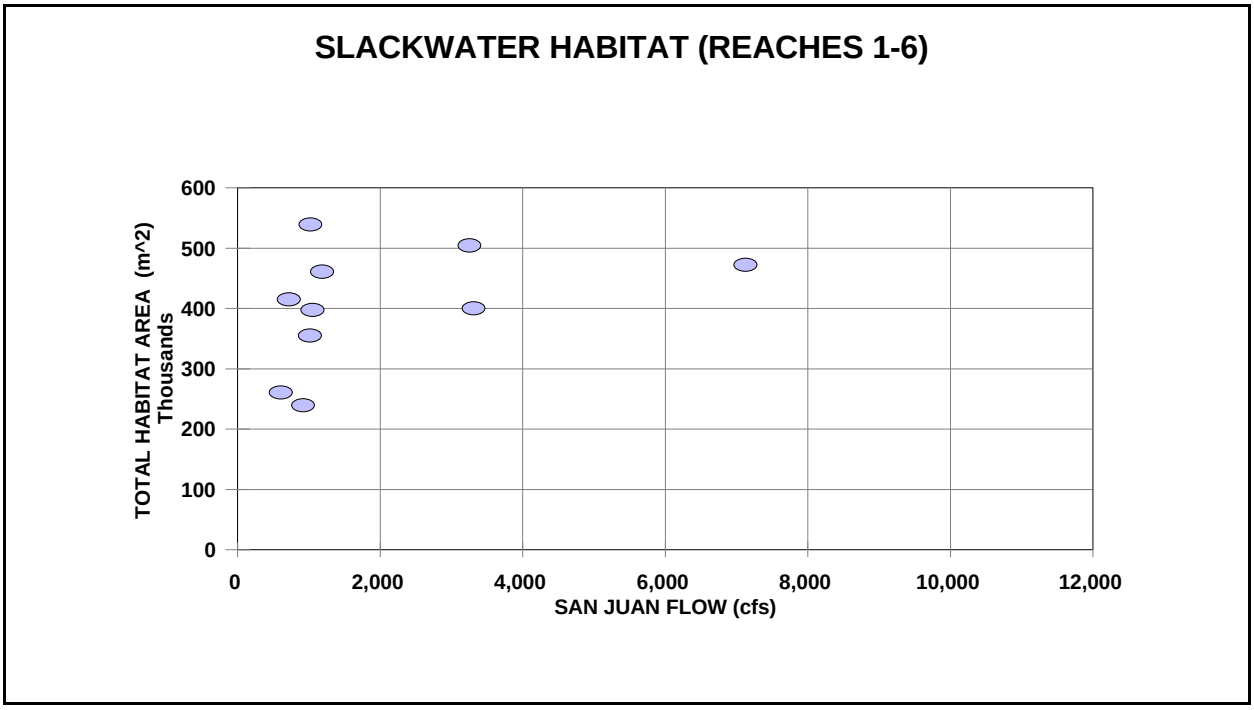


Figure 4.8. **The Comparison Between Habitat Area (m2) and Mapping Flow for the Sum of Reaches 1 Through 6 in the San Juan River for Slackwaters**

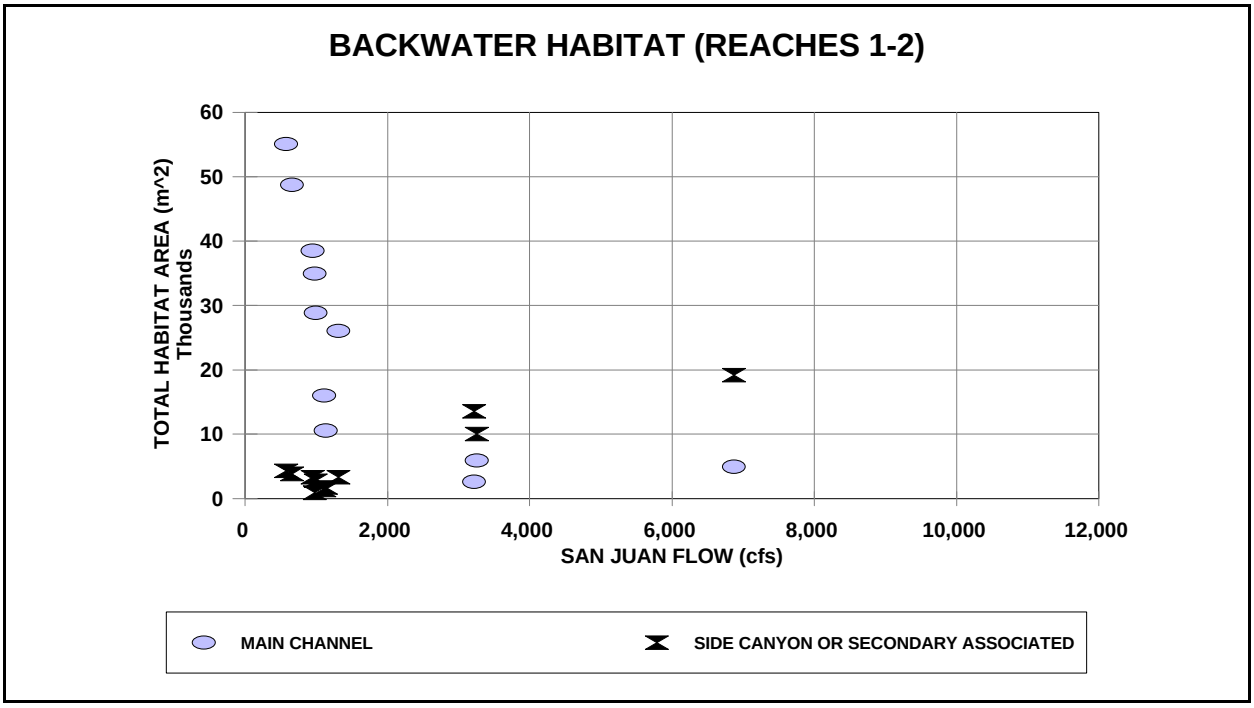


Figure 4.9. **The Relationship Between Backwater Surface Area and Flow for Reaches 1 and 2 Based upon Location Within the Channel**

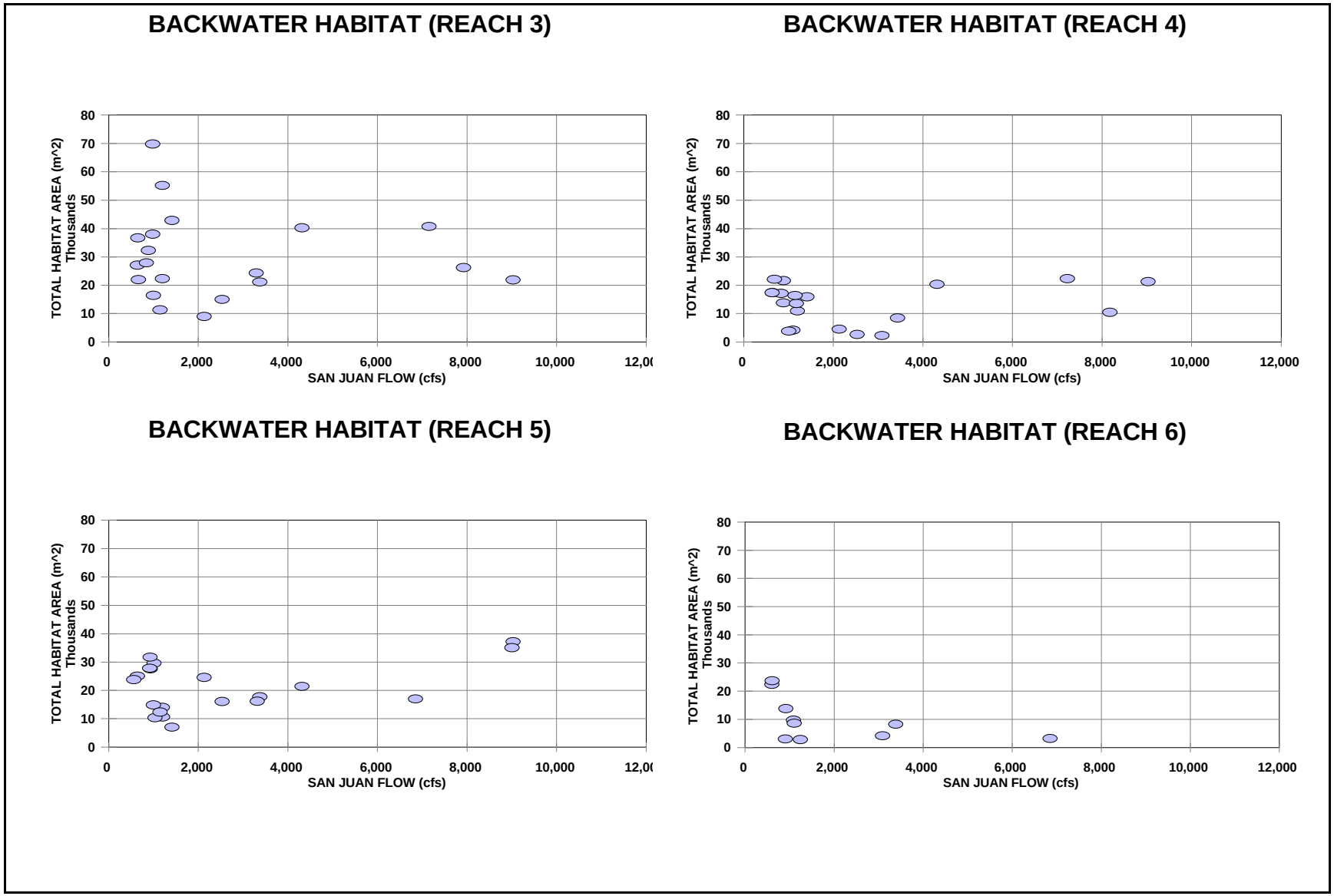


Figure 4.10. The Relationship Between Backwater Surface Area and Flow for Reaches 3, 4, 5 and 6 in the San Juan River

In Reach 6, backwater decreased with flows similar to the main channel backwaters in Reaches 1 and 2. This is consistent with the largely single channel (or channelized) form in this reach, which makes it similar to the canyon bound Reaches 1 and 2.

As noted previously, run type habitats were the most common for all San Juan River flow levels. These habitat types were 81.5%, 84.3%, and 79.6% of the TWA for the high-,medium-, and low-flow mapping runs, respectively (Figure 4.4).

Riffle and shoal habitat types represented the second most abundant habitat types found in the San Juan River at medium and low flows. Riffle habitats were found to be 5.7% at medium flows and 6.0% at low flows, while shoals were 3.2% and 9.5% for medium and low flows. At high flows, riffles and shoals were only 0.5% and 2.3% of the TWA, respectively. However, inundated vegetation was 5.6% of the TWA at high flows, the only flows where this habitat type was greater than 1% of the TWA.

Slackwaters and low-velocity habitats (embayments, eddies, pools, etc.) together made up 3.4% of high-flow habitats, 3.6% of medium flows, and 3.5% of low flows. Backwater types had the lowest overall percent of TWAs with 0.5%, 0.3%, and 0.9% for high, medium, and low flows, respectively.

Many of the habitats that are relatively rare in the San Juan River are used to a large degree by the native fish species. Though they are rare, the quantity of many of these habitats varies with flow. As noted in Figure 4.4, low-velocity habitat quantity makes up a larger amount of the available habitat at low flows (1.55% of habitat), and is lowest at intermediate flows (0.98% of habitat). Backwaters, as a percent of total habitat, nearly double (0.47% to 0.90% of habitat) from high flows (greater than 7,000 cfs) to low flows (less than 700 cfs). The percent of shoal area also dramatically increases at low flows (2.25% to 9.55% of habitat) compared with high flows.

In summary, habitat quantity varies in the San Juan River with both flow level and location in the river. Run habitats dominate, and many of the other habitats important to the native fish community are relatively rare in the system.

DISCUSSION

The analysis of the habitat surface area and flows described above indicates that the surface areas of habitats used by Colorado pikeminnow and razorback sucker, as well as other native species, varied significantly with the flows measured at the time of habitat mapping. In addition, the quantity of habitat from year to year was believed to be dependent upon the hydrologic conditions necessary to form and maintain the habitat.

For backwater habitat, a critical habitat for YOY pikeminnow, the flow/habitat area relationship was also found to vary between geomorphic reaches of the river. In order to evaluate the physical response and mechanism of formation of these habitat types to total area, each habitat type was normalized to 1,000 cfs and compared with runoff conditions immediately preceding each respective mapping period.

The normalization process utilized the following procedure: for each runoff cycle (baseflow-runoff-baseflow) sequential mapping dates were plotted as hysterysis loops. Because backwater habitat area was very sensitive to flow, for each year post runoff backwater habitat area was interpolated to 1000 cfs along the hysterysis loop.

In November 1992 and 1993, mapping occurred near 1000 cfs, therefore, normalization of these data were minimal.

The hydrologic characteristics (Figure 2.5) for each year from 1991 to 1997 were analyzed relative to their impact on backwater habitat surface areas (Table 4.3). At least one mapping session was conducted after each spring runoff period, and four years (1992, 1993, 1994, and 1996) included replicate data. Although an attempt was made to investigate unique features of these hydrographs, initial analysis indicated substantial auto-correlations among several characteristics. In total, 71% of the parameter pairs were auto correlated. These analyses suggest strongly that both the duration and magnitude of the runoff are important for providing backwater habitat in the subsequent summer/fall session.

As noted in the previous section, analysis of backwater habitat areas indicated that the flow/habitat area relationships in geomorphic Reaches 1, 2 and 6 (Figure 1.1) were similar, while Reaches 3, 4, and 5 were different. Further analysis indicated that within Reaches 1 and 2, the type of backwater (i.e. main channel or side canyon associated) was also an important factor in the flow/habitat relationship.

Table 4.3. A Comparison of Significant Correlations (P#0.05) Between the Hydrologic Parameters Investigated for Antecedent Conditions Relative to Backwater Surface Areas

PARAMETER	% AUTO-CORRELATED
Total Days [(a)] >3000 cfs	89
Days Pre-peak >3000 cfs	67
Total Days >5000 cfs	78
Days Pre-peak >5000 cfs	55
Total Days >8000 cfs	78
Days Pre-peak >8000 cfs	67
Total Days >10,000 cfs	33
Peak (cfs)	89
Total Run-off volume (ac-ft)	89
Duration	89
TOTAL	**71**

(a) Total days and days pre-peak are summarized between April 1 and July 31.

Within Reaches 3, 4, and 5, backwater locations were associated with two different geomorphic processes categorized broadly into main or secondary channel processes. Backwaters were formed through shoreline scour of sand bars, recirculation in main channel processes, or backwaters formed at the entrance or exit of ephemeral secondary channels. These two backwater types (main channel vs. secondary channel) were analyzed separately in Reaches 3, 4, and 5.

The coefficients of determination (r^2) for backwater habitats normalized to 1,000 cfs compared with antecedent runoff conditions at the time of mapping (Figure 2.5) are summarized in Table 4.4.

A statistical analysis of the relationship between backwater quantity and hydrologic characteristics (Table 4.4) indicated that within Reaches 1 and 2, total backwater area was not related to hydrologic characteristics regardless of backwater type. Although significant relationships were not found, trends in the data were evident (Figure 4.9). In Reaches 3, 4, and 5, main channel backwaters were not related to hydrologic conditions; however, secondary channel associated backwaters in these reaches were significantly related to all days above 3,000 and 8,000 cfs, as well as total runoff volume. For all backwaters (Reaches 3, 4, and 5) all hydrologic factors were bound to be significant(coefficients of determination 0.95 to 0.91).

In summary, the significant relationships shown in Table 4.4 indicate that hydrologic conditions significantly impact the amount of backwater habitats formed through secondary channel processes; however, because of the auto-correlations between hydrologic parameters, it is difficult to determine if one characteristic has a greater influence than any other. Because the backwaters associated with secondary channels are the dominant component of the regressions in Table 4.4, those factors that affect secondary channel modification may also drive backwater habitat area. For example, results from channel morphology studies on secondary channels indicate that flows exceeding 5,000 cfs initiate secondary channel flushing. Consequently, days above 5,000 cfs may be a driving factor for backwater quantity.

Backwater habitats demonstrated a high degree of variability at low flows. The degree of this variability was different for each geomorphic reach with Reaches 3 and 4 being highly variable. Inspection of the GIS database indicated that specific backwaters would vary in size dependant upon the number of summer storms. In order to further investigate this mechanism, an analysis of storm impacts was undertaken. Part of that effort was to develop a perturbation model for San Juan River backwaters.

Table 4.4. the Coefficient of Determination Expressed as r^2 and Their Associated p Values for Backwater Habitat Area Normalized to 1000 Cfs Compared to Various Antecedent Hydrologic Conditions

Reach	Location	HYDROLOGIC CONDITIONS [a]					
		Days > 3000 cfs	Days > 5000 cfs	Days > 8000 cfs	Peak Flow (cfs)	Total Runoff Volume (ac-ft^2)	Duration (Days)
1-2	Main Channel	0.58 (0.15)	0.15 (0.99)	0.64 (0.56)	0.60 (0.35)	0.63 (0.12)	0.44 (0.22)
1-2	Abandoned Secondary Associated	0.47 (0.28)	0.47 (0.21)	0.52 (0.38)	0.49 (0.80)	0.43 (0.35)	0.38 (0.85)
1-2	All Backwaters	0.60 (0.13)	0.16 (0.89)	0.63 (0.68)	0.61 (0.98)	0.64 (0.12)	0.39 (0.26)
3-5	Main Channel	0.34 (0.15)	0.12 (0.89)	0.36 (0.52)	0.23 (0.41)	0.38 (0.11)	0.04 (0.67)
3-5	Abandoned Secondary Associated	0.95 (0.002)	0.85 (0.07)	0.91 (0.005)	0.88 (0.22)	0.92 (0.009)	0.76 (0.14)
3-5	All Backwaters	0.95 (0.04)	0.89 (0.02)	0.85 (0.006)	0.91 (0.03)	0.93 (0.05)	0.81 (0.003)
1-4	Main Channel	0.28 (0.42)	0.22 (0.60)	0.39 (0.50)	0.43 (0.32)	0.33 (0.37)	0.55 (0.17)
1-4	Abandoned Secondary Associated	0.92 (0.05)	0.87 (0.19)	0.91 (0.16)	0.89 (0.52)	0.85 (0.16)	0.89 (0.10)
1-4	All Backwaters	0.85 (0.13)	0.73 (0.63)	0.83 (0.63)	0.82 (0.17)	0.87 (0.13)	0.84 (0.07)
1-5	Main Channel	0.54 (0.24)	0.31 (0.93)	0.57 (0.55)	0.68 (0.24)	0.59 (0.21)	0.61 (0.21)
1-5	Abandoned Secondary Associated	0.93 (0.04)	0.77 (0.82)	0.93 (0.18)	0.84 (0.47)	0.93 (0.06)	0.84 (0.13)
1-5	All Backwaters	0.90 (0.05)	0.73 (0.42)	0.89 (0.43)	0.86 (0.21)	0.92 (0.05)	0.81 (0.10)

(a) Between April 1 and July 31.

As a first step, flow/habitat relationships for backwaters were developed for each of Reaches 1 to 6. Because Reaches 3 and 4 were easily filled with sediment by summer/fall storm events, two relationships were developed. The first relationship was developed using data for which no perturbating storms occurred between the end of runoff and mapping. The second relationship was developed from a perturbation model relating the number of storm-event days to the amount of habitat area lost.

A storm-event day was defined as a day when the daily gain in flow between Farmington, New Mexico, and Bluff, Utah, and the daily flow at Bluff, Utah, were each more than 150 cfs greater than the preceding 5-day average. A storm-event day was given a weight of 2 if the gain in flow was 3,000 cfs or more. These two parameters were selected based on calibration against known storm events in the last 3 years, optimizing for the number of storm events accurately predicted. There were 19 storm events with sediment concentration measurements during the 7-year research period of which 16, or 84%, were predicted with the model. The three storm events that were not predicted had elevated sediment concentrations with a very small change in flow. There was no statistically significant relationship between sediment concentration and flow for these 19 storm events.

Based on this model, the perturbating storm events were predicted for each month for the period August through December, measured by the weighted storm event days. For each habitat mapping, the number of storm-event days was computed between the end of runoff and the time of mapping. Habitat-mapping data were grouped into three categories: (1) nonperturbated and flushed (runoff adequate to clean backwaters), (2) nonperturbated and not flushed, and (3) perturbated. A flow/habitat relationship was developed for each reach utilizing the nonperturbated measurements. A second curve was developed for Reaches 3 and 4 for nonflushed conditions. The average perturbation (loss of habitat area) per weighted event day was computed for Reaches 3 and 4 by comparing the measured habitat area with the prediction of the flow/habitat model for nonperturbated conditions and dividing the average loss by the average number of weighted event days for that reach. By this process, it was found that Reach 3 lost 6% of the habitat area for every weighted event day, and Reach 4 lost 5%. The other reaches did not show a consistent trend, indicating that the variability of data from the model is random rather than associated with perturbation. Figure 4.11 shows the individual data points and model curves for Reach 3. Figure 4.12 presents the combined model curves for Reaches 1 to 4 (flushed and nonflushed) and Reaches 1 to 5 (flushed and nonflushed).

In application, if runoff flows exceeded 5,000 cfs for 21 days or more, then the flushed model was used, and the average habitat available for the month was predicted to be that available at the mean monthly flow, less the perturbations to date. If the runoff flows were over 5,000 cfs for 1 day but less than 21 days, the post-runoff maximum was linearly interpolated between the nonflushed and flushed curves and then perturbated as above. If runoff flows did not exceed 5,000 cfs, then the previous December value was used as the new base from which to perturbate. In all cases, the minimum habitat area computed was 322,800 ft^2 for Reaches 1 to 4 and 430,400 ft^2 for Reaches 1 through 5. A linear regression of the modeled backwater area against the actual area for the available data utilizing this model yielded an r^2 of 0.89 ($p<.01$, $n=78$) for the combination of Reaches 1 through 5. This model was applied to each year of the historical hydrograph and each year of each modeled condition to determine the impact to backwater habitat area for each level of development analyzed.

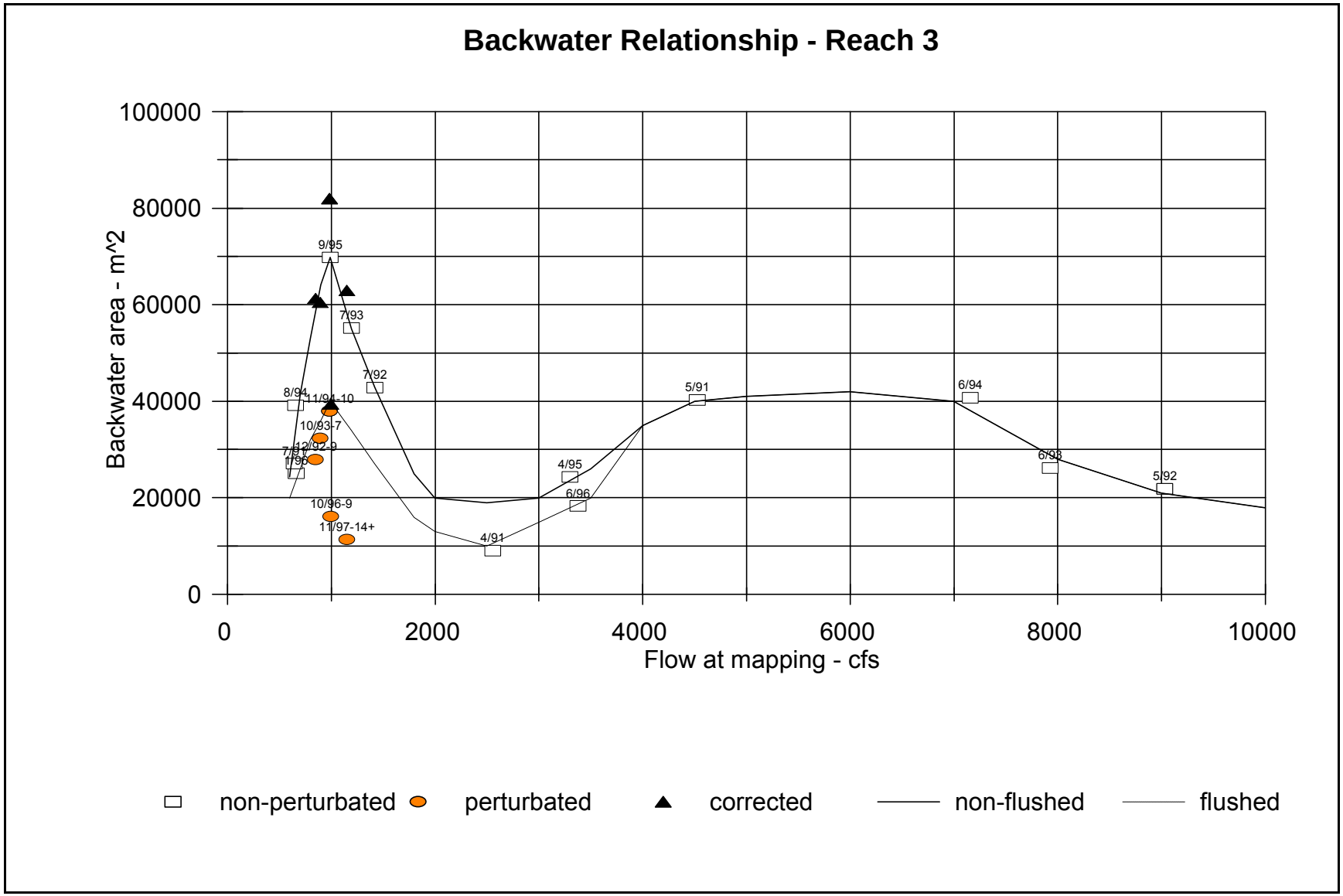


Figure 4.11. Flow/backwater Habitat Area Relationships for Reach 3

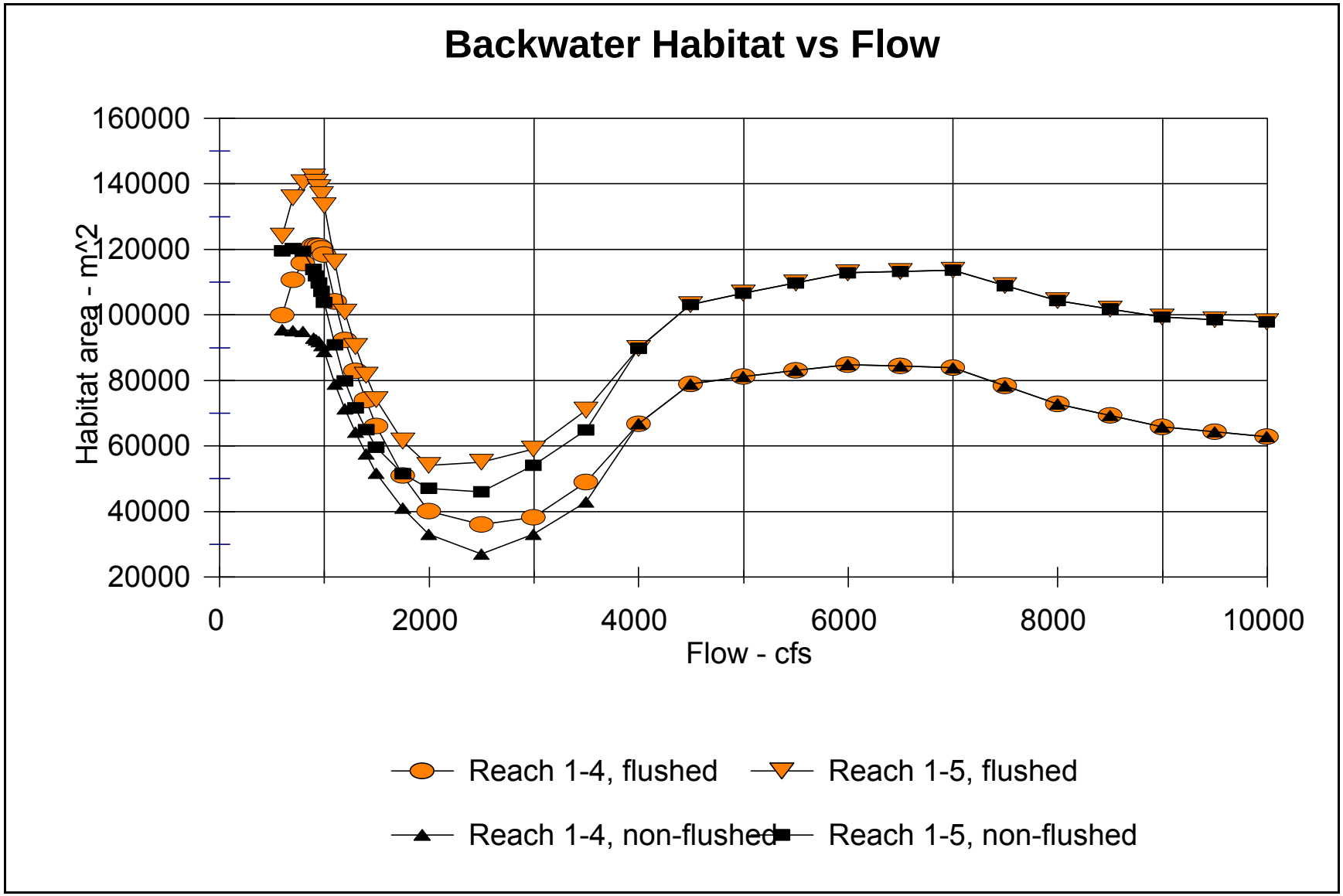


Figure 4.12. Flow/backwater Habitat Model for Reaches 1 to 4 and 1 to 5 Based on Flushed and Nonflushed Conditions

SUMMARY AND CONCLUSIONS

Habitat surface areas in the San Juan River were mapped thirteen separate times with flows ranging from 525 to 8,000 cfs. Some habitat types displayed strong relations with mapping flows (runs, eddies, inundated vegetation and shoal) while other habitats displayed high variability (slackwaters) with no relationship with flow.

Backwater habitats, although variable, demonstrated a systematic pattern related to the inundation of the mouths of secondary channels and the subsequent loss via flow through these channels at higher flows. Backwater habitats were also found to be diminished due to summer silt-laden storm events.

CHAPTER 5: PHYSICAL HABITAT DESCRIPTIONS

INTRODUCTION

Since November, 1992, the abundance of aquatic habitat types has been quantified for distinct portions of the San Juan River. This has been accomplished by ground crews mapping upon images obtained from aerial videography of the river at various discharges. The number of categories used to delineate aquatic habitats has expanded during the study as researchers have made improved distinctions between different habitat types. Presently, there are nearly 40 different types described (Table 5.1). However, the vast majority of the habitat present in the river at any time is comprised of only several types. Runs typically compose at least 70% of the total habitat, regardless of discharge. Secondarily in abundance are usually riffles and riffle-runs. Combined, these three constitute approximately 85-90% of the total habitat (Bliesner and Lamarra 1996). The remainder is comprised primarily of shoals and low velocity types like slackwaters, pools, and backwaters.

In the winter of 1994, a study was initiated to characterize the major aquatic habitat types in the San Juan River using a number of different physical measures. These included mean water column velocity, depth, embeddedness of substrate, and substrate composition. Initially, the principal goal was simply to determine whether and how individual habitat types differed and whether original habitat definitions obtained from the U.S. Fish and Wildlife Service and New Mexico Game and Fish were valid or of sufficient detail. Subsequently, it became important to understand whether particular habitats changed in various physical measures of quality through time and space. This latter objective was undertaken as the potential impacts of frequent storm events in the drainage on habitat quality became more evident and more of a concern, particularly with regard to the ramifications toward on-going efforts to recover the endangered Colorado pikeminnow and razorback sucker. For example, a decrease in the depth of some low velocity habitats following summer storms, particularly backwaters, was observed during the first few years of the study. Some backwaters were physically cut off from the river by sand bars and others completely filled in with fine sediments. These habitats have been identified as important to the early life stages of Colorado pikeminnow and other native fishes in the San Juan River (Buntjer et al. 1994, Archer et al. 1995, 1996) and elsewhere in the Upper Basin (Valdez et al. 1982, McAda et al. 1994). It was also suspected that the productivity of different habitats would be reduced following these storms, at least in the short term, as a number of studies have indicated (Niemi et al. 1990, Meffe and Minckley 1987, Fisher et al. 1982, Kennedy and Tash 1979). This could have profound implications for the condition of various life stages of the native fish community. Eventually, two studies were initiated to address these issues in detail and are summarized in separate reports.

METHODS

A total of eight habitat types were selected for study, based either on their abundance or their perceived importance to native fishes. These included riffles, riffle-runs, runs, cobble shoals, eddies,

slackwaters, pools, and backwaters. Within each habitat, water velocity, depth, depth to the embedded layer of substrate, and substrate composition were quantified. Water velocity was measured in centimeters per second at several equidistant points along four or five transects in each habitat using a Marsh-McBirney current meter at 60% total depth. Depth was measured in feet (to nearest 0.1 ft), but later converted to meters. Depth to the embedded layer (DTE) was considered to be the distance to the layer of substrate completely embedded by fine sediment. This was determined by working one's hand into the substrate until the embedded layer was reached and then measuring that distance to the nearest centimeter. It was determined at four to ten random points in each habitat. One composited sample of interstitial substrate was taken at several random points in each habitat using a 5-cm diameter PVC coring tube inserted below the surface layer. This sample was stored in a zip-lock bag and later dried and sieved for determination of the percent composition of various size fractions by dry weight. Fifty randomly selected particles of substrate were measured along the y-axis (intermediate axis of the three axes with respect to depth) within each habitat to the nearest 0.5 centimeter (Wolman 1954). Sand and finer substrate was classified as less than 0.2 cm. Pebble count and interstitial substrate composition data were integrated for each habitat to provide a more complete depiction of the percent composition of the substrate present.

The San Juan River was arbitrarily segregated into three non-contiguous sections. These were: Section 1 (RM 224-195, or Navajo Dam to Bloomfield, New Mexico, bridge); Section 2 (RM 158-119, or Hogback diversion to Four Corners, New Mexico, bridge); and Section 3 (RM 93-52, or Montezuma Creek, Utah, bridge to Mexican Hat boat launch) (Figure 1.1). The delineation of sections was largely access-driven, but was intended to incorporate the majority of the river with some separation between sections. Sampling occurred a total of four times in November-December, 1994, and February-March, August, and September, 1995. However, during the first two trips sampling occurred in Section 2 only. During the third trip in August, 1995, sampling occurred in Sections 1 and 2 only. During the last trip in September, 1995, sampling occurred in all three sections. Hence, only Section 2 was sampled during all four trips. Four to six habitats of each type were sampled per section during a particular trip. Sampling during the first two trips was geared toward merely describing the specific habitat types, while sampling during the last two trips began to address the issue of spatial and temporal differences within habitat types during the summer-fall storm season.

RESULTS

Discharge throughout the four trips was fairly consistent (Figure 5.1). Trip 1 during November and December, 1994, averaged 1102 cfs (mean daily averages used) with a range of 952 to 1550 cfs. Trip 2 during February-March, 1995, averaged 1258 cfs with a range of 1170 to 1490 cfs. Trip 3 during August, 1995, averaged 1356 cfs with a range of 1210 to 1570 cfs. Trip 4 during September, 1995, occurred on the descending limb of a storm with flows averaging 1308 cfs and ranging from 1040 to 2080 cfs. Levene's test for homogeneity of variances indicated that variances in discharge between trips were not significantly different ($P=0.37$). A one-way analysis of variance (ANOVA) was then applied to the flow data (Zar 1984). The results of this analysis indicated that there were no significant differences in discharge between trips ($P>0.15$). This consistency in discharge between

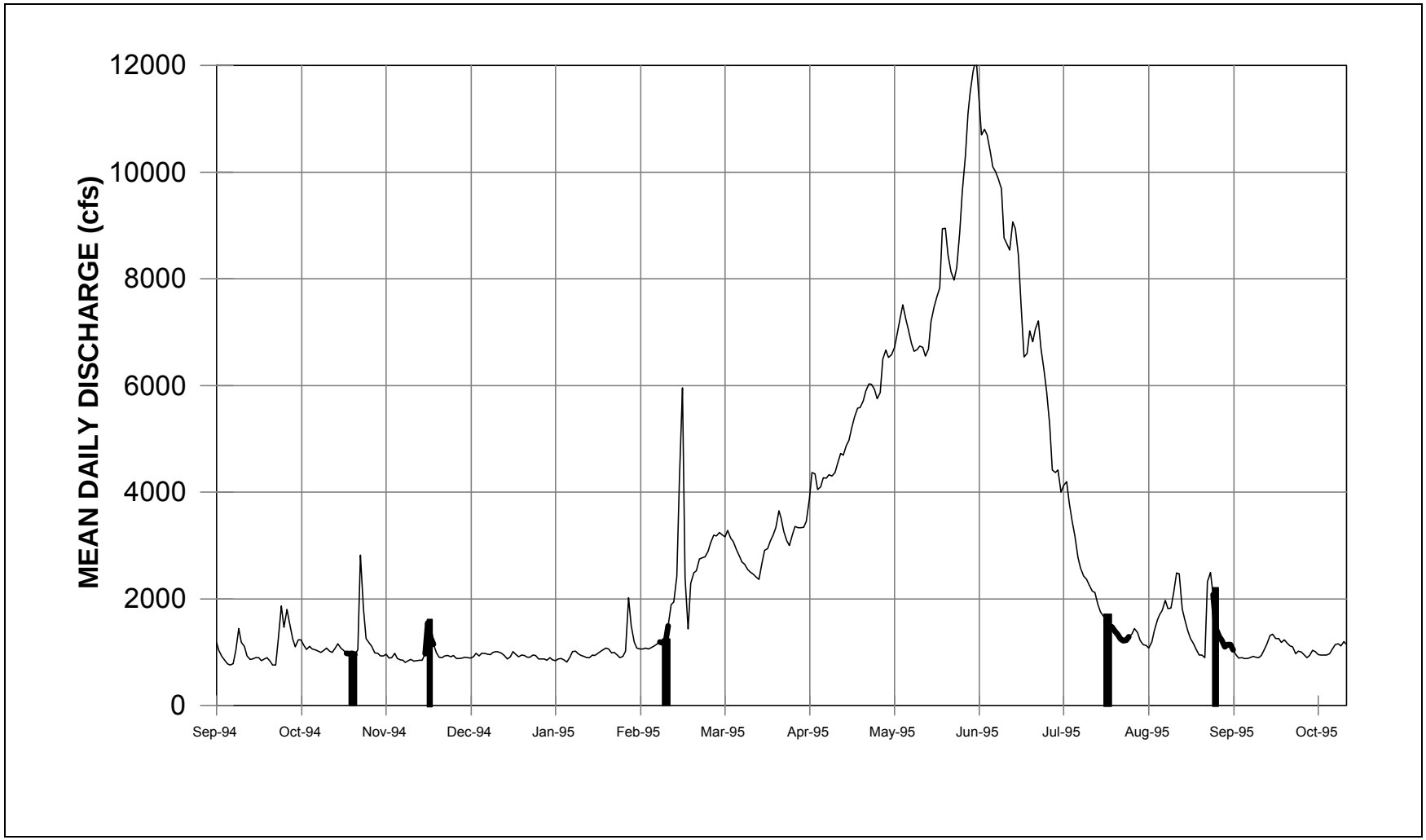


Figure 5.1. **San Juan River mean daily discharge over study period as measured at Four Corners, New Mexico gaging station. Vertical bars indicate habitat sampling trips.**

trips was desirable because changes in discharge through time may influence the physical characteristics of certain habitats.

To test for differences between habitat types, the physical parameters were grouped several ways. First, we combined all the data for each habitat type collected in Section 2 only, considering that there may be spatial differences in the physical characteristics of certain types. Secondly, we examined potential spatial differences within habitat types for Sections 1, 2, and 3 during the last trip in September. Lastly, we examined temporal changes within specific habitats for Section 2 only from November, 1994, to September, 1995. The analysis for temporal differences was conducted for substrate composition and DTE only since it was hypothesized that the percentage of fine sediments would increase and DTE would decrease in certain habitats following storm events and that the reverse would occur following runoff.

Our final treatment of the data involved the use of discriminant functions analysis to determine the relative contributions of the various physical parameters measured toward explaining the overall separation between habitat groups.

Mean Water Velocity

Water velocity is a key physical characteristic separating specific habitat types and is surely the most readily distinguished feature during field observations. To test for differences between habitats using Section 2 data only, we first tested the habitat groups for homogeneity of variance, a precursor to analysis of variance (ANOVA), using Levene's Test (Zar 1984). The results indicated highly significant differences between the groups ($P<0.001$) as did the ANOVA ($P<0.001$); therefore, we elected to use Dunnett's C test to discriminate between the groups because it does not assume homogeneity of variances. In future cases where homogeneity of variance has been established, we will use Tukey's Honest Significant Difference Test, a relatively conservative multiple comparison procedure that is less sensitive to unequal sample sizes (Zar 1984).

Dunnett's C test indicated that significant differences ($P<0.05$) existed between all eight habitat types; that is, all habitat categories were significantly different from each other (Figure 5.2). As can be seen, habitats were arranged from fastest to slowest from left to right and will be presented in that order in later figures for other physical parameters. Riffles were the swiftest habitats, averaging about 100 cm/sec (Figure 5.2 and Table 5.1). Riffle-runs were much more similar to riffles than runs, averaging about 90 cm/sec. Runs were a very distinct intermediate type relative to the whole range of habitats, with less variability than riffles or riffle-runs and averaging about 60 cm/sec. Cobble shoals, eddies, slackwaters, pools, and backwaters might all be considered low velocity types, averaging less than 30 cm/sec, with the last four averaging less than 20 cm/sec. Backwaters were the only type with no measurable current, although minimum velocities of 1 cm/sec or less were measured in at least one location within the five lowest velocity habitats (Table 5.1).

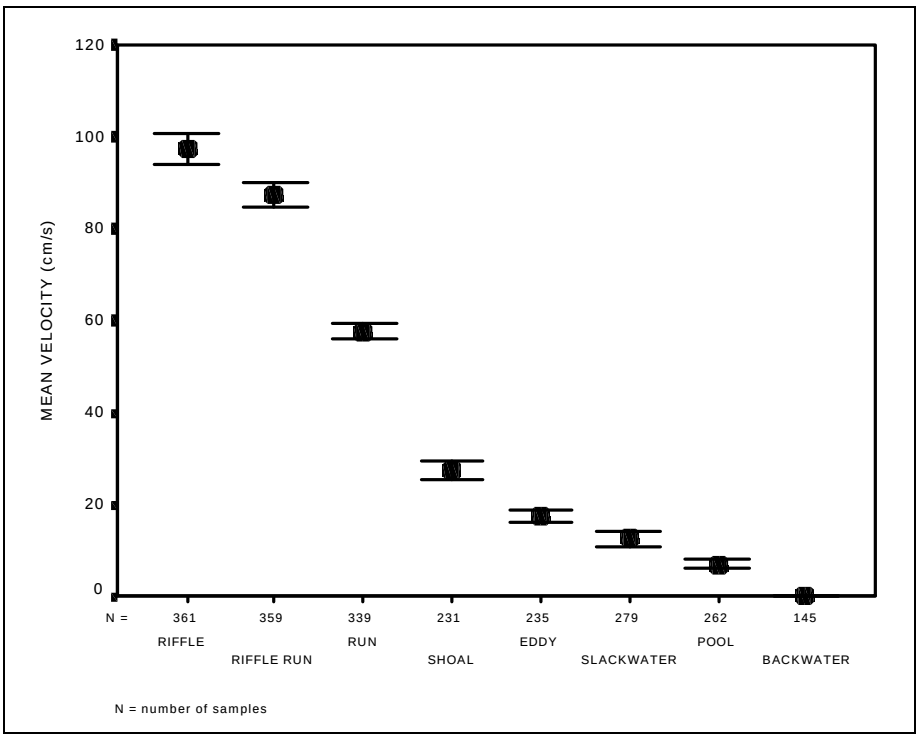


Figure 5.2. Mean (± 1 SE) Water Velocity for Eight Habitat Types in the San Juan River

Table 5.1. Mean Water Column Velocity (cm/sec) Statistics for Eight Habitat Types in Section 2 for November, 1994, to September, 1995

Habitat Type	Mean	Standard Deviation	Standard Error	95% Confidence Interval		Minimum	Maximum
				Lower	Upper		
Riffle	97.1	32.2	1.7	93.7	100.4	15.0	185.0
Riffle-run	87.4	26.3	1.4	84.7	90.1	32.0	175.0
Run	57.4	14.8	0.8	55.8	59.0	17.0	110.0
Cobble shoal	27.6	15.3	1.0	25.6	29.6	1.0	85.0
Eddy	17.3	11.3	0.7	15.9	18.8	0.0	57.0
Slackwater	12.6	13.3	0.8	11.0	14.1	0.0	58.0
Pool	7.0	7.1	0.4	6.1	7.9	0.0	28.0
Backwater	0.0	0.0	0.0	0.0	0.0	0.0	0.0

To determine whether there were spatial differences within habitat types, we examined the data from trip 4 in September, 1995. The results were inconsistent between habitat types. Riffles, runs, and slackwaters in Section 1 had significantly lower velocities than those in the lower two sections ($P<0.05$; Dunnett C) (Figure 5.3). Riffle-runs had significantly lower velocities in Sections 1 and 2 than in Section 3 ($P<0.05$; Dunnett C). Shoals and pools had significantly lower velocities in Section 2 than in Sections 1 and 3 ($P<0.05$; Dunnett C), while eddies had significantly lower velocities in Section 3 than in Sections 1 and 2 ($P<0.001$; Tukey HSD). The high number of measurements within each habitat type (Figure 5.3) probably contributed to the high number of differences found, and some may not be particularly meaningful. However, the substantially lower velocities observed in riffles and runs in Section 1 were especially pronounced and nearly 30 cm/sec lower on average than in Sections 2 and 3. Gradient within Section 1, which includes geomorphic Reach 8 and most of Reach 7, has a channel slope of about 1.17 ft/ft, while Sections 2 and 3 probably average about 1.14 and 1.10 ft/ft, respectively. Thus, one might expect somewhat higher velocities for these habitats in Section 1 than in the lower sections on that basis. However, just the opposite was observed. The slight differences in gradient between sections are probably insufficient to produce consistent differences in riffle velocities, and so another factor must be responsible.

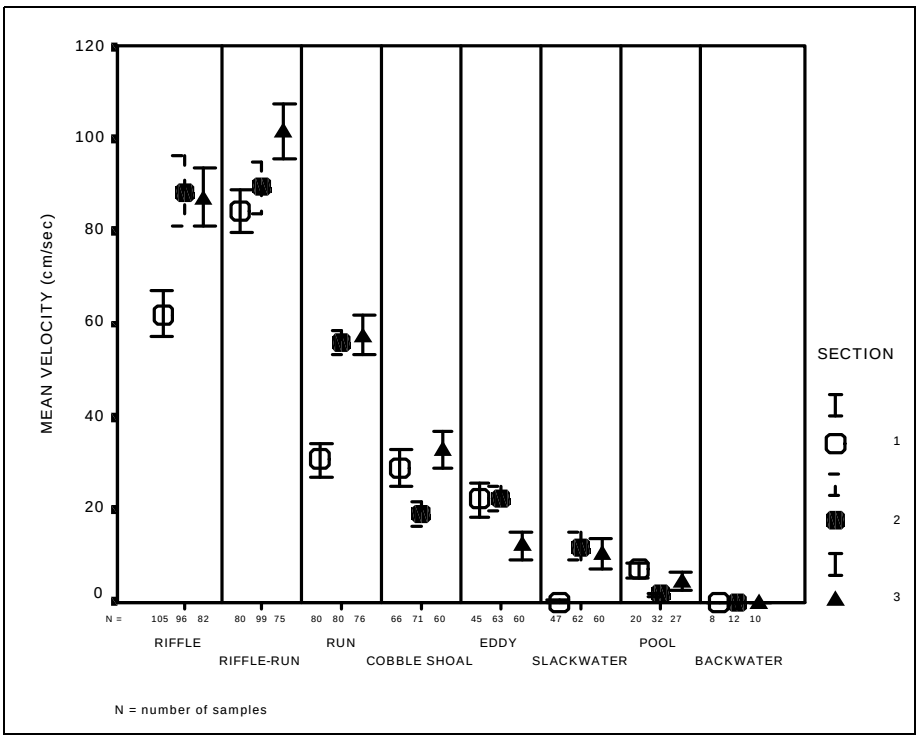


Figure 5.3. Mean (± 1 SE) Water Velocity for Eight Habitat Types in the San Juan River by Section During September, 1995

Depth

Significant differences in water depth for the eight habitat types were detected for nearly every comparison (P<0.05; Dunnett C) (Figure 5.4 and Table 5.2). However, riffles were similar in depth to slackwaters and pools, and riffle-runs were similar to eddies (P>0.05; Dunnett C). Runs were the deepest habitat, averaging about 0.7 m, and cobble shoals were the shallowest at about 0.15 m. There were clear disparities between the three swiftest and most abundant habitats in the river (riffles, riffle-runs, and runs), with riffles being the shallowest and runs the deepest. The slowest habitats (slackwaters, pools, and backwaters) had more similar and relatively shallow depth profiles with a range of about 0.2 to 0.3 m.

A variety of spatial differences in depth for particular habitat types were observed, but a few are noteworthy (Figure 5.5). Riffles were significantly shallower in Section 1 than in the other two sections (P<0.05; Dunnett C). The more shallow nature of these habitats in the upper section may have been correlated with the lower velocities observed there (Figure 5.3). Velocities tend to be reduced in the more shallow portions of riffles. Conversely, slackwaters (P<0.05; Dunnett C), eddies (P<0.001; Tukey HSD), and pools (P<0.05; Dunnett C) were deeper in Section 1 than either Section 2 or 3 or both. The river is relatively confined throughout its upper portion in this Section, with the narrowest valley width within the study area (Bliesner 1999). This may contribute to any overall increase in channel depth, favoring the creation of deeper "holes". Most likely the largest contributing factor, however, is the lower suspended sediment load in this section relative to the other sections

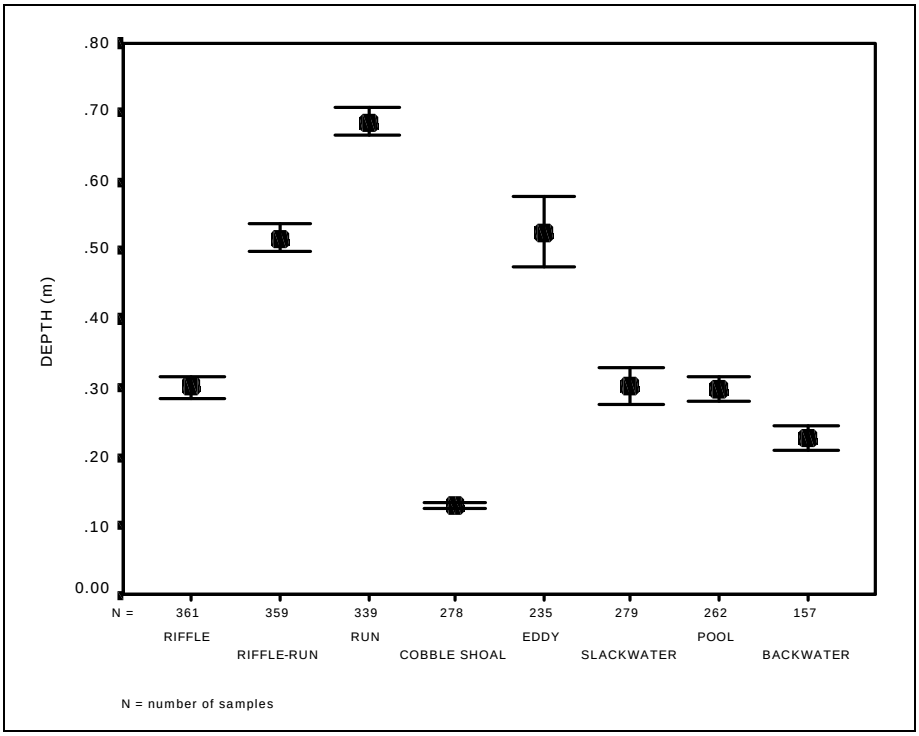


Figure 5.4. Mean (± 1 SE) Depth for Eight Habitat Types in the San Juan River

Table 5.2. Water Depth (m) Statistics for Eight Habitat Types in Section 2 for November, 1994, to September, 1995

Habitat Type	Mean	Standard Deviation	Standard Error	95% Confidence Interval Lower	95% Confidence Interval Upper	Minimum	Maximum
Riffle	0.30	0.15	0.008	0.29	0.32	0.06	0.82
Riffle-run	0.52	0.18	0.009	0.50	0.54	0.18	1.04
Run	0.69	0.19	0.010	0.67	0.71	0.15	1.16
Cobble shoal	0.13	0.05	0.003	0.12	0.14	0.03	0.30
Eddy	0.53	0.39	0.025	0.48	0.58	0.06	1.90
Slackwater	0.30	0.21	0.012	0.28	0.33	0.03	1.19
Pool	0.30	0.14	0.009	0.28	0.32	0.03	0.63
Backwater	0.23	0.12	0.010	0.21	0.25	0.06	0.61

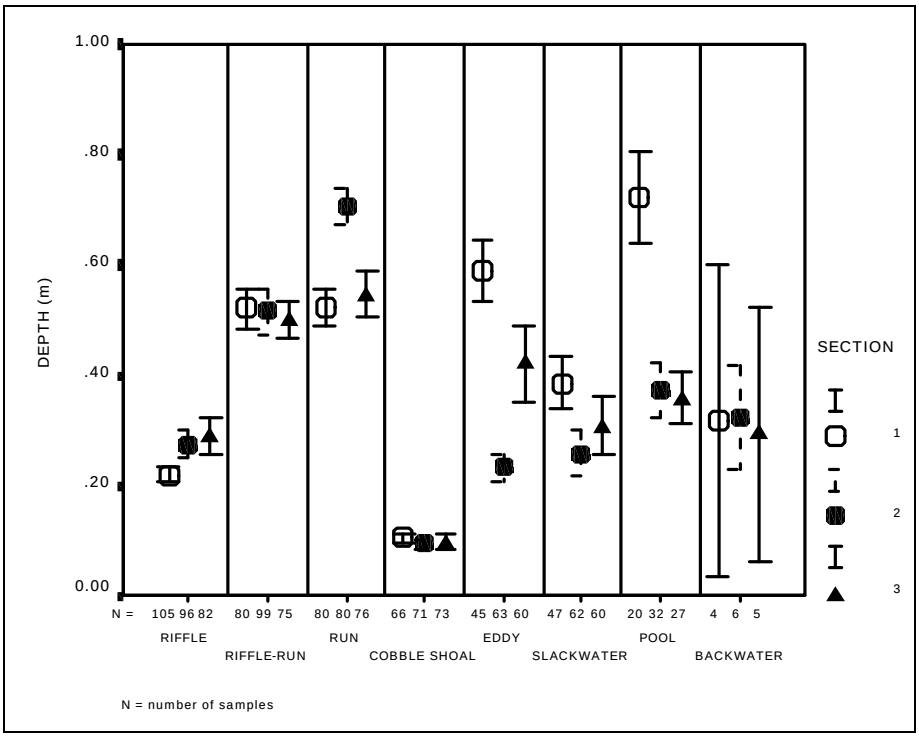


Figure 5.5. Mean (± 1 SE) Depth for Eight Habitat Types in the San Juan River by Section During September, 1995

Depth to Embeddedness

Depth to the embedded layer was significantly different for most habitat types (P<0.05; Dunnett C) which would reduce filling of eddies and slackwaters over time. Pools in this upper section are actually main channel pools, characteristically deeper than the secondary channel pools that are exclusively found in the lower sections. Main channel pools typically do not occur in the lower sections except at extremely low flows and upstream of major diversions.

(Figure 5.6 and Table 5.3). However, riffle-runs were similar to runs (P>0.05; Dunnett C) in this measure at about 7 cm, while riffles averaged nearly 10 cm. Slackwaters, eddies, and pools were all similarly and highly embedded habitats averaging about 1-2 cm to the embedded layer (P>0.05; Dunnett C). There was a fairly pronounced disparity between swifter, generally cobble dominated habitats (riffles, riffle-runs, runs, and cobble shoals) and the lower velocity habitats (Figure 5.6).

Within most habitat types, there was a trend toward greater depths to the embedded layer (i.e., less embedded substrate) in upper than lower sections (Figure 5.7). Significant differences between Section 1 and Section 2 and/or Section 3 were detected within riffles (Section 2 and 3; P<0.005; Tukey HSD), runs (Section 2; P<0.05; Dunnett C), shoals and slackwaters (Section 2 and 3; P<0.05;

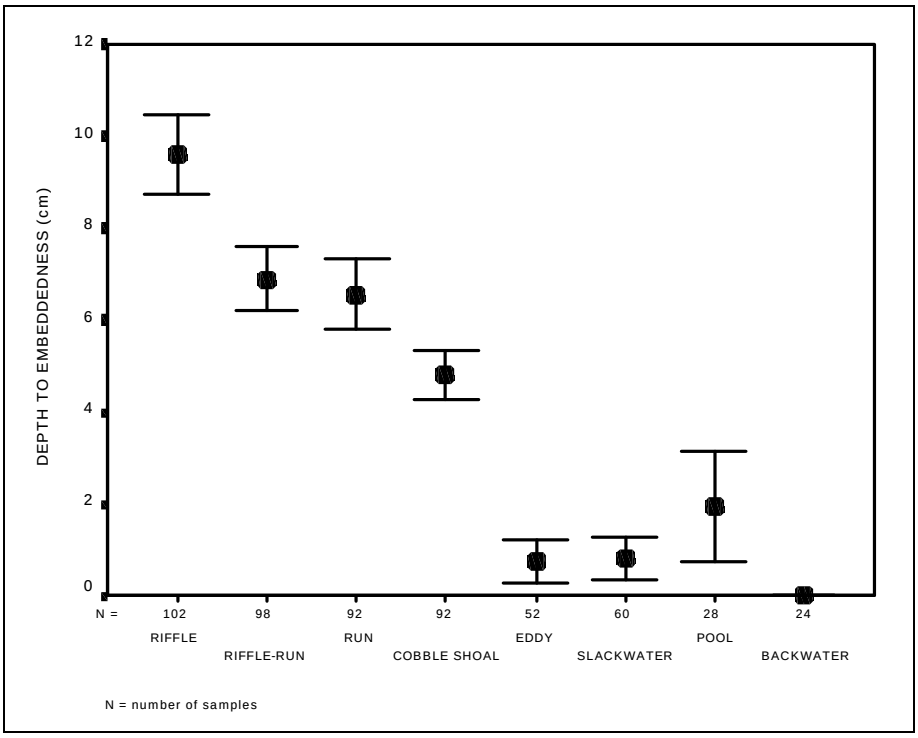


Figure 5.6. Mean (± 1 SE) Depth to Embeddedness for Eight Habitat Types in the San Juan River

Table 5.3. Depth to Embeddedness (cm) Statistics for Eight Habitat Types in Section 2 for November, 1994, to September, 1995

Habitat Type	Mean	Standard Deviation	Standard Error	95% Confidence Interval		Minimum	Maximum
				Lower	Upper		
Riffle	9.6	4.5	0.45	8.7	10.5	0.0	22.0
Riffle-run	6.9	3.5	0.36	6.2	7.6	0.0	17.0
Run	6.6	3.7	0.38	5.8	7.3	0.0	17.5
Cobble shoal	4.8	2.6	0.28	4.3	5.3	0.0	14.5
Eddy	0.8	1.7	0.23	0.3	1.2	0.0	6.0
Slackwater	0.8	1.8	0.23	0.4	1.3	0.0	7.0
Pool	1.9	3.1	0.59	0.7	3.2	0.0	11.0
Backwater	0.0	0.0	0.0	0.0	0.0	0.0	0.0

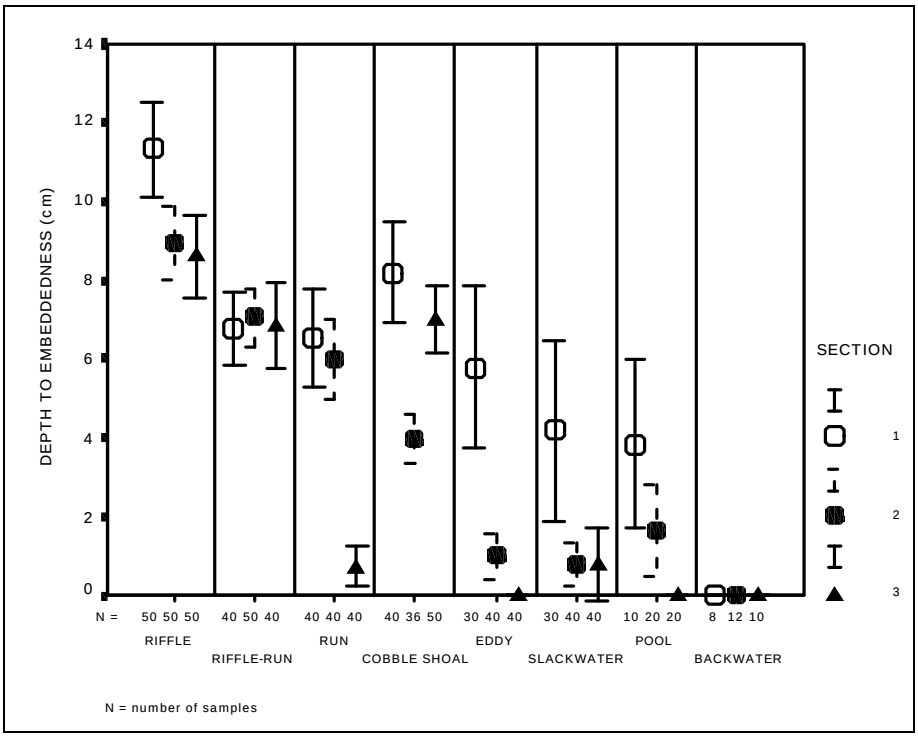


Figure 5.7. Mean (± 1 SE) Depth to Embeddedness for Eight Habitat Types in the San Juan River by Section During September, 1995

Dunnett C), and pools (Section 3; P<0.05; Dunnett C). Significant differences between Section 2 and Section 3 were detected within runs (P<0.05; Dunnett C), eddies (P<0.05; Dunnett C), and pools (P<0.05; Dunnett C). Again, our theory is that the greater suspended sediment load in the lower sections from tributary inflow contributed greatly to the more highly embedded substrate found in those lower sections.

As stated previously, it was also an objective to determine whether DTE within particular habitat types varied through time within Section 2. Specifically, the effects of runoff and storms on measures of substrate condition were of most interest. Riffles (P<0.001; Tukey HSD), riffle-runs (P<0.05; Dunnett C), and runs (P<0.001; Tukey HSD) exhibited significant declines in DTE from November, 1994 to February, 1995 (Figure 5.8). Inspection of the hydrograph indicated that one major storm occurred over this interval in early February (Figure 5.1). By August, following runoff, DTE had increased significantly in all three habitats, but still lagged behind that observed the previous November. Following two storms, DTE remained unchanged in September in all of these habitats (P>0.05). The large decline in DTE between the first two trips may reflect the accumulation of fines in the interstitial voids over the three-month period in addition to the effect of the single storm as no

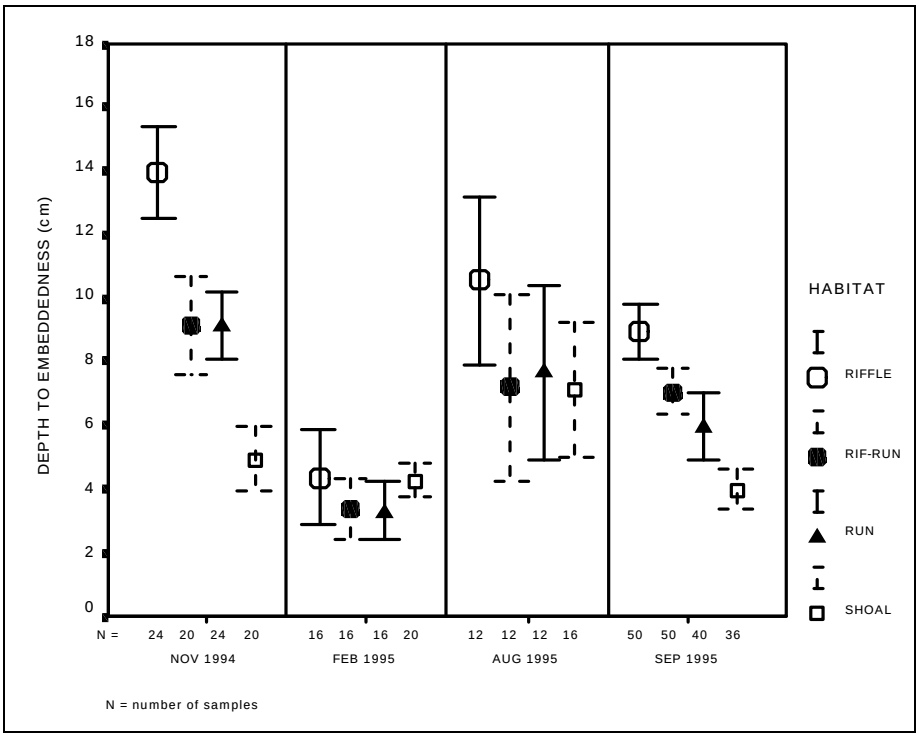


Figure 5.8. Mean (± 1 SE) Depth to Embeddeness for Eight Habitat Types in the San Juan River in Section 2 During Four periods from November, 1994 to September, 1995

such decline was observed over a one-month period between the last two trips when two larger storms occurred. The one storm in February may also have introduced greater sediment loads than the two later storms. However, concentrations of total suspended solids during the September storm were very high at 3,000-6,500 mg/L, as measured during a related study (Ecosystems Research Institute, in press). No significant changes in DTE occurred over the study period in any of the other five habitats examined (P>0.05; Dunnett C), with all being completely embedded or nearly so.

Interstitial Sediment

A total of six interstitial sediment categories were used. These were: (1) less than 0.063 mm in diameter; (2) 0.063-0.25 mm; (3) 0.25-0.50 mm; (4) 0.50-4.0 mm; (5) 4.0-12.5 mm; and (6) greater than 12.5 mm. For the sake of brevity, only the smallest and largest fractions, encompassing the range of sediment sizes, will be considered in the following analyses. However, all size fractions will be considered in the discriminant analysis at the end of this section.

Particles <0.063 mm

Ultra-fine particles less than 0.063 mm displayed an increasing pattern as expected in lower velocity habitats (Figure 5.9); however, due to inequality of variances between groups (P<0.001; Levene's Test) these differences were not significant (P>0.05; Dunnett C). These fine sediments were totally lacking in riffles and riffle-runs, the swiftest habitats, but represented about 5-10% of the interstitial sediment from samples in runs and cobble shoals. In the remaining lower velocity habitats it represented only about 7-15% of the sediment present on average.

Examination of the presence of these ultra-fine particles in habitats within the three sections during September, 1995 revealed no significant differences by section for any habitat type (P>0.05; ANOVA) (Figure 5.10). Runs, eddies, slackwaters, and pools all showed trends toward increasing percentages of these fines in lower sections; however, these differences were not significant (P>0.08; ANOVA).

Most higher velocity habitats displayed some accumulation of ultra-fines during February, 1995 (Figure 5.11), which followed soon after a storm event (Figure 5.1). Riffles exhibited a significant increase from November, 1994 (P<0.05; Tukey HSD); however, no other differences were significant (P>0.05). The accumulation of sediment in these habitats was reflected in lower DTE measurements (Figure 5.8). Lower velocity habitats exhibited similar though much larger increases in these ultra-fines over this same time interval (Figure 5.12), with significant increases occurring in eddies, pools, and backwaters (P<0.05; Dunnett C).

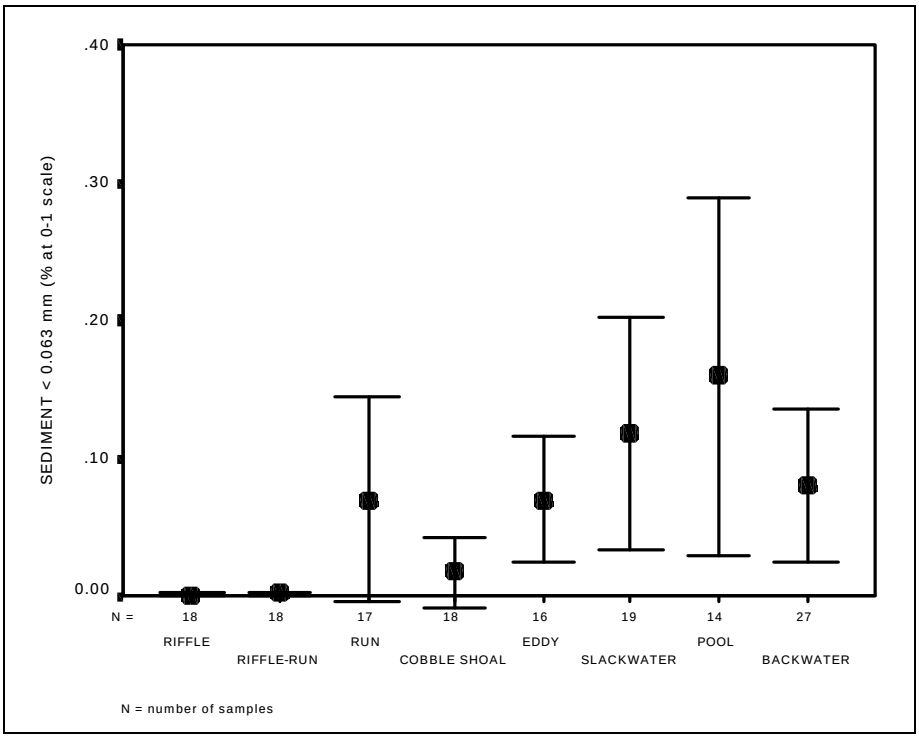


Figure 5.9. **Mean (± 1 SE) Percentage (100% at 0-1 scale) of Sediment <0.063 mm for Eight Habitat Types in the San Juan River**

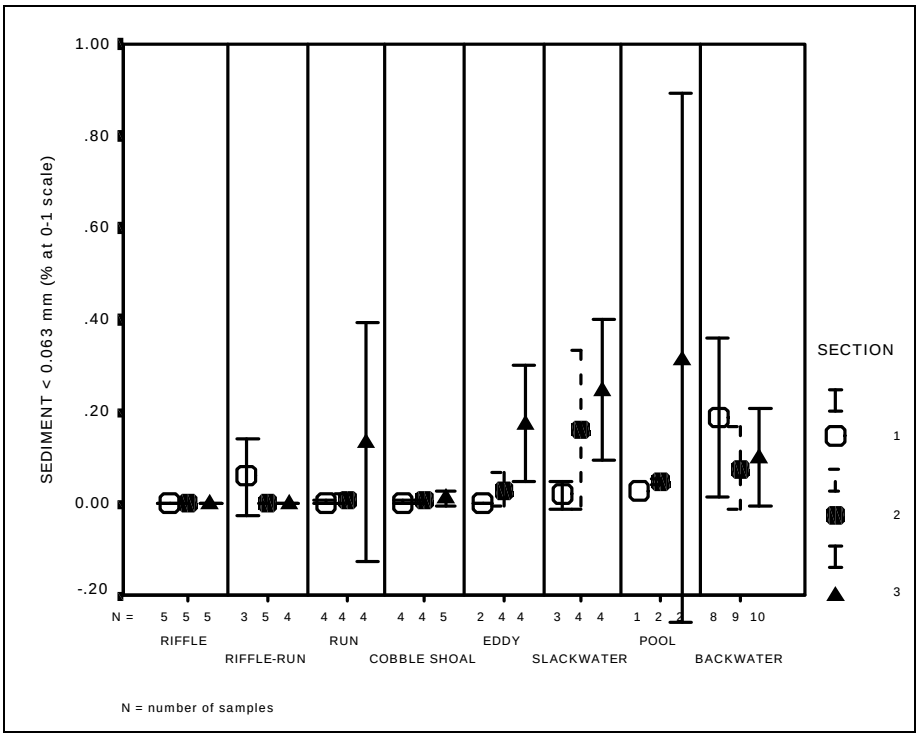


Figure 5.10. **Mean (± 1 SE) Percentage (100% at 0-1 scale) of Sediment <0.063 mm for Eight Habitat Types in the San Juan River by Section During September, 1995**

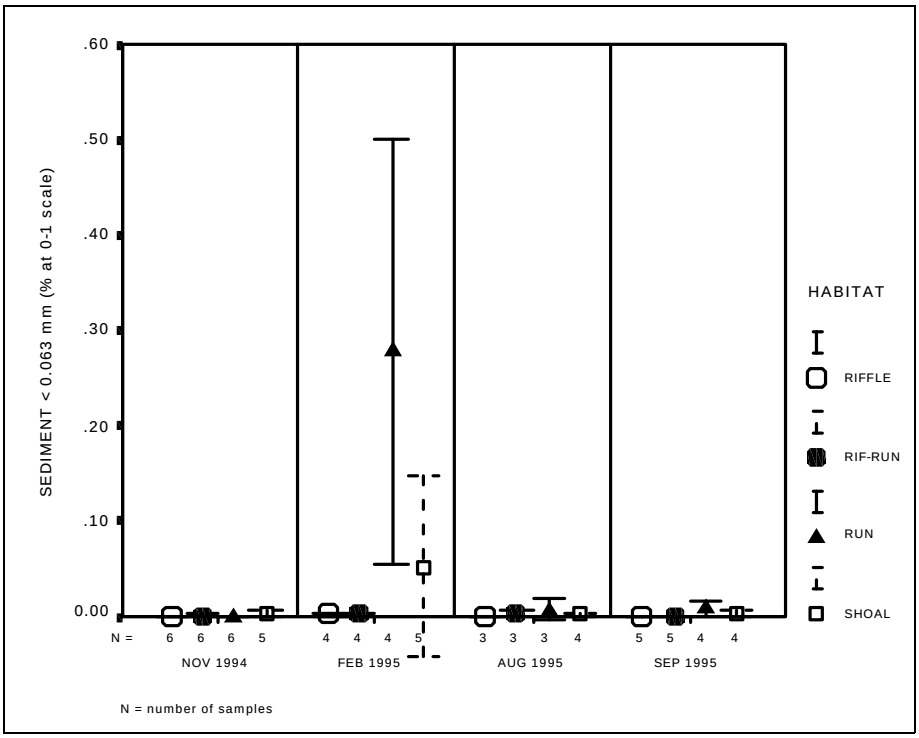


Figure 5.11. Mean (± 1 SE) Percentage (100% at 0-1 scale) of Sediment <0.063 mm for Riffle, Riffle-run, Run, and Cobble Shoals in the San Juan River in Section 2

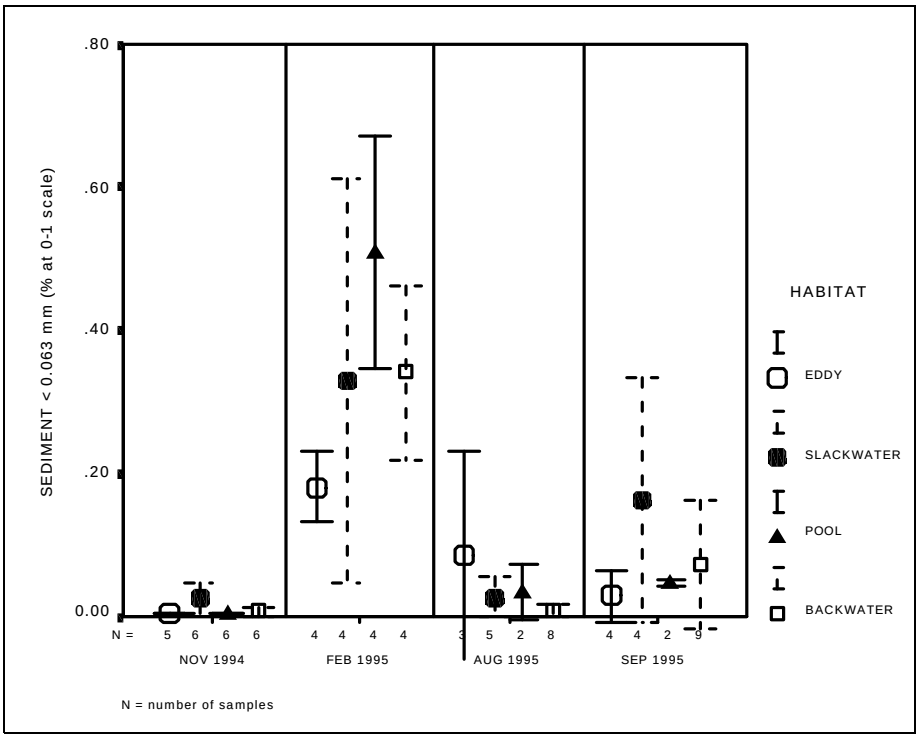


Figure 5.12. Mean (± 1 SE) Percentage (100% at 0-1 scale) of Sediment <0.063 mm for Eddies, Slackwaters, Pools, and Backwaters in the San Juan River in Section 2

Particles >12.5 mm

The largest particles defined as >12.5 mm in diameter (approximately gravel sized) were significantly more abundant in the four higher velocity habitats (P<0.05; Dunnett C) than in most of the lower velocity habitats (Figure 5.13). Riffles contained significantly more of this coarser substrate than runs (P<0.05; Dunnett C), while there were no differences among the four lowest velocity types (P>0.05; Dunnett C).

Few spatial differences were observed within these habitat types during the trip in September, 1995 (Figure 5.14). Runs contained substantially more of these coarser grains in both upstream sections (P<0.001; Tukey HSD), while eddies had higher percentages in Section 1 than Section 3 (P<0.05; Tukey HSD). Generally, higher velocity habitats like riffles, riffle-runs, runs, and shoals had about 50% or more of the interstitial substrate >12.5 mm, while lower velocity types like slackwaters, eddies, and backwaters had typically less than about 20%.

No temporal differences in this substrate size were found in the four higher velocity habitats (P>0.25; ANOVA) except for runs which had higher levels in September, 1995 than February (P<0.05; Tukey HSD) (Figure 5.15). This may reflect the lingering effects of flushing of fine sediments that occurred following a relatively high runoff (Figure 5.1). No significant differences were detected over the study period within the four lower velocity habitats (P>0.15; ANOVA).

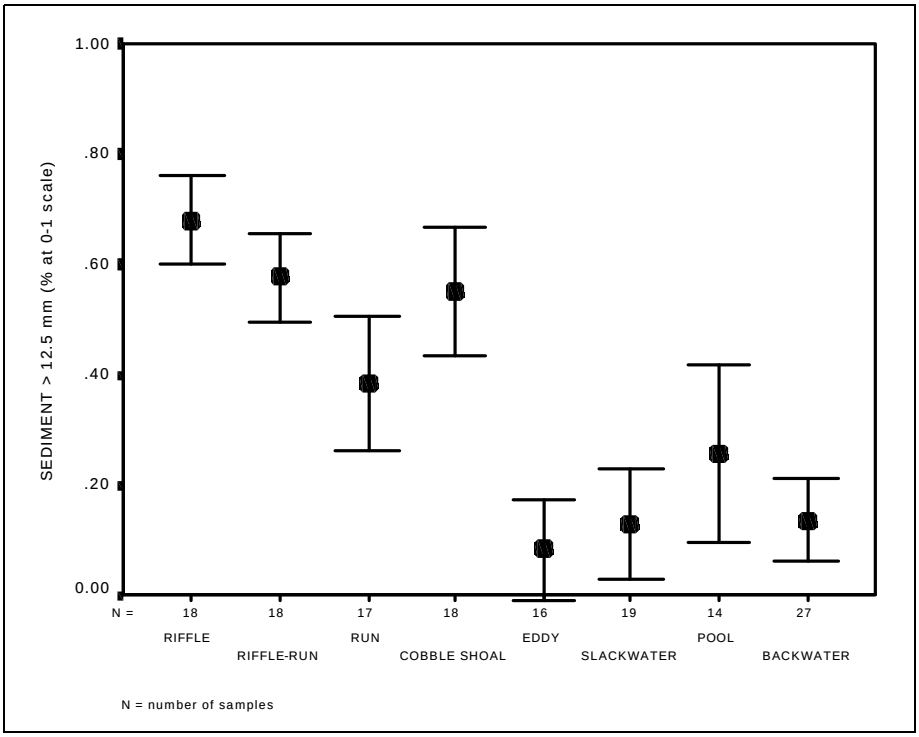


Figure 5.13. Mean (± 1 SE) Percentage (100% at 0-1 scale) of Sediment >12.5 mm for Eight Habitat Types in the San Juan River

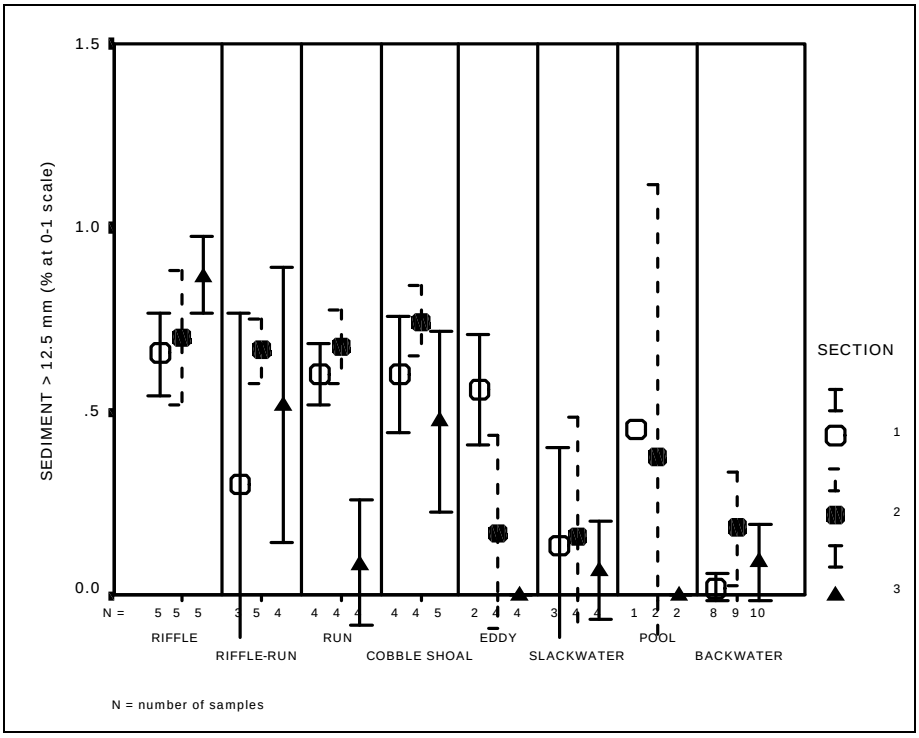


Figure 5.14. Mean (± 1 SE) Percentage (100% at 0-1 scale) of Sediment >12.5 mm for Eight Habitat Types in the San Juan River by Section During September, 1995

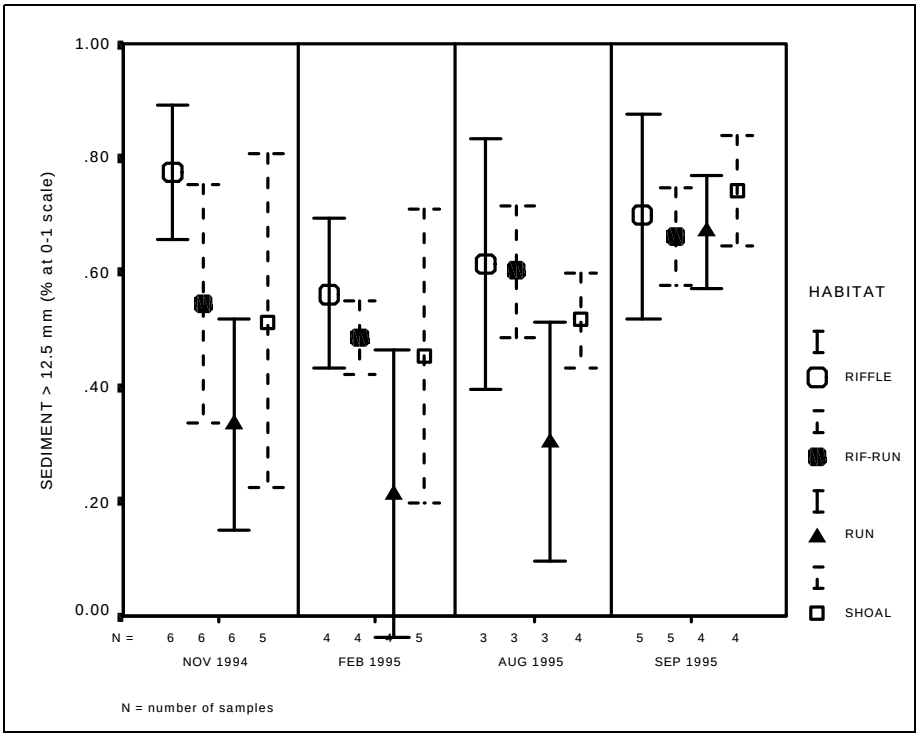


Figure 5.15. Mean (± 1 SE) Percentage (100% at 0-1 scale) of Sediment <0.063 mm for Riffle, Riffle-run, Run, and Cobble Shoals in the San Juan River in Section 2 During Four Periods from November, 1994 to September, 1995

Discriminant Functions Analysis

As stated previously, a discriminant analysis (DA) was performed on the physical data collected within the eight habitat types in Section 2 over the study to determine which physical parameters contributed most toward distinguishing between the groups. This type of analysis generates a discriminant function (or, for more than two groups, a set of discriminant functions) based on linear combinations of the predictor variables that provide the best discrimination between groups.

Prior to application of DA, several assumptions must be met. First, the attribute values of one parameter should not affect another. A correlation matrix revealed that the physical parameters selected were not significantly correlated ($P>0.05$), with r values ranging from -0.42 to 0.33. The second assumption requires that each parameter is multivariate normally distributed. Nonparametric testing indicated that all three parameters significantly deviated from the normal distribution ($P<0.001$; Chi-Square Test). Therefore, this assumption was violated. However, the canonical discriminant functions themselves can apparently be derived regardless of whether the data are normally distributed or not; it is the P values that become suspect. Therefore, it was felt that the violation was allowable, but that caution would be exercised in assessing the significance levels. The third assumption requires that variance-covariances across groups be equal (Duarte Silva and Stam 1995). Levene's test for homogeneity of variances indicated that all three parameters had unequal variances between habitat groups ($P<0.001$). However, this can be allowed if the variance-covariances are roughly proportional between groups (that is, proportional to their respective means). This appeared to be satisfied in most cases. The decision was made to continue with the analysis and thereafter determine whether the output seemed reasonable.

The first step in DA is a multivariate analysis of variance (MANOVA), which tests whether any of the parameters contributes to group separation. Higher significance levels would indicate greater contribution to group separation (Duarte Silva and Stam 1995). The results indicated that mean velocity, depth, and DTE contributed greatly to group separation ($P<0.001$; Wilks' Lambda), but that the other physical (substrate-related) parameters did not contribute to the separation ($P>0.05$). However, considering that substrate >12.5 mm was nearly significant ($P=0.09$), it was decided to include this parameter in the initial DA. Using a backward elimination approach, the remaining substrate-related variables ($P>0.30$) were discarded from the analysis.

A canonical DA was performed on mean velocity, depth, DTE, and substrate >12.5 mm for the eight habitat types. The output of this analysis is indicated in Table 5.4. Higher eigenvalues indicate greater contribution of discriminant functions to group separation. Each discriminant function represents a linear expression of some combination of the physical parameters. Canonical correlations indicate the predictive power of each function toward assigning a random sample of physical parameters to the appropriate habitat type. The percent contribution of each function to the model is also indicated. More than 70% of the variability in the groups was attributed to function 1, with approximately 22% being explained by function 2. The remaining two functions explained only about 5% of the separation between the habitat types. A plot of the first two functions illustrates their use in separating the habitats into their proper groups (Figure 5.16). The functions are described by the contributions

Table 5.4. The Results of Discriminant Analysis Performed on Mean Column Velocity, Depth, DTE, and Substrate Larger than >12.5 mm Data Collected from Eight Habitat Types in the San Juan River

Function	Eigenvalue	% of variance	Cumulative %	Canonical correlation
1	4.374	72.3	72.3	0.902
2	1.337	22.2	94.5	0.756
3	0.272	4.5	99.0	0.463
4	0.063	1.0	100.0	0.244

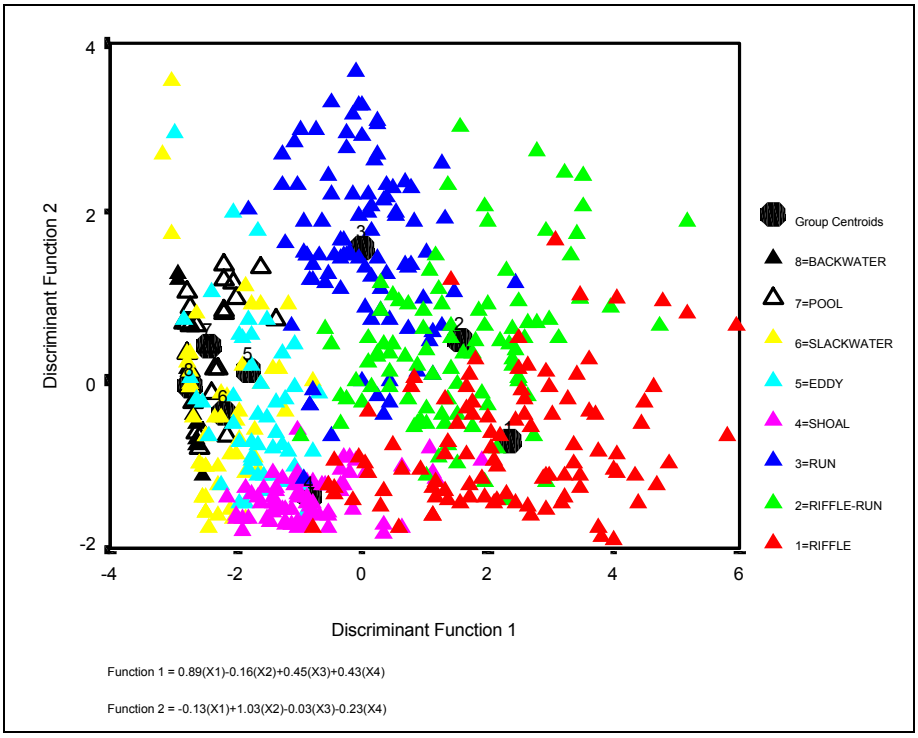


Figure 5.16. Plot of Primary Functions Derived from Discriminant Functions Analysis for Eight Habitat Types in the San Juan River

of velocity (X1), depth (X2), DTE (X3), and substrate >12.5 mm (X4). As can be seen, function 1 is largely driven by the influence of velocity, while function 2 is driven primarily by depth. Riffles, riffle-runs, runs, and cobble shoals emerge as very distinctive habitats, while the lower velocity habitats appear to be more similar to each other, but still emerging as separate groups.

CONCLUSIONS

In summary, during this study it was found that the eight habitat types selected significantly differed in most cases with respect to mean velocity, depth, and DTE. Substrate composition also differed between some habitats with generally finer substrates being more abundant in lower velocity types and coarser substrates in higher velocity types. DTE tended to be higher in most habitats in the most upstream section below Navajo Dam, indicating less embedded substrate in those areas. Highly reduced sediment loads in the upper section was a likely explanation for that finding.

Storms were observed to increase the percentage of fines and/or decrease the DTE in every habitat described. Conversely, the cleansing action of high runoff was noted in nearly all habitats as well. This illustrated the necessity for considering the effect of hydrology on these particular attributes when describing specific habitats. For example, using DTE as a measure to distinguish between riffles and other relatively high velocity habitats following a large storm event might be counter-productive as riffle habitats would likely be similarly, highly embedded.

As stated previously, one goal of this study was to determine whether original habitat definitions obtained from U.S Fish and Wildlife Service and New Mexico Game and Fish personnel were accurate or of sufficient detail. At the close of this final report, we compare old and refined habitat descriptions for the eight habitat types studied (Table 5.5). Greater detail for velocity, depth, embeddedness and substrate characteristics were provided for all habitats. The only major discrepancies occurred for velocity in the old definition of riffles and runs which were substantially less than measured during our investigation.

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Table 5.5. Old and Revised Habitat Definitions for Eight Habitat Types in the San Juan River

Old Definition	Revised Definition
Riffle Area within channel where gradient moderate (5 cm/m), water velocity usually moderate to rapid (10 to 31 cm/sec), and water surface disturbed. Substrate usually cobble and rubble and portions of rocks may be exposed. Depth vary from <5 to 50 cm, rarely greater.	*Riffle* Area within channel where gradient is relatively steep and velocity rapid (90-100 cm/sec). Surface is usually disturbed with substrate consisting primarily of relatively loose cobble and rubble with interstitial gravels. Depths vary from about 6 to 60 cm, rarely greater, and average about 30 cm.
Riffle-run Same as run but with some surface disturbance evident, substrate usually cobble or rubble.	*Riffle-run* Area within channel where gradient is relatively steep, typically less than for riffles, with velocity moderately rapid (80-90 cm/sec) and depth typically greater than riffles at about 50 cm. Generally less surface agitation than riffles. Substrate mostly cobble and rubble, usually more embedded than riffles.
Run Typically, moderate or rapid velocity water 10-30 cm/sec and no or little surface disturbance. Depths usually 10-74 cm but may exceed 75 cm. Substrate usually sand but may be silt in slow velocity runs and gravel or cobble in rapid velocity runs.	*Run* Area within channel where gradient is moderate with little or no surface disturbance. Velocities average about 60 cm/sec with less variability than riffles or riffle-runs. Depths ranging from about 10 to 120 cm or greater, averaging about 70 cm. Substrate consists of more homogeneous mix of coarse and fine substrates, depending on local conditions, with more embedded substrate than riffles.
Cobble Shoal Generally shallow areas (#25 cm/sec) with laminar flow (very slow to slow velocity) over cobble and rubble substrates. Such areas found most often on inside curve of broad channels.	*Cobble Shoal* Generally shallow areas (10-15 cm) averaging 25 to 30 cm/sec and flowing over cobble or rubble substrate. More highly embedded than most other coarse substrate habitats. Such areas found most often on inside curve of river bends, at heads of islands, or adjacent to cobble bars.
Eddy Same as pool, except water flow usually evident (but slow) and direction typically opposite that of channel or circular.	*Eddy* Low velocity shoreline feature with current typically circular and opposite main channel flow. Velocities average 15 to 20 cm/sec with depths averaging about 50 cm at low flow, but can be much deeper at higher flows. Substrate consists of mixture of silt or sand or highly embedded gravels.
Slackwater Mid-channel habitat generally located below sand shoals or other instream structure where decreased velocity provides resting areas for fish.	*Slackwater* Low velocity habitat (10 to 15 cm/sec) located below debris piles or bars along shoreline or mid-stream. Also found along inside margins of river bends. Depths and substrate characteristics similar to eddies.
Pool Area within channel where flow not perceptible or barely so; water depth usually $30 cm; substrate silt, sand, or silt over gravel, cobble, or rubble.	*Pool* Area within channel where velocity is very slow (5 to 10 cm/sec) and depths range from about 30 cm in secondary channel pools to 70 to 90 cm in main channel pools. Substrate consists of fines or highly embedded gravels.
Backwater Typically an embayment of channel, water depth from <10 cm to >1.5 m, no perceptible flow, substrate typically silt or sand and silt. Little or no mixing of backwater and channel water.	*Backwater* Typically an embayment of channel, with no perceptible flow and depths from <10 cm to >1.5 m at higher flows. Substrate consists of silt, sand, or highly embedded cobble or gravel.

CHAPTER 6: MAINSTREAM HABITAT QUALITY

INTRODUCTION

The carrying capacity of upper trophic levels in riverine environments is, to a large degree, dependent upon the biomass and productivity of food organisms. This trophic structure in the San Juan River was defined prior to and after spring runoff during 1994, 1995, and 1996. The overall objective of this investigation was to:

> ***Evaluate temporal and longitudinal distribution of physical and biological components of the benthic community associated with riffle and run habitats in the San Juan River.***

The river continuum concept (Vannote et al. 1980) was central to the formulation and fulfillment of the above objective. This concept proposes that the structure and function of river communities are in direct response to physical conditions within the river which change from the headwaters to the mouth. It contends that the biological community responds predictably to physical habitat characteristics which are largely regulated by fluvial geomorphic processes. To assess changes in the biological community in response to different hydrographics requires an understanding of the interrelationships between the physical and biological environment.

The major objective of the San Juan Recovery Implementation Program is to recovery the threatened and endangered Colorado pikeminnow and razorback sucker. An understanding of the dynamics of the primary and secondary trophic levels within the San Juan River are critical in this process. The carrying capacity of these two rare fishes, as well as the remaining native fish community, will be in part determined by the primary and secondary trophic levels.

METHODS

This investigation was undertaken in the San Juan River (Figure 1.1) from the tailwater of Navajo Reservoir to the confluence of the San Juan River with Lake Powell. This portion of the San Juan River was sampled based upon previously defined geomorphic reaches. Table 6.1 summarizes the number of riffle and run habitats sampled by date and location. Over the duration of the study, Reaches 2 through 7 were sampled between 13 and 18 times, with Reach 1 being sampled only once and Reach 8 sampled eight times. As stated previously, sample dates corresponded to before and after runoff in 1994, 1995, and 1996.

Sample methods and protocols were the same as those employed by Lamarra (1999) and are summarized below.

Measurements to evaluate primary and secondary trophic levels were collected from replicate riffle and run habitats selected randomly from each geomorphic reach. At each site, samples were collected

from three locations parallel to the shore at approximately 1 to 1.5 feet water depth within these two habitats. These samples were collected from locations that were similar in depth, velocity and substrate within each sample reach and habitat to aid in a longitudinal comparison.

Physical Parameters

Physical parameters (Table 6.2) collected within each sample reach were assumed to have the greatest influence on primary and secondary trophic levels based upon literature data. Most parameters were collected at each sample location parallel to the shoreline.

Table 6.1. A Summary of the Number of Riffle and Run Habitats Sampled by Date and Geomorphic Reach in the San Juan River.

	GEOMORPHIC REACH																
	1		2		3		4		5		6		7		8		TOTAL
	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	
APR. 94	1	1	2	0	3	3	2	2	2	2	2	2	3	3	1	1	29
NOV.94	0	0	3	3	3	3	2	2	3	3	2	2	3	3	1	1	34
APR. 95	0	0	3	3	3	3	3	3	4	4	3	3	5	5	2	2	46
FEB. 96	0	0	5	5	3	3	3	3	3	3	4	4	3	3	2	2	46
SEP. 96	0	0	5	5	3	3	3	3	3	3	3	3	3	3	2	2	44
TOTAL	**1**	**1**	**18**	**18**	**15**	**15**	**13**	**13**	**15**	**15**	**14**	**14**	**17**	**17**	**8**	**8**	**202**

A=Riffle; B=Run

Table 6.2. Physical and Biological Parameters Collected Within Each Sample Reach for Selected Run and Riffle.

WITHIN SAMPLE LOCATION	UNIT
Physical	
Water depth	meters
Bottom and average column water velocity	ft/sec
Dominant substrate size	D_{16}, D_{50}, D_{84}
Interstitial substrate size fractions	mm
Depth to embeddedness	mm
Percent surface area embedded	%
Interstitial void volume	cm^3/m^2
Biological	
periphyton biomass	mg/m^2
macroinvertebrate biomass	gm/m^2
coarse particulate organic matter	gm/m^2
fine particulate organic matter	% loss on ignition

Water column depth, bottom velocity and mean column velocity (0.6 depth) were collected at each sample location. Depth was measured with a stadia rod and velocities with a Marsh-McBirney current meter.

The percent of cover of the two dominant substrate size fractions were estimated at sample locations. Wolman pebble counts (Wolman 1954) were also conducted within the vicinity of the three samples parallel to the shoreline to quantify the size distribution of substrates in these regions. The percent embeddedness of large substrates at each sampling point was estimated from the portion of the substrate exposed above interstitial sediments. Depth to embeddedness was measured as the distance from the top of large substrates to the upper boundary of interstitial sediments. Interstitial substrates were collected at each sample location with a core tube. These samples were dried in the laboratory and separated into size fractions. The percent organic composition of the smallest sediment size fraction (<2 mm) was measured and used as an estimate of fine particulate organic matter (FPOM).

Biological Parameters

Biological parameters collected at each sample location included periphyton biomass, benthic detritus, and biomass of benthic macroinvertebrates. Periphyton was quantitatively collected from cobble-sized rocks. Chlorophyll-*a* content of these samples was used as a measure of periphyton biomass and was measured in the laboratory with a spectrophotometer. Benthic macroinvertebrates were collected at each sample location with a Hess sampler. Samples were preserved in alcohol and analyzed in the laboratory. Organic material from these samples was dried and weighed to provide estimates of detritus coarse particulate organic matter (CPOM).

RESULTS

Between 1994 and 1996, the trophic structure of the San Juan River was quantitatively described during five time periods. The experimental design required sample periods to be before and after spring runoff during baseflow conditions. Because the San Juan basin is subject to summer and fall monsoons, baseflows during the three study years varied greatly. Table 6.3 summarizes the hydrologic conditions of the spring runoff period as well as the subsequent summer/fall baseflow period. As can be seen from this table, each year was significantly different relative to the magnitude of the runoff hydrograph, as well as the summer baseflow period. Figure 6.1 shows the times of the five sample periods relative to the flows in the San Juan River.

The lowest magnitude runoff year was 1996 which also contained the most storm events (12) post runoff. The 1994 hydrograph was intermediate in both magnitude and the number of storm events (9), however, the amount of runoff was considered above average for the post dam period (1962-current). The highest magnitude runoff (1995) during the habitat quality period, also had the lowest (5) number of post runoff monsoon summer storms. As noted in Table 6.3, a number of physical and biological parameters were measured during the course of this investigation. The sample design (Table 6.2) provided data from various reaches of the San Juan River during three runoff cycles. Results are first summarized temporally, followed by a spatial analysis. In each analysis, the data is

Table 6.3. A Summary of the 1994, 1995, and 1996 Runoff Hydrograph and Subsequent Monsoon Periods Prior to Each Sample Date (Data from Four-Corners, NM).

	1994	1995	1996
Peak Runoff (cfs)	10,000	12,100	3,540
Days > 10,000	0	11	0
Days > 8,000	13	27	0
Days > 5,000	49	72	0
Days > 2,500	67	135	36
Storms [a]	9	5	12

[a] Summer/Fall storms after runoff but prior to the specified sample date.
1994 - November 15, 1994; 1995 - February 21, 1996; 1996 - September 20, 1996

evaluated on a river-wide basis as well as by habitat type (run or riffle). To determine significant differences by sample date, reach or habitat types, for the parameters measured in this study, a one-way ANOVA was preformed. A post ANOVA Tukeys HSD (%=.05) was used to determine which types, reaches, or habitats were significantly different from other factors. The complete statistical results can be seen in Appendix C.

Temporal Variations

Physical Parameters

The major physical parameters measured at each sample location involved the quantitative description of streambed materials. The three physical parameters measured characterized the bed structure. Wolman pebble counts, in combination with bed size fractions of materials less than 2 cms, quantitatively determined the size distribution of bed materials. The second physical parameter, depth to embeddedness (DTE), is a measure of the distance from the top of the substrate to the top of the layer of fines in which the substrate is embedded. It represents an index of the available interstitial depth for aquatic organisms. The third parameter, the percent of surface area embedded (PAE), is a measure of the two-dimensional surface area (% surface area), covered by fine material.

The substrate size is expressed by three calculated values D_{16}, D_{50}, and D_{84}. The overall average values for each trip, as well as the 95% confidence intervals, can be seen in Figure 6.2. In each case, the one way ANOVA indicated that significant differences were found between trips for all habitats combined. For the D_{84} and D_{50} values, the April 1995 trip was found to be significantly different from all other trips. For D_{16}, no significant differences were found. A comparison of the same three calculated values by habitat type also showed significant differences not only by trip but also between habitat type (Figure 6.2). On each sample date (with the exception of April 1994), riffles had significantly larger substrate size compared to run habitats. Although no significant differences were found for D_{50} values in riffle habitats by date, runs did demonstrate significant difference.

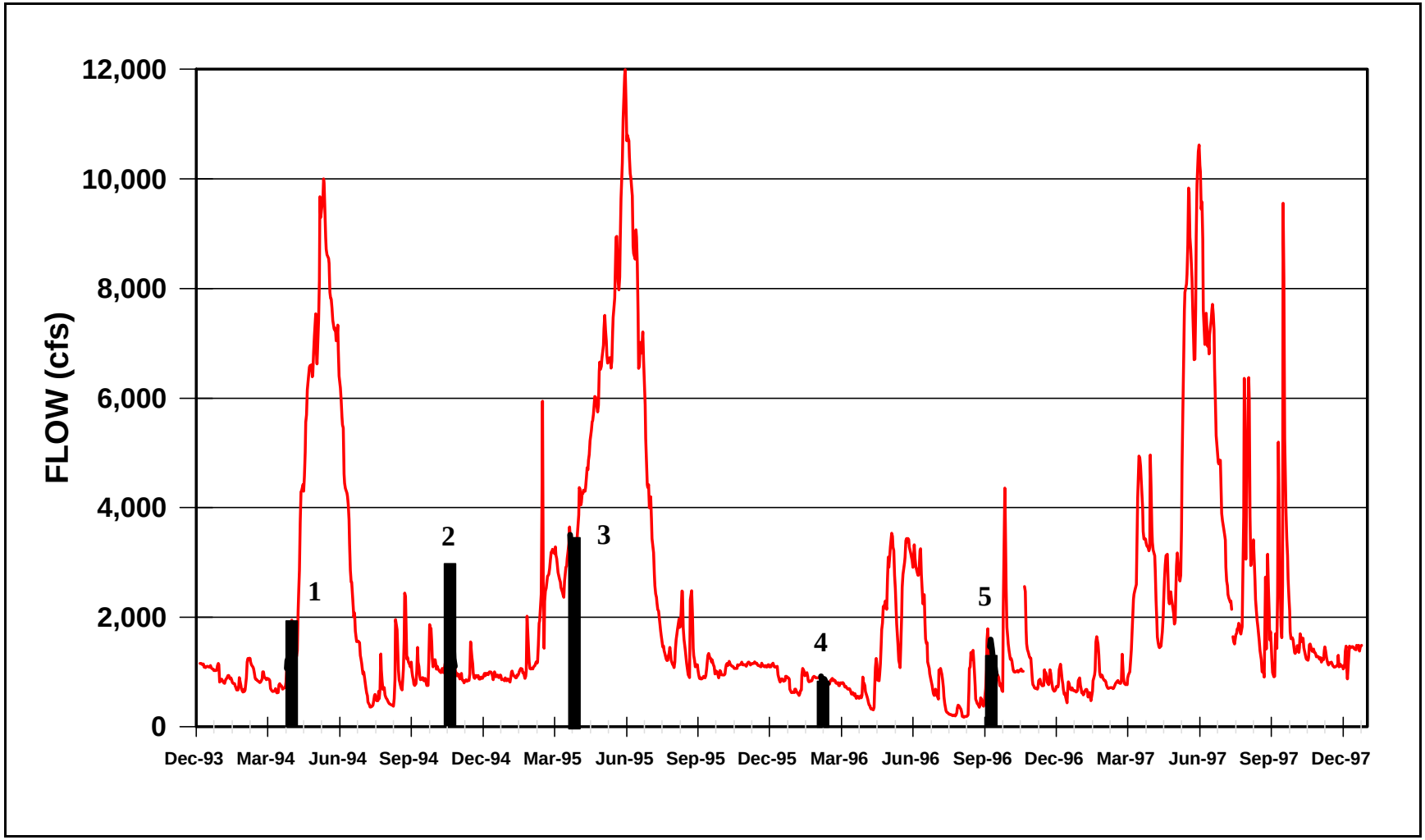

Figure 6.1 **The 1994 to 1997 Hydrograph at Four Corners, NM for the San Juan River. Habitat Quality Sample Periods Are Shown as Dark Columns on the Hydrograph**

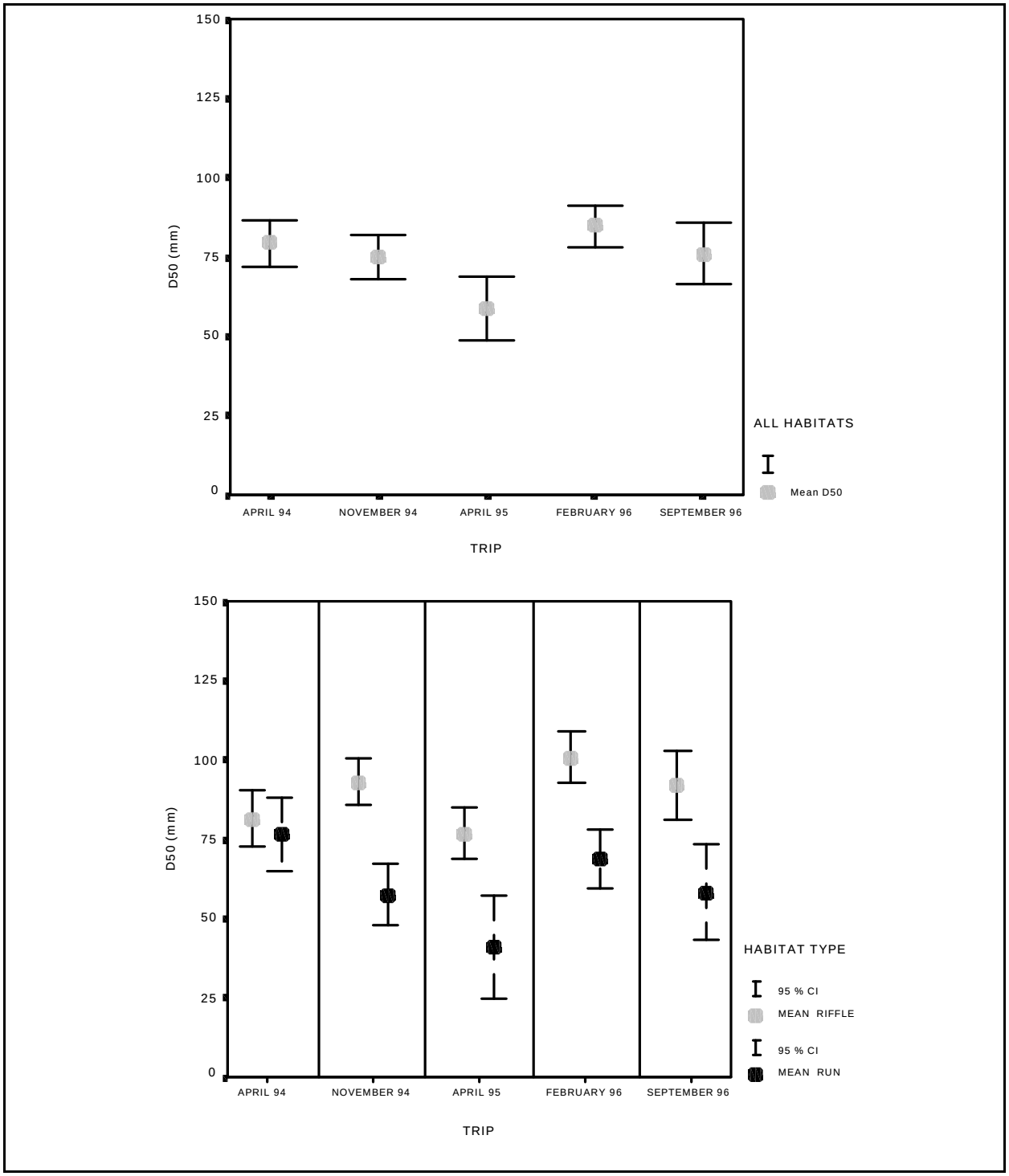

Figure 6.2 **The Temporal Distribution of the Substrate D_{50} Values for Each Trip Date for All Habitats Combined (above) and for Each Habitat Type (below) for the San Juan River**

Comparisons of the depth to embedded layer (DTE) for riffles and runs can be seen in Figure 6.3. For all habitats combined, the February 1996 trip was significantly less than all other trips. This sample date had the longest time period between the end of runoff and the sample date. In four of the five sample dates, riffles had deeper depth to embedded layer when compared to runs. As stated previously, the shallowest depth to embedded layer for both habitats occurred in February 1996.

The percent surface area embedded (PAE) represents a measure of the sand or silt covering the dominant substrate type. As can be seen in Figure 6.4, significant differences occurred between dates for all habitats combined and for separate habitats. For all habitats combined, no differences were found for April 1994 compared to the other dates, while November 1994, April 1995 and September 1996 were found to be significantly different from other trips. In addition, inspection of Figure 6.4 indicates that run habitats had significantly greater surface areas embedded when compared to riffle habitats for all five samples. Runs averaged between 32.5% and 56.9% surface area embedded while riffles averaged only 14% to 26.6%.

Biological Parameters

In order to define the trophic structure of the San Juan River, primary and secondary producers were quantified in the same locations where physical parameters were measured.

Primary producers were quantified by determining the *in-situ* standing crop of periphyton (gm/m^2) and the concentration of benthic detritus (gm/m^2) associated with the substrate. Periphyton biomass expressed as a river-wide mean concentration was significantly different for both the April 1994 and November 1994 sample dates compared to the other sample periods (Figure 6.5). April 1995, February 1996, and September 1996 were not significantly different from each other. River-wide maximum biomass levels of periphyton occurred in April 1994 (6.4 gm/m^2) and river-wide minimum concentrations occurred in September 1996 (1.9 gm/m^2). The comparison of periphyton biomass by habitat type demonstrates the same temporal pattern for each habitat type with no significant differences between habitats. The same significant differences by date noted in the river-wide comparisons was also found for the two habitat types (riffle and run).

The concentration of coarse particulate organic material (detritus) in the substrates of the San Juan River were found to differ by sample date. The September 1996 sample period had significantly greater (65.2 gm/m^2) biomass compared to the February 1996 and April 1995 samples. The April 1995 detritus levels were the lowest (21.7 gm/m^2) of any sample date. The April 1994 and November 1994 detritus concentrations were not found to be significantly different from February or September 1996.

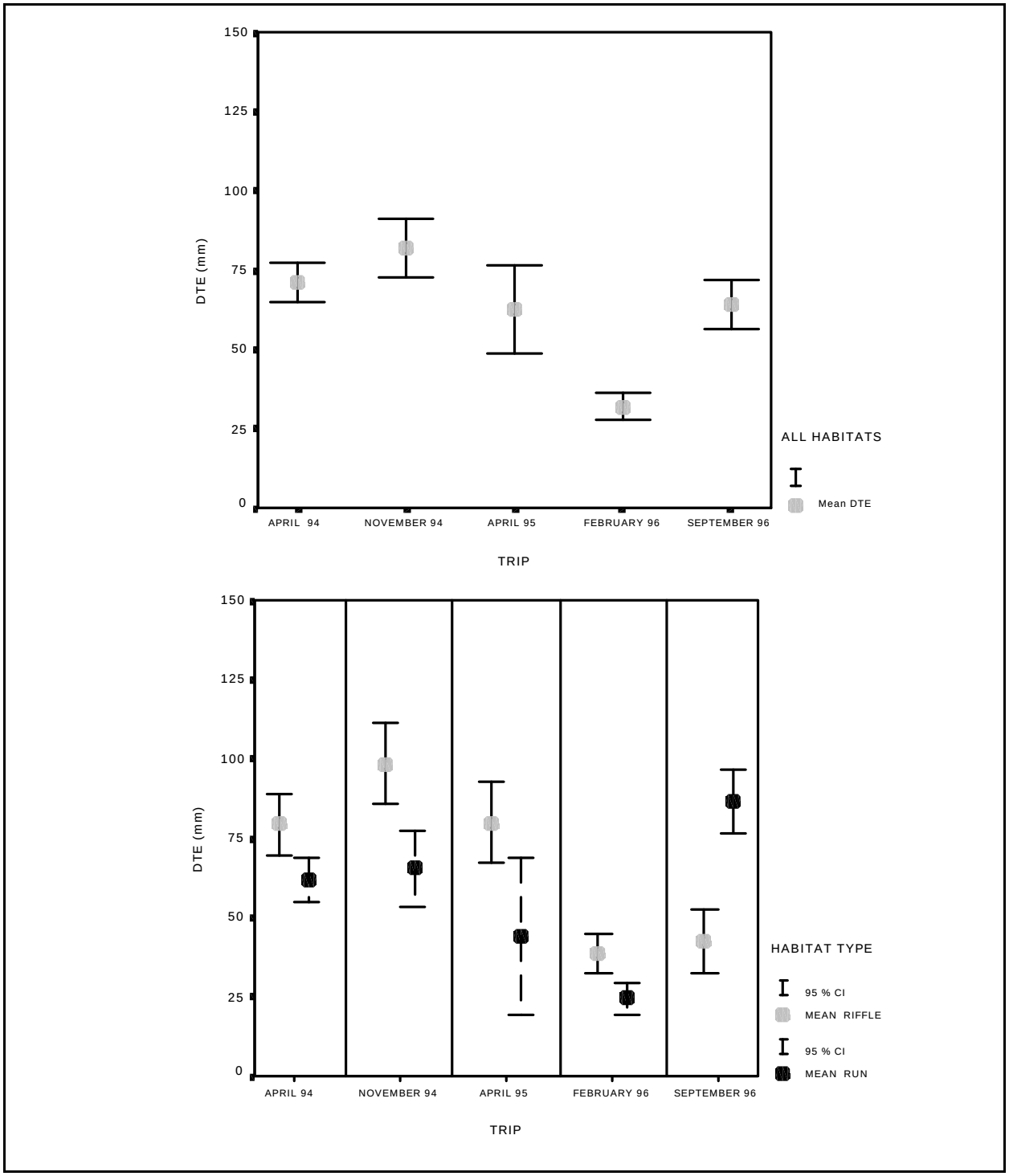

Figure 6.3 The Temporal Distribution of the Depth of Embedded Layer (DTE) for Each Trip Date for All Habitats Combined (above) and for Each Habitat Type (below) for the San Juan River

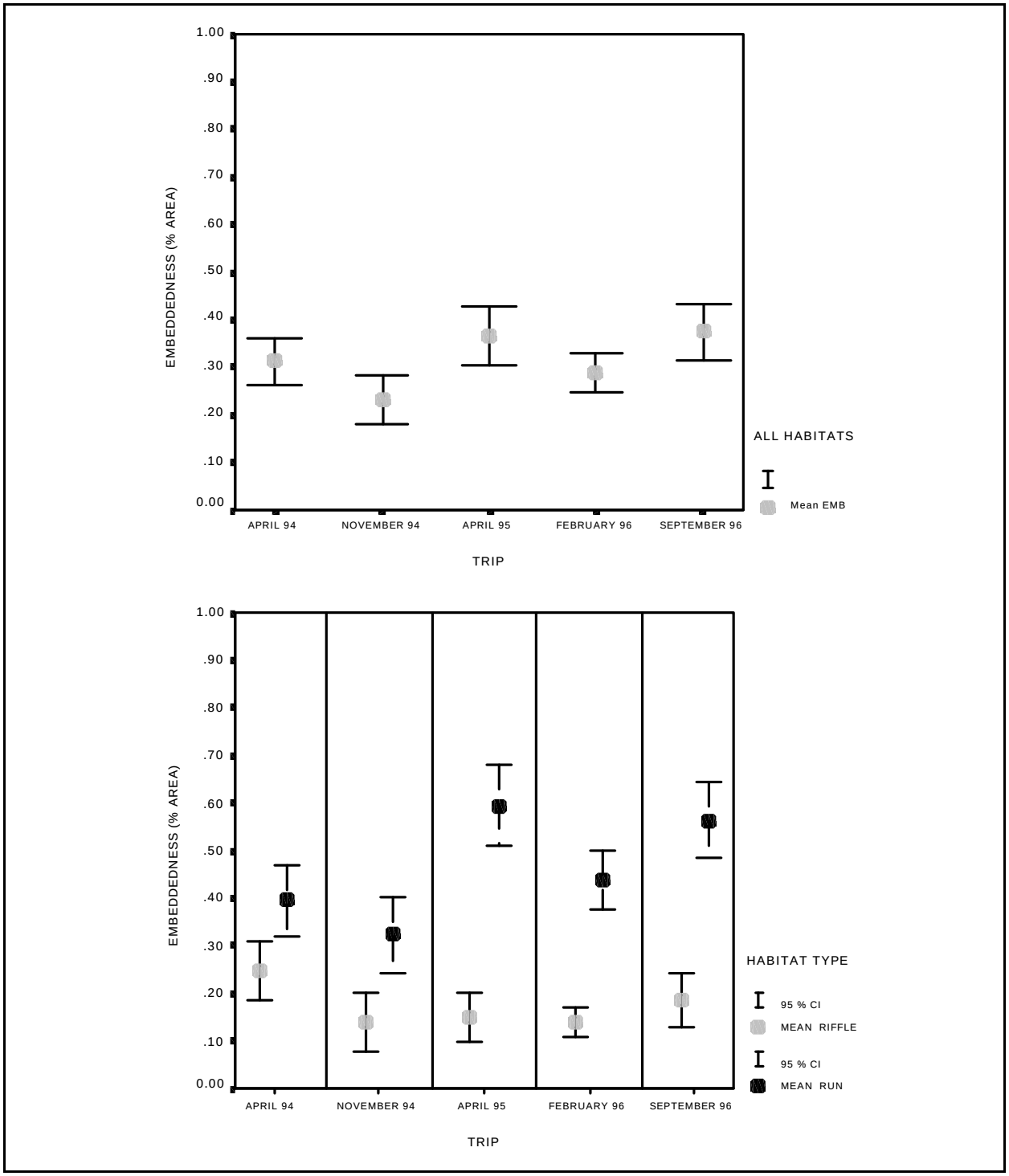

Figure 6.4 The Temporal Distribution of the Percent Surface Area Embedded (PAE) for Each Trip Date for All Habitats Combined (above) and for Each Habitat Type (below) for the San Juan River

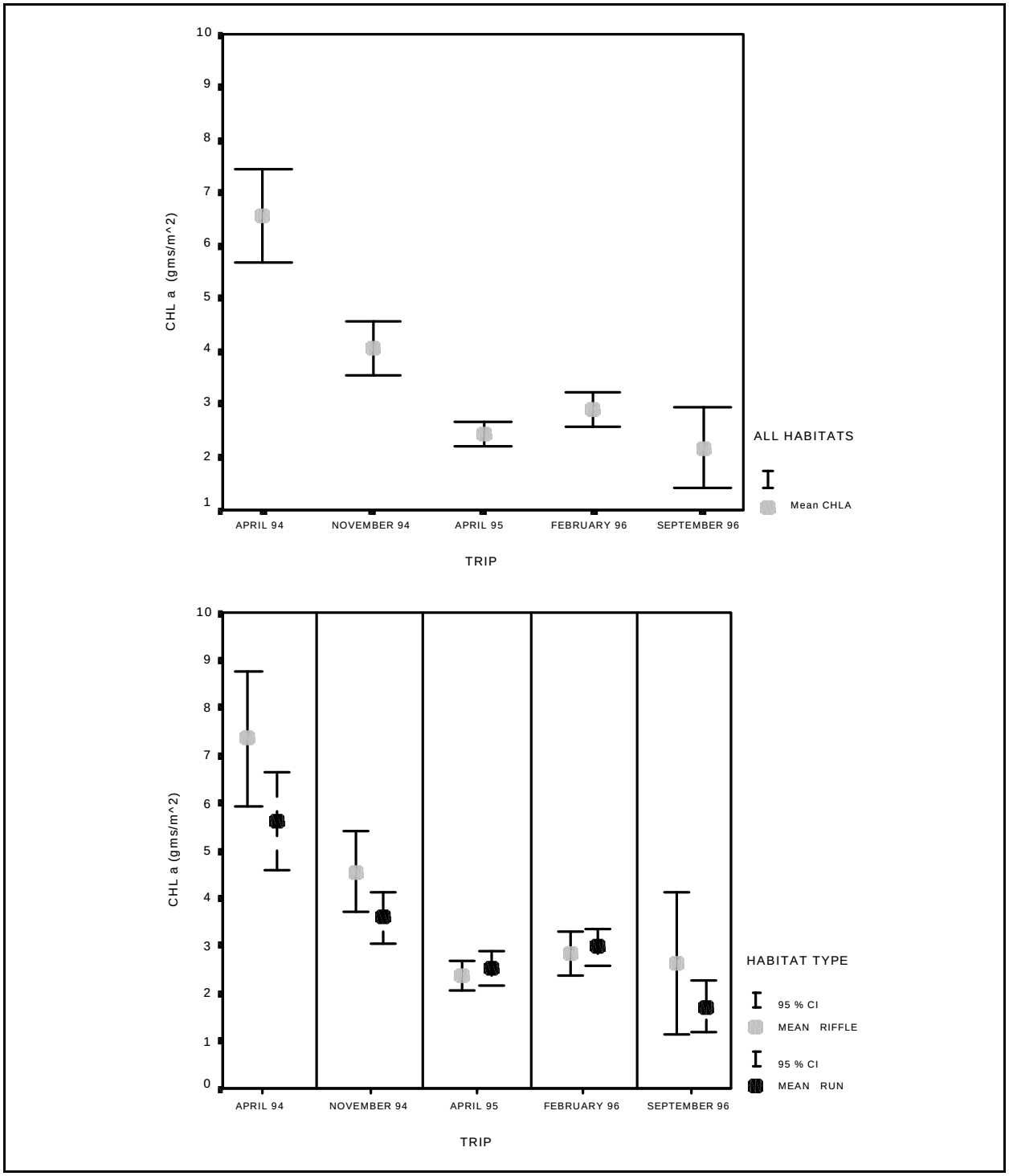

Figure 6.5 The Temporal Distribution of the Biomass of Periphyton (gms chla/m^2) for Each Trip Date for All Habitats Combined (above) and for Each Habitat Type (below) for the San Juan River

The concentration of detritus within habitats was also found to be significantly different by sample date. The pattern found was the same for each habitat and followed the river-wide mean concentrations. The comparison between habitats (Figure 6.6 lower graph) indicated that there was no difference between habitats for April and November 1994 but significant differences (riffles greater than runs) for April 1995, February 1996, and September 1996. The largest difference occurred in September 1996 with riffles having an average density of 99.8 gm/m^2 and runs only 30.9 gm/m^2.

Biomass of secondary producers was determined by quantitatively sampling the benthic macroinvertebrate community. The river-wide mean invertebrate dry weights (gm/m^2) for the San Juan River are presented in Figure 6.7. There were significant differences in the San Juan River by sample period. The highest invertebrate biomass estimates were found in April 1994 (5.5 gm/m^2) and February 1996 (5.25 gm/m^2). The lowest levels were found in September 1996 (0.74 gm/m^2). Significant differences between riffles and runs were found in four of the five sample dates with riffles having higher invertebrate biomass levels.

Because of the combination of runoff hydrograph characteristics and the post runoff storm events prior to fall sampling, it is difficult to separate the effects of different runoff characteristics. Post runoff storm events and their associated sediment loading may deteriorate or enhance the effects of a particular runoff pattern. Table 6.4 summarizes the response of the measured parameters pre- and post runoff for three years (1994, 1995, and 1996). Of the 48 pair-wise comparisons, fifteen (31%) were found to be significantly different. Most notable was the biological response to a low flow/high storm sequence which negatively decreased periphyton and invertebrates and positively increased detritus concentrations in both riffles and runs.

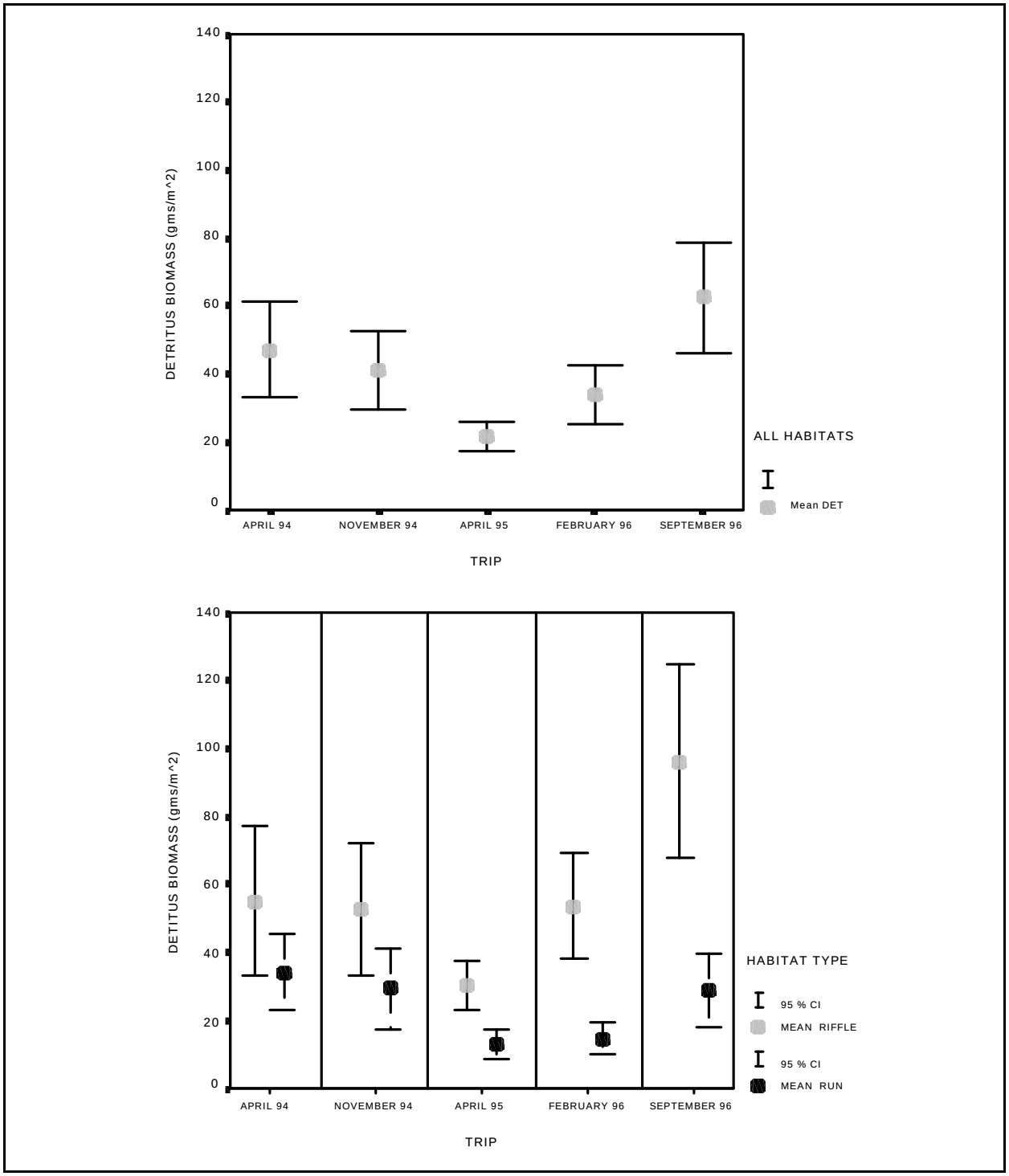

Figure 6.6 The Temporal Distribution of the Benthic Detritus (gms cpom/ m^2) for Each Trip Date for All Habitats Combined (above) and for Each Habitat Type (below) for the San Juan River

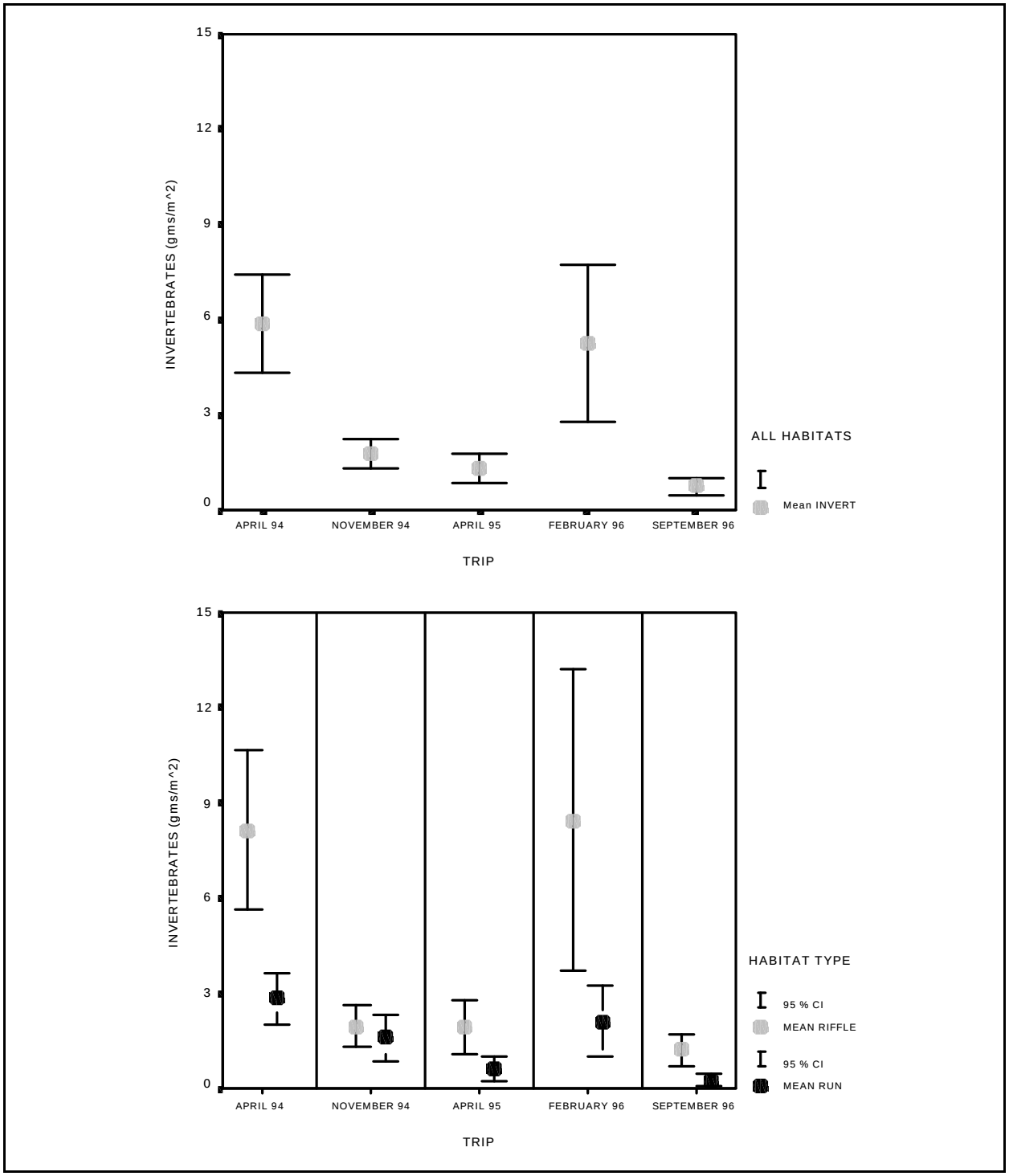

Figure 6.7 The Temporal Distribution of the Benthic Invertebrate Biomass (gm/m^2) for Each Trip Date for All Habitats Combined (above) and for Each Habitat Type (below) for the San Juan River

Table 6.4 The comparison between pre- and post-runoff samples for each physical and biological parameter measured in the San Juan River.

Run Off Magnitude	Low (1996)	Medium (1994)	High (1995)
RIFFLES			
Physical			
D_{16}	&	&	%
D_{50}	&	%	%
D_{84}	&	%	0
DTE	0	%	&
PAE	%	&	0
Biological			
Periphyton	0	&	&
Detritus	%	0	0
Invertebrates	&	&	%
RUNS			
Physical			
D_{16}	&	&	&
D_{50}	&	&	%
D_{84}	&	&	%
DTE	%	%	&
PAE	%	&	%
Biological			
Periphyton	&	&	&
Detritus	%	0	&
Invertebrates	&	0	0

Trends: +=increase; 0=no change; - =decrease; + or - =significant P#.05

Spatial Variations

In order to evaluate the spatial pattern exhibited by the parameters investigated in this study, mean values and confidence intervals (%=.05) were calculated by averaging the five sample dates. Reach 1 was only sampled once, but is included in this analysis. Significant differences for all habitats combined, as well as for riffles or runs, were initially determined by a one-way ANOVA followed by the Tukeys HSD which determined significant differences between specific reaches. All data was plotted by reach with mean values and 95% confidence intervals. Summary statistics are provided in Appendix C.

Physical Parameters

D_{50}, which estimates the size diameter of the median substrate, demonstrates significant differences by geomorphic reach both on a river-wide average and on a habitat specific basis (Figure 6.8). The river-wide lowest D_{50} values were found in Reach 1 (56 mm) and 3 (57 mm) with the largest median substrate in Reaches 6 (94 mm) and 8 (80 mm). On a river-wide basis, there appeared to be a decreasing trend with distance downstream, with the exception of Reach 2 which increased to 80 mm. Reach 2 is a canyon bound reach with steep gradient and large substrate associated with side canyon alluvial fans.

The comparison between habitat types also demonstrated significant differences between geomorphic reaches. Riffle habitats had significantly larger D_{50} values in six of the eight geomorphic reaches with its longitudinal pattern similar to the river-wide pattern. Runs were also similar to riffles in their distribution except for Reach 8, which decreased.

The percent surface area embedded (PAE) did not demonstrate any longitudinal pattern on a river-wide or habitat specific basis. Reaches 2, 5 and 8 had significantly lower PAEs compared to Reaches 3, 4, 6, and 7. On a habitat specific basis, riffles had significantly low PAEs in all eight geomorphic reaches (Figure 6.9) ranging from 7% to 29%. Runs were higher, ranging from 28% to 70%.

The depth to the embedded layer (DTE) plotted on a river-wide basis indicated that the most embedded geomorphic reaches were 3 and 8 (33 mm and 30 mm, respectively), while Reach 2 was the least embedded (85 mm). Comparisons made by habitat type indicated that only Reach 6 had a significant difference between DTEs in riffles and runs (Figure 6.10).

Biological Parameters

The spatial patterns observed in the biological components (periphyton, detritus, and macroinvertebrates) were very similar with the upper Reaches (6, 7, and 8) of the river being higher than the middle Reaches (3, 4, and 5). Reach 2 had the lowest concentration of organic materials.

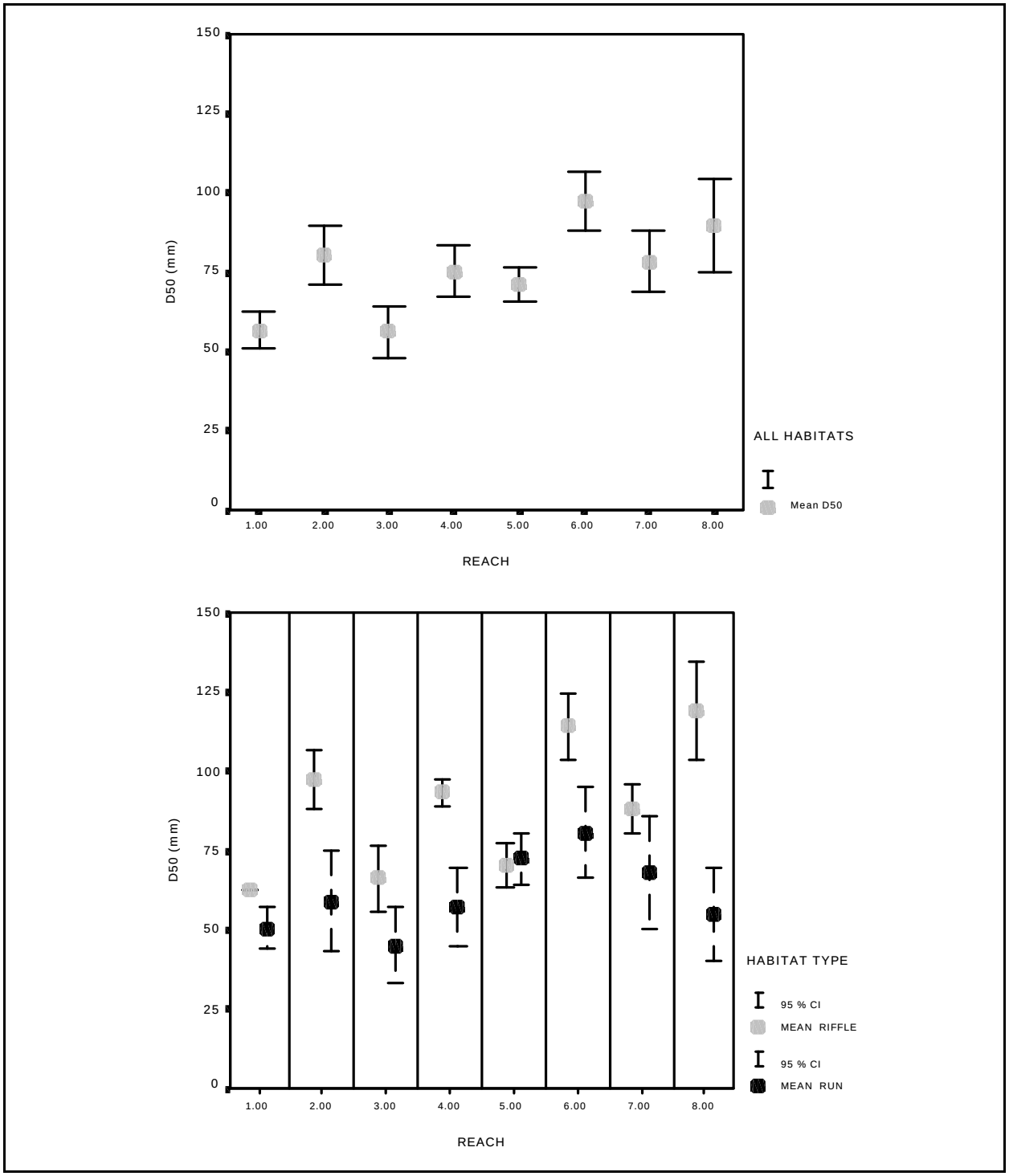

Figure 6.8 The Spatial Distribution of the D_{50} for Each Trip Date for All Habitats Combined (above) and for Each Habitat Type (below) for the San Juan River

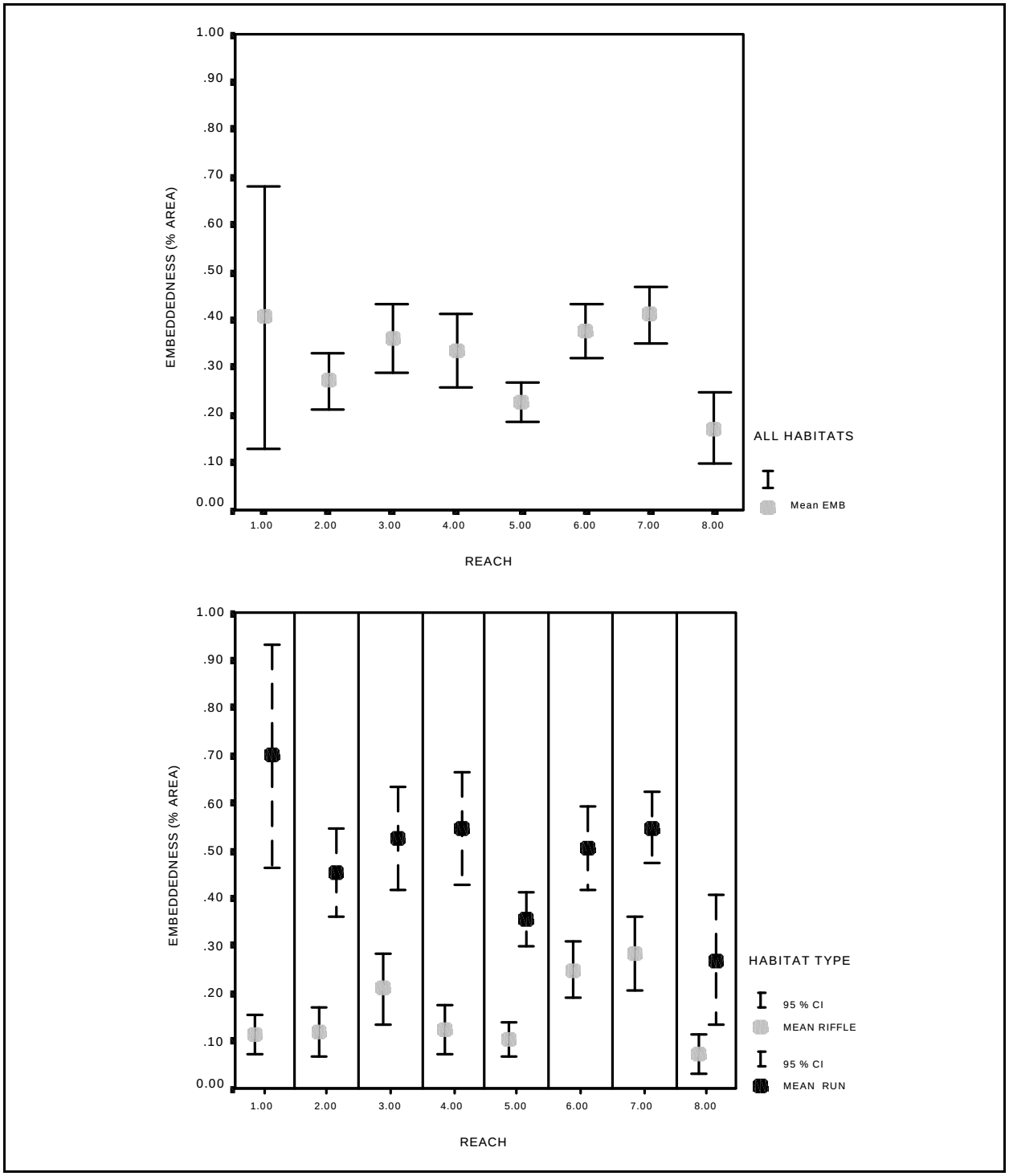

Figure 6.9. The Spatial Distribution of the Percent Surface Area Embedded for Each Trip Date for All Habitats Combined (above) and for Each Habitat Type (below) for the San Juan River

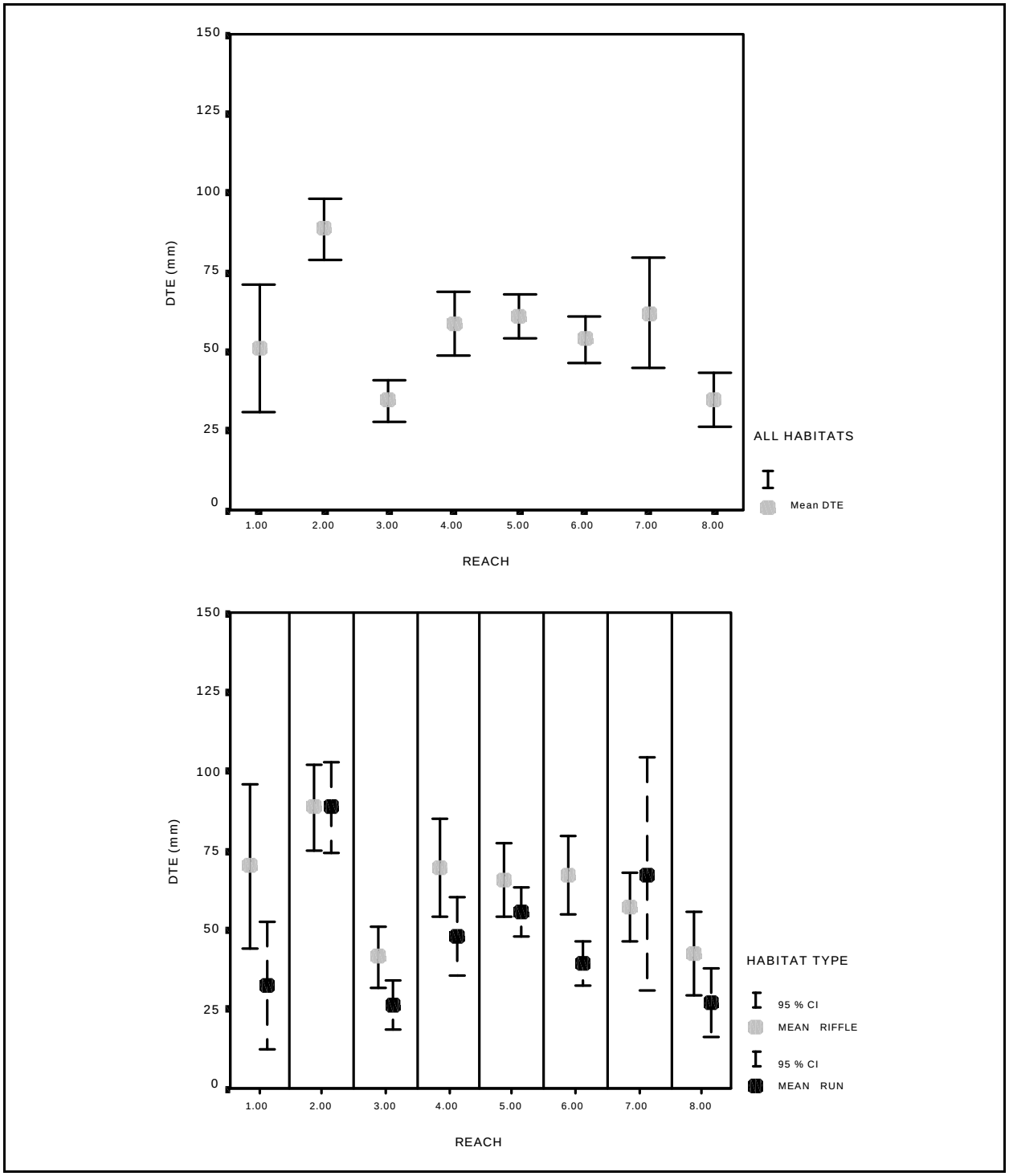

Figure 6.10 The Spatial Distribution of the Depth to Embedded Layer for Each Trip Date for All Habitats Combined (above) and for Each Habitat Type (below) for the San Juan River

Periphyton biomass (Figure 6.11) peaked in Reach 6 and was lowest in Reach 2, both on a river-wide basis as well as a habitat specific basis. It is interesting to note that there were no significant differences between riffles and runs in any geomorphic reach in the San Juan River.

Benthic detritus demonstrates a strong longitudinal pattern with the lowest biomass in Reach 2 (38 gm/m^2) which steadily increased with distance upstream, reaching its highest river-wide average in Reach 8 (92 gm/m^2). The comparison between habitats (Figure 6.12) indicated that riffles contained significantly greater detrital biomass in five of the eight reaches. For both habitats, the same longitudinal pattern was evident.

The longitudinal pattern for benthic macroinvertebrates can be seen in Figure 6.13. As in the spatial pattern observed in detritus, invertebrates also increased with distance upstream in both a river-wide and habitat specific manner. Lowest densities (0.40 gm/m^2) were found in Reach 2 and the highest densities (12.4 gm/m^2) in Reach 8. A comparison by habitat types indicated that five of the eight reaches had significantly greater invertebrate biomass in riffles compared to run habitats. The greatest differences between habitats occurred in Reaches 6, 7, and 8 within the San Juan River.

DISCUSSION

A similar survey of abiotic and biotic parameters was undertaken on the Colorado River during 1994 and 1995 (Lamarra 1999) utilizing the same protocols. In the case of the Colorado River, eleven geomorphically similar reaches were sampled compared to the eight in the San Juan River. The Colorado River also exhibited vastly different gradients compared to the relatively constant gradient of the San Juan River (Figure 3.1).

Comparisons of the physical and biological parameters can be seen in Figure 6.14 for both rivers on a river-wide average (riffles plus runs) by geomorphic reach. The data are averages over all sample periods.

The physical data (D_{50}, depth to embedded layer, and percent surface area embedded) demonstrates that the ranges of data encountered within the two river systems are similar. The D_{50} values in the San Juan River have less variability river-wide than do the D_{50} values in the Colorado. However, comparing areas of similar gradient (all of the San Juan vs. Reaches 7, 8, and 9 of the Colorado) resulted in similar D_{50} values and variabilities.

The biological data between the two rivers was very similar both in spatial distribution and magnitude. The exception was periphyton biomass (expressed as chlorophyll-*a*). The biomass of chlorophyll-*a* was two to four times greater in the San Juan River. This may be a reflection of the more turbid environment in the San Juan River and the associated low light adaption of increased chlorophyll levels. Steemann-Nielson and Jorgenson (1968) and Jorgenson (1969) found that algal cells of green algae adapted to high light intensity by lowering their chlorophyll-*a* content per cell, while those algae in low light had ten times more chlorophyll per cell. The actual rate of photosynthesis was not much greater in the high light climate compared to the low light climate.

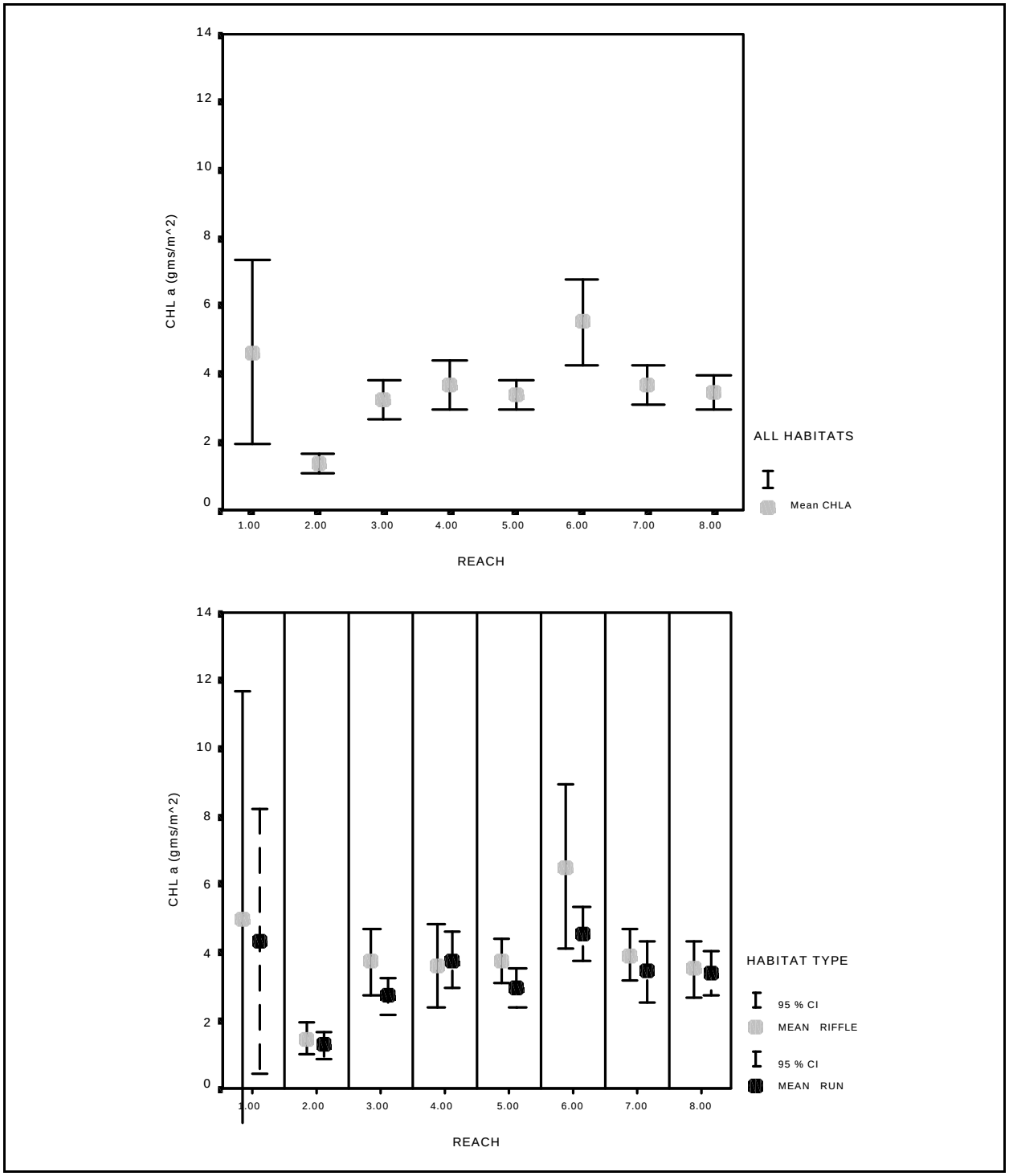

Figure 6.11 The Spatial Distribution of Periphyton Biomass (gms chla/m^2) for Each Trip Date for All Habitats Combined (above) and for Each Habitat Type (below) for the San Juan River

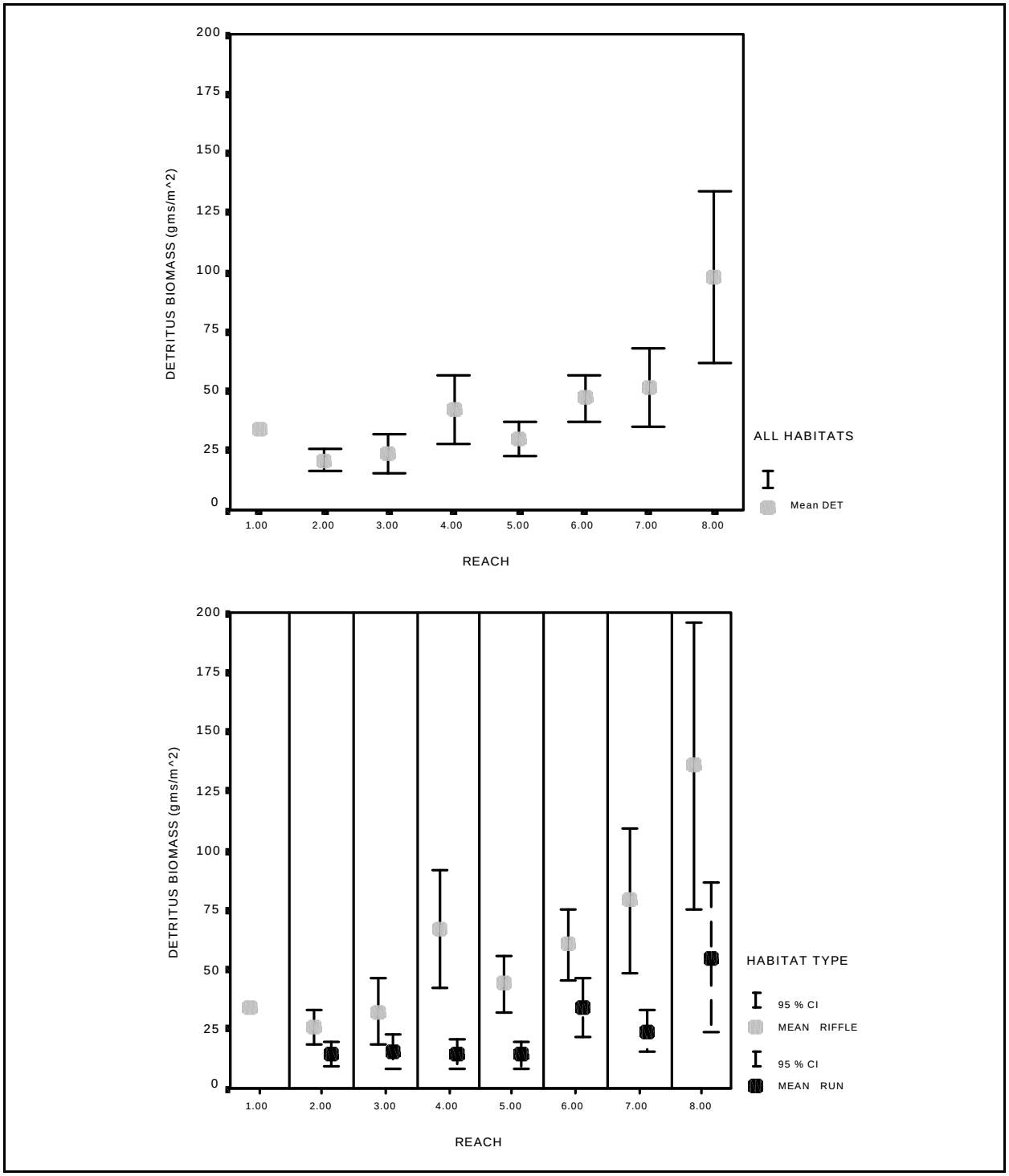

Figure 6.12 The Spatial Distribution of Benthic Detritus (gm/m^2) for Each Trip Date for All Habitats Combined (above) and for Each Habitat Type (below) for the San Juan River

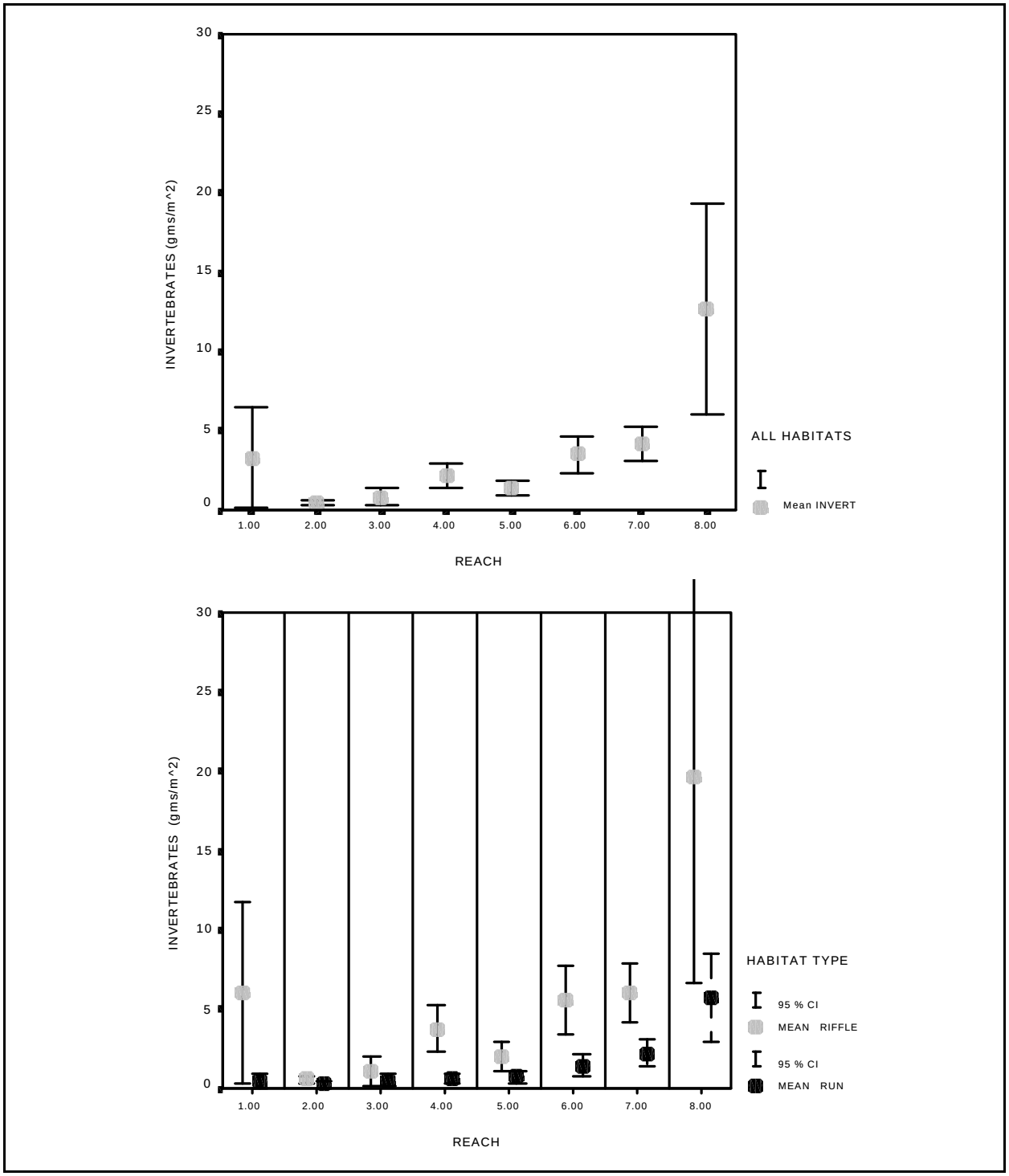

Figure 6.13 The Spatial Distribution of Benthic Invertebrates (gm/m^2) for Each Trip Date for All Habitats Combined (above) and for Each Habitat Type (below) for the San Juan River

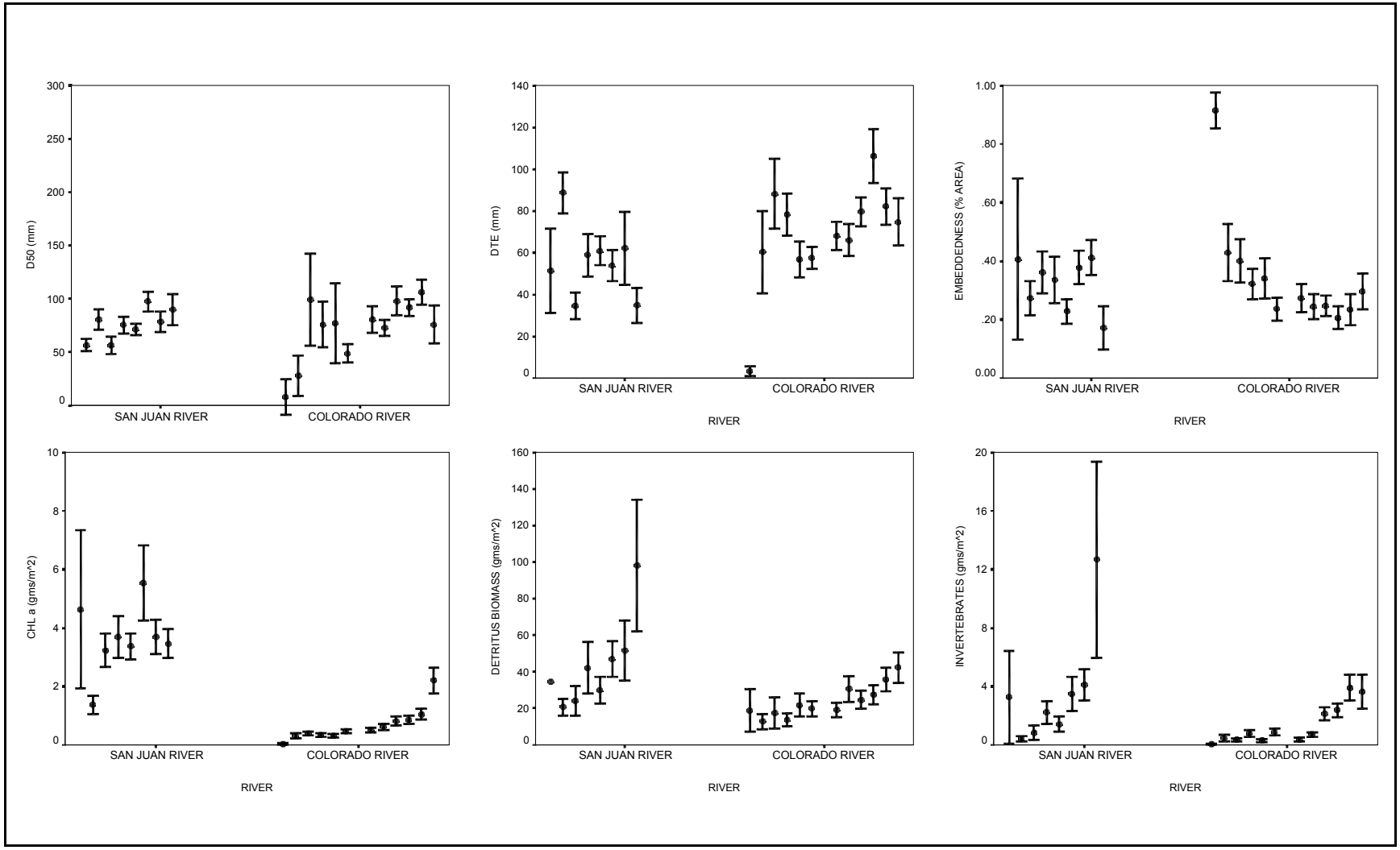

Figure 6.14 The comparison for physical (above) and biological (lower) trophic parameters collected on the San Juan and Colorado River during 1994, 1995, and 1996. Within each river, the lowest geomorphic reach is on the left, with movement upstream toward the right. The San Juan has eight reaches, while the Colorado has eleven.

Detritus and invertebrates were slightly higher in the San Juan but overlapped with most Colorado River reaches (especially Reaches 7, 8, and 9) where river gradients are similar to the San Juan River.

Figure 6.15 provides an overall summary of the data collected on the San Juan and Colorado rivers by habitat type. These data are averages and 95% confidence intervals for all dates (1994-1996) and all river reaches by habitat type. It is interesting to note that for all parameters, the two rivers had identical patterns when comparing riffles to runs. In both rivers, riffles had higher D_{50}, DTE, periphyton, detritus, and invertebrates while runs had higher percent embedded surface areas. A comparison between the rivers indicated that D_{50} and percent embedded surface areas did not differ for either habitat between rivers. The DTEs in riffles was, however, significantly greater in the Colorado (95 mm) compared to the San Juan (60 mm) while runs remained the same. Periphyton and invertebrates were significantly greater in the San Juan for both habitat types while detritus was significantly greater only in riffle habitats. It should be noted that although both data sets cover approximately 200 river miles, the Colorado data include areas of lower gradient and lower productivity. This is reflected in the lower overall biomass of the biological parameters.

SUMMARY AND CONCLUSIONS

Riffle and run habitat types were sampled for abiotic and biotic parameters before and after spring runoff for the years 1994, 1995 and 1996. The physical parameters (depth to embedded layer, D_{50}, and percent surface area embedded) were significantly different between riffles and runs. Biological parameters (periphyton, detritus and invertebrates) were not different between habitat types. The comparison of sample locations (geomorphic reach) by habitat types for the abiotic and biotic parameters indicated significant longitudinal differences for periphyton, detritus and invertebrates with upper geomorphic reaches having higher densities (greater biomass) than lower reaches. The comparison between the lower 200 miles of the Colorado with the San Juan study area indicated similar characteristics in abiotic conditions and similar biomass levels for biological components.

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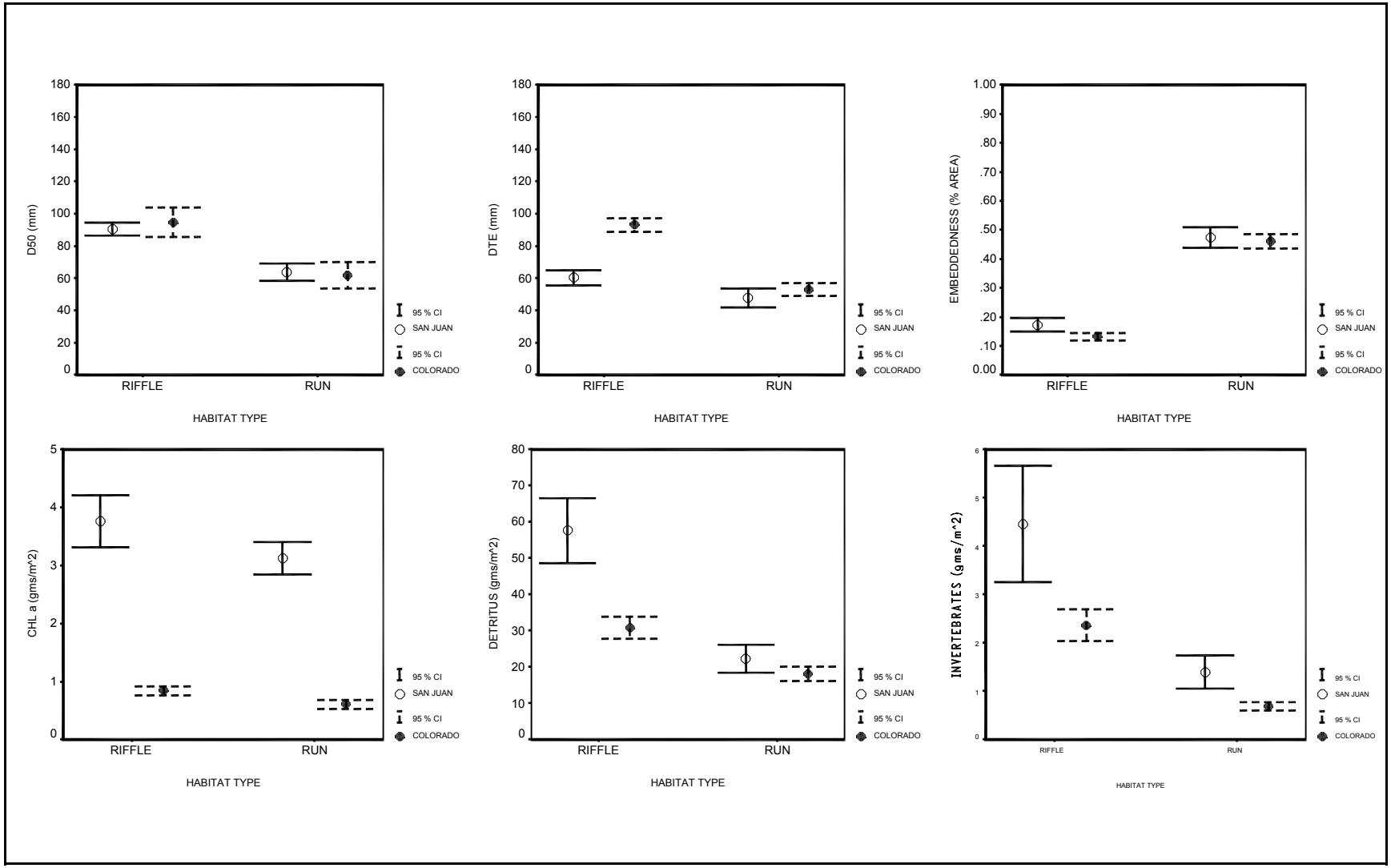

Figure 6.15 the Overall Averages of Physical (above) and Biological (lower) Benthic Parameters Collected in Riffles and Runs in the San Juan and Colorado Rivers

CHAPTER 7: BACKWATER PRODUCTIVITY

INTRODUCTION

The highly ephemeral nature of backwaters, the principal habitat for young-of-year (yoy) Colorado pikeminnow and other native fishes, is well known to Upper Basin researchers. Storm events within the San Juan River Basin are common during the summer-autumn monsoon season (typically July to October). These storms have caused discharge spikes in excess of 8,000 cfs during the recovery program and are often accompanied by large inputs of suspended sediment from various tributaries. The combination of these pulses of discharge and sediment have strong implications for the stability and productivity of backwaters and therefore the suitability of these habitats for pikeminnow yoy and young of other native fishes. Pikeminnow yoy may be particularly vulnerable to these effects because adults spawn typically in mid-July, later than other native fishes such as bluehead sucker which spawn from about May through June. Hence, pikeminnow yoy are generally more prevalent in these habitats during this monsoonal period than earlier spawning fishes and are also relatively smaller sized due to the later spawn, factors which may predispose these individuals to higher risk of downstream displacement.

Storm events can impact the quality of backwater habitats in several ways. One potential impact is a decrease in backwater depth caused by the gradual filling of these habitats with fine sediments. This phenomenon occurs naturally due to background suspended sediment loads, but can be accelerated greatly by storms. Water depth has been determined to be an important factor in the usage of backwaters by pikeminnow yoy in other Upper Basin studies (Holden 1977, Tyus and Haines 1991). In studies on the lower Green River, pikeminnow yoy were significantly more abundant in backwaters greater than 0.3 m than those less than that depth (Melissa Trammel, Utah Division of Wildlife Resources, pers. comm.). Thus, filling of backwaters following storms may reduce the availability and suitability of these habitats for this life stage. Additionally, storms can disrupt algal and invertebrate production through a variety of mechanisms. These mechanisms include the physical displacement of organisms, the smothering of periphyton (algae) and invertebrates via sediment deposition, or simply through a temporary reduction in primary productivity caused by increased turbidity.

Zooplankton and benthic invertebrates (primarily chironomids) are the major food sources for pikeminnow larvae and yoy, respectively (Vanicek 1967, Osmundson and Kaeding 1989). Stable flows should increase growth rates of these fishes by increasing the abundance of those food organisms. Improved growth should benefit these fishes by reducing susceptibility to predation (Kaeding and Osmundson 1988, Bestgen et al. 1997) and by improving overwinter survival (Thompson 1989, Bestgen 1996, Cargnelli and Gross 1997). So, developing a greater understanding of how the frequency and severity of storms affects the quality and productivity of these habitats should be important information for use in the recovery of this species. Management options may exist to ameliorate these negative effects.

The objectives of this study were to: (1) determine whether and to what degree storm events affect various measures of backwater productivity; (2) determine whether longitudinal patterns in various measures of backwater productivity existed; and (3) determine whether various measures of productivity in San Juan River backwaters differed from those in pikeminnow nursery areas of the Colorado and Green Rivers.

STUDY AREA

A study was initiated in the summer of 1995 to address the preceding objectives. To facilitate research efforts the San Juan River was divided into four non-contiguous, arbitrary reaches, which were delineated as follows: Reach 1 (RM 224-195), or Navajo Dam to Bloomfield bridge; Reach 2 (RM 158-119), or Hogback to Four Corners bridge; Reach 3 (RM 93-52), or Montezuma Creek bridge to Mexican Hat; and Reach 4 (RM 40-2), a canyon-bound reach ending at Clay Hills Crossing. However, once the study was underway, the data was analyzed utilizing the eight geomorphically unique reaches identified earlier that year (Bliesner and Lamarra 1995) to maintain consistency with other studies (Figure 1.1). Beginning in 1996, sampling in Reaches 7 and 8 was discontinued due to a shift in research emphasis by the recovery program. Sampling occurred at various times (approximately monthly) prior to, usually during, and then after the monsoonal seasons in 1995, 1996, and 1997 and prior to runoff in the springs of 1996 and 1997. Table 7.1 presents a summary of the timing of sampling trips and the number of backwater habitats sampled during each trip by geomorphic reach.

The geomorphology of the San Juan River changes considerably throughout its course. Reach 1 is a canyon-bound reach, heavily influenced by the elevation of Lake Powell (Figure 1.1). It is the lowest gradient reach of the river, most similar in gradient to Colorado pikeminnow nursery areas on the Colorado and Green Rivers, and contains numerous migrating sand bars. Backwaters within this reach are associated with these bars at reduced discharge and more so with side canyon mouths at higher flows. Reach 2 is also completely canyon-bound, but is generally narrower, steeper, and more meandering than Reach 1. Due to these factors, backwaters are typically scarce and usually associated with side canyons or debris fans. Reach 3 is a broad floodplain, braided channel with relatively low gradient, high sinuosity, and a high percentage of sand substrate. Backwaters are usually associated with main channel bars and side channels, although several major tributaries enter the river in this reach and produce backwaters at higher flows. The surface area of backwaters can be the highest in the river in this reach, however, these backwaters are also the most susceptible to filling by storms as well. Reach 4 is somewhat of a transitional reach with moderate gradient, sinuosity, and braiding. Backwaters are relatively scarce in this reach and are mostly associated with cobble and sand bars and secondary channels. Reach 5 is a highly braided reach, steeper than downstream reaches, with dense riparian habitat consisting mainly of Russian olive and more cobble and gravel than downstream reaches. Backwaters are less easily perturbated by storms in this reach and are associated with both secondary channels and cobble/sand bars along the shoreline and in the mid-channel. Reach 6 is a much more channelized section of river that is fairly steep, containing high percentages of cobble and gravel substrate and relatively few backwaters. The Animas River enters at the upstream extent of this reach. Like Reach 6, Reach 7 is highly channelized, but has a more

armored cobble bottom and is generally less turbid. Again, backwaters are quite scarce in this reach, typically associated with cobble and sand bars, and less susceptible to perturbation. Reach 8 occurs immediately below Navajo Dam and thus is most directly affected by its operation. It has the least turbid, coldest water of any of the reaches and is primarily a single channel with little braiding. A number of its backwaters have been created or altered by human activity. The uppermost section of this reach occurs upstream of any tributaries and is managed as a blue ribbon rainbow trout fishery (Bliesner 1999a).

Sampling occurred in the Colorado River for all 12 trips during which sampling occurred in the San Juan; however, since only one backwater was sampled on the Colorado during each of the first four trips, these data were not included. Two to six backwaters were sampled on any given trip between the Highway 191 bridge west of Moab, Utah, to just below Potash boatlaunch, approximately 18 miles downstream. This reach is located within a general area where capture rates of young pikeminnow are relatively high (McAda et al. 1994). Sites were accessed with a motorized raft. This is a relatively low gradient stretch of river (~1-3 ft/mile) dominated by slow, sand-bottomed runs and intermittent sand bar complexes.

Table 7.1 The number of backwaters sampled per geomorphic reach from 1995 through 1997 by dated and numbered sampling period. Mean discharge (Q) during each trip as measured at Four Corners, New Mexico (USGS no. 09371010) is also indicated.

			GEOMORPHIC REACH								MEAN Q (cfs)
YEAR	TRIP DATE	TRIP #	1	2	3	4	5	6	7	8	
1995	August 4-12	1	1	1	4	2	3	1	3	1	1356
	September 6-15	2	2	3	4	2	3	1	3	1	1475
	November 2-8	3	2	2	3	2	3	1	3	1	1096
1996	April 15-19	4	4	4	4	4	4	4	NS	NS	583
	July 22-25	5	2	1	4	4	4	4	NS	NS	514
	August 26-29	6	3	3	4	4	3	3	NS	NS	1313
	December 2-6	7	2	1	4	3	4	3	NS	NS	901
1997	February 5-10	8	2	0	2	2	3	1	NS	NS	898
	April 22-23	9	1	1	3	3	1	3	NS	NS	1663
	August 12-13	10	1	1	4	2	2	2	NS	NS	2998
	September 16-18	11	3	1	3	4	3	0	NS	NS	3527
	October 20-22	12	3	0	2	4	2	2	NS	NS	1278

NS = not sampled

Sampling on the Green River did not commence until the third year, during trips 9-12 (see Table 7.1). Two to four backwaters were sampled during each trip from Mineral Bottom boatlaunch (near Dead Horse Point, Utah) upstream about eight miles. The physical characteristics of the Green River in this area are very similar to the Colorado River stretch described above, but with generally more side canyons. Sampling usually occurred in backwaters within these side canyons, as these were often the only habitats available; whereas sampling in the Colorado usually occurred in backwaters associated with main channel sand bars. This reach also occurs within a larger area known to provide good nursery habitat for young pikeminnow (McAda et al. 1994).

A variety of physical and biological parameters were measured in backwater habitats. Physical parameters included: (1) water depth; (2) total suspended solids; (3) dissolved oxygen; and (4) temperature. Water depth appears to be important to some fishes and might be negatively affected by storms. Total suspended solids is an indirect measure of potential sediment-related impacts of storms on primary and secondary productivity. Dissolved oxygen and temperature are basic water quality parameters that could also influence habitat suitability for fishes. Measures of productivity included: (1) phytoplankton biomass; (2) zooplankton abundance; (3) periphyton biomass; (4) benthic invertebrate biomass; and (5) benthic detrital biomass. Phytoplankton abundance is an indirect measure of backwater stability, as higher levels are usually present under more stable conditions, and it also represents a food source for herbivorous zooplankton. Periphyton, detritus, benthic invertebrates, and zooplankton represent potential food sources for young native fishes. A detailed description of the methodology employed in the measurement of these parameters follows in the Methods section.

METHODS

Water depth (m)

Taken at three equidistant points along each of four equally spaced transects using a stadia rod and measured to nearest 0.01 m. Transects range from the mouth (T1) to the closed end or toe (T4) of the backwater. Mean water depth in each backwater was calculated using these 12 measurements.

Total Suspended Solids (mg/L)

Water samples were taken at transects T2, T3, and T4 and composited in a 1-pint bottle. Subsample of 100 ml was filtered, oven-dried at 40° C, and weighed to nearest mg.

Temperature (^{o}C)

Taken at every point in which water depths were taken (total 12 points per backwater) and also in adjacent river using Hydrolab unit.

Dissolved oxygen (mg/L)

Measured at the midpoints of transects T2 and T4 and also in river adjacent to backwater with Hydrolab unit.

Phytoplankton (µg/L)

Water samples were collected just below the water surface with ½-pint plastic bottles at transects T2 and T4. These samples were wrapped in aluminum foil and frozen. The samples were thawed and filtered in the laboratory for analysis of chlorophyll a content using a spectrophotometer.

Zooplankton (#/m^3)

Horizontal plankton tows were pulled just beneath the water surface. Net aperture was 11.2 cm diameter (0.01 m^2 area). One tow was pulled at transects T2 and T4, or wherever water was deep enough to sample. Distance of tow was recorded to calculate total water volume sampled. Samples were rinsed into whirl packs and preserved in isopropyl alcohol for later enumeration.

Periphyton (mg/m^2)

Sampled with 1.25-inch diameter clear plastic tube. Inserted just below the substrate, the core was lifted out intact by keeping hand over the bottom of the sampler. Core could be viewed from the side and was slowly removed with only uppermost layer of periphyton-covered sediment retained. Samples were stored in aluminum-wrapped whirl packs and placed on dry ice. Samples were collected at transects T2 and T4. Chlorophyll a content was determined using a spectrophotometer.

Benthic invertebrates (g/m^2)

Sampled with Ekman-type dredge at midpoint of transects T2, T3 and T4. Each sample encompassed an 18.6 cm x 14.4 cm, or 0.027 m^2 area. Samples were placed in zip-lock bags or jars and preserved in isopropyl alcohol. Biomass was determined by first measuring the volume of invertebrates (ml) per sample in the laboratory. A relationship was then established between volume and total dry weight (to nearest 0.1 g) of invertebrates for a subset of the total samples collected. This mathematical relationship was then applied to volumes determined for the remaining samples.

Detritus (g/m^2)

Coarse and fine particulate organic matter found in benthic invertebrate samples was separated from inorganic material, oven-dried at 60° C, and weighed to the nearest 0.1 g.

Sediment (% dry wt.)

Collected within approximately the upper 15 cm of substrate in the backwater with 5-cm diameter coring tube. Sample was stored in a zip-lock bag, oven-dried at 60°C, and sieved. Each size fraction was weighed to the nearest 0.1 g.

RESULTS

Hydrology

San Juan River

Considering that discharge played such a large role in the findings of this study, it is worth first considering the timing of sampling trips relative to the hydrograph. A total of 12 sampling trips occurred over the 3-year study. The timing of these trips is superimposed over the San Juan River hydrograph for the 1995 to 1997 period (Figure 7.1). The first series of trips in 1995, which followed an above average runoff (1,625,000 ac-ft for March-July period), occurred prior to (August), during (September), and after (November) what could be considered a relatively mild monsoon season compared to what was observed in the subsequent two years. The next sampling trip in April, 1996, preceded a below average runoff (432,000 ac-ft) and followed the longest storm-free period (5½ months) observed during the entire study. Sampling occurred again after runoff in July on the descending limb of a small storm, in August at the peak of a larger storm, and again in December at base flow, but following several large storms. Sampling occurred two months later in February, 1997, immediately following a small storm, and again in April after a series of large storms, prior to the bulk of runoff. The volume of runoff in 1997 (1,319,000 ac-ft) was nearly equal to 1995. Lastly, sampling occurred throughout the 1997 monsoon season in August, September, and October. The first two trips occurred during large storms, while the last occurred after the end of the monsoons (Figure 7.1).

In summary, sampling occurred throughout three consecutive monsoon seasons from 1995 to 1997. Ranked in terms of both the frequency and magnitude of storm severity, 1995 ranked as the least severe and 1997 as the most severe, with 1996 being intermediate but closer in severity to 1997. Backwater conditions were determined in the spring of 1996, following a long storm-free period, and again in 1997 following a fairly intense period of storms (Figure 7.1). Additionally, sampling in 1995 occurred after a relatively large runoff. According to detailed HEC-6 modeling studies undertaken during the San Juan River Recovery Implementation Program, discharges in excess of 5,000 cfs are needed for a minimum of 21 days to thoroughly purge backwaters throughout the entire river of fine sediment (Bliesner 1999b). This discharge was exceeded during 72 days in 1995 (March-July period); hence, backwater cleaning occurred that year. In 1996, however, the threshold of 5,000 cfs was never exceeded, and thus cleaning did not occur. During 1997, there were a total of 49 days in excess of 5,000 cfs, and so removal of fine sediments from backwaters should have occurred that year also.

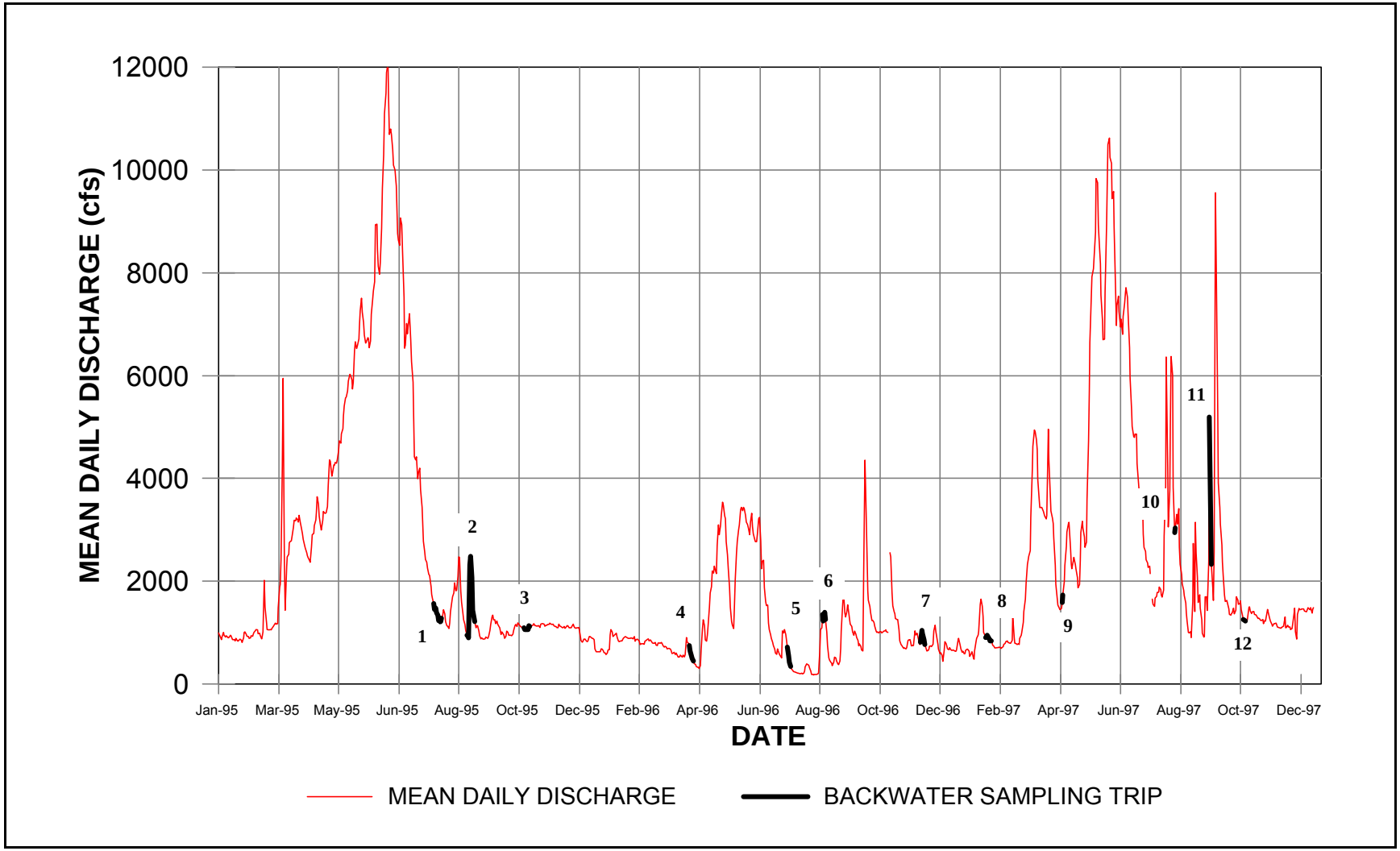

Figure 7.1. San Juan River Mean Daily Discharge for the 1995-97 Period as Measured at the Four Corners, New Mexico Gauge with the Timing and Numbering of Backwater Sampling Trips Indicated

Colorado and Green Rivers

Discharge during the same period of record (1995-97) for the Colorado and Green Rivers is indicated in Figure 7.2. As stated previously, sampling in the Colorado and Green Rivers occurred on trips 5-12 and trips 9-12, respectively. The timing of sampling trips 5-11 are superimposed on the Colorado River hydrograph. The last trip is not indicated due to unavailability of those flow records.

Similar to the San Juan River, discharge was greater in both rivers during 1995 and 1997 than in 1996. Discharge during the fall to spring period of 1996-97 on the Colorado River appeared to be fairly stable, a notable departure from the San Juan River during the same period when several large storms occurred (Figure 7.1). Sampling in the spring of 1997 (trip 9) occurred on the ascending limb of the hydrograph for both rivers. The first post-runoff sampling (trip 10) occurred during the peak of a substantial storm on the Colorado and a relatively weaker one on the Green River. The next trip took place a month later, immediately prior to large storms within both drainages. The last trip (not pictured) occurred shortly after those storms. Thus, during the last monsoon season when all three rivers were sampled, storms were prevalent in all of the drainages.

Backwater Quality/Productivity

To facilitate interpretation, analysis of the results of the backwater productivity studies is considered by each parameter separately. First, temporal and spatial trends within the San Juan River are presented using the entire data set or various subsets thereof, and then comparisons are made with backwaters sampled in the Colorado and Green Rivers for correspondingly sampled time periods.

Throughout this study, backwaters sampled in the San Juan River were relatively permanent in nature, defined as those that were present in at least two of three aquatic habitat mappings of the San Juan River conducted by Ecosystems Research Institute and Keller-Bliesner Engineering during October, 1993, and August and November, 1994. Ideally, the same backwaters would be sampled from one sampling period to the next for comparative purposes. This was accomplished whenever possible, otherwise alternate backwaters were selected when available. Selected backwaters were generally larger and deeper than the majority of backwaters, although this was not always the case. Thus, backwater selection during this study was not a random process. Practically speaking, considering their impermanent nature, the location and even presence of these habitats could not be relied upon. On a number of occasions, only one or no suitable backwater habitats could be found in some reaches, particularly Reach 2 (Table 7.1).

Water Depth

Mean (± 1 SE) water depth by trip for San Juan River backwaters is plotted in Figure 7.3. Levene's test for homogeneity of variance indicated unequal variances amongst the trips ($P<0.005$); therefore, a one-way analysis of variance (ANOVA) was used followed by Dunnett's multiple comparison C-test which does not assume equal variance. For future analyses, Tukey's Honest Significant Difference (HSD) multiple comparison test will be used in instances where equal variance between

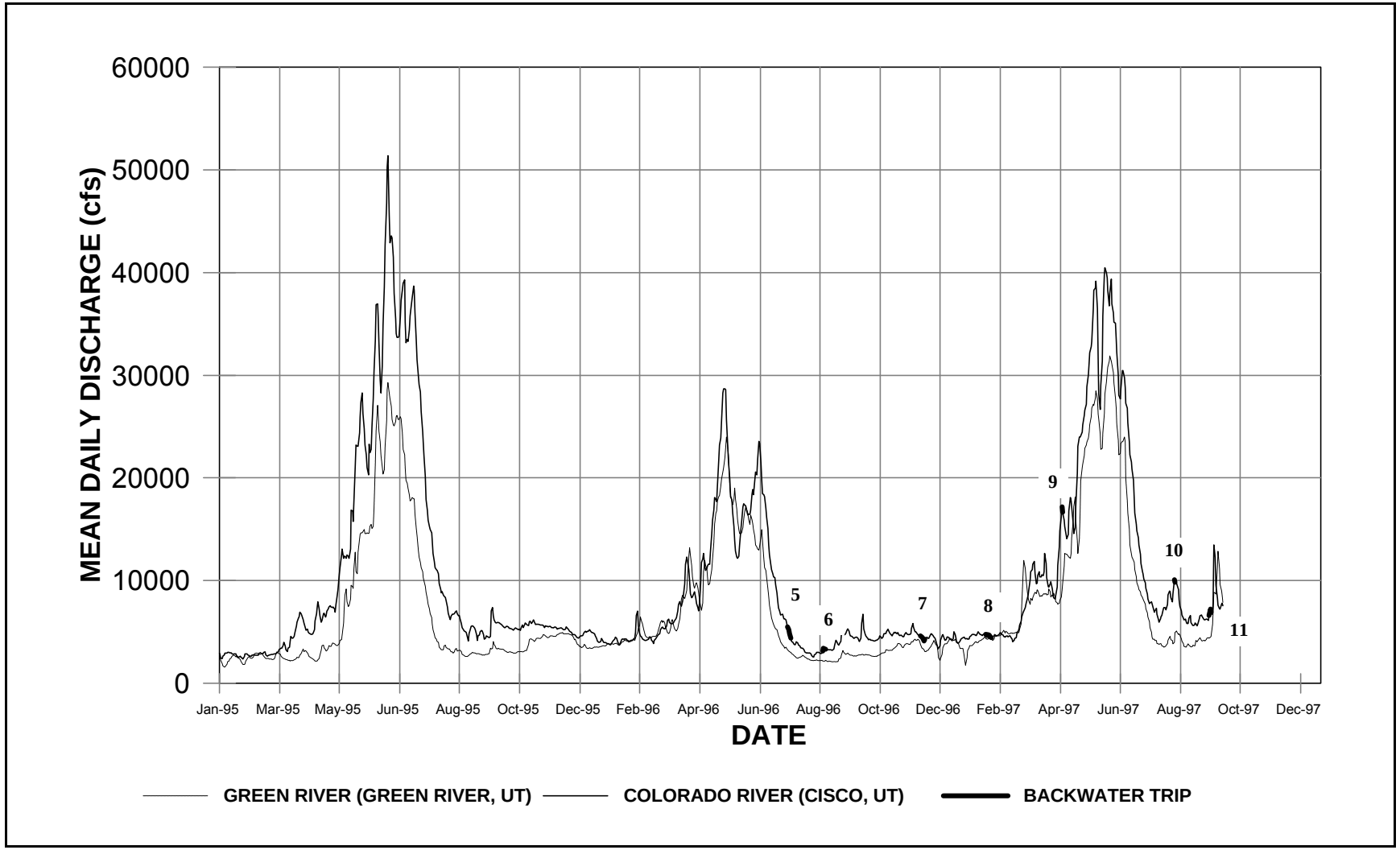

Figure 7.2. Colorado River and Green River Mean Daily Discharge for the 1995-97 Period as Measured at the Cisco, Utah, and Green River, Utah Gauges with the Timing and Numbering of Backwater Sampling Trips Indicated

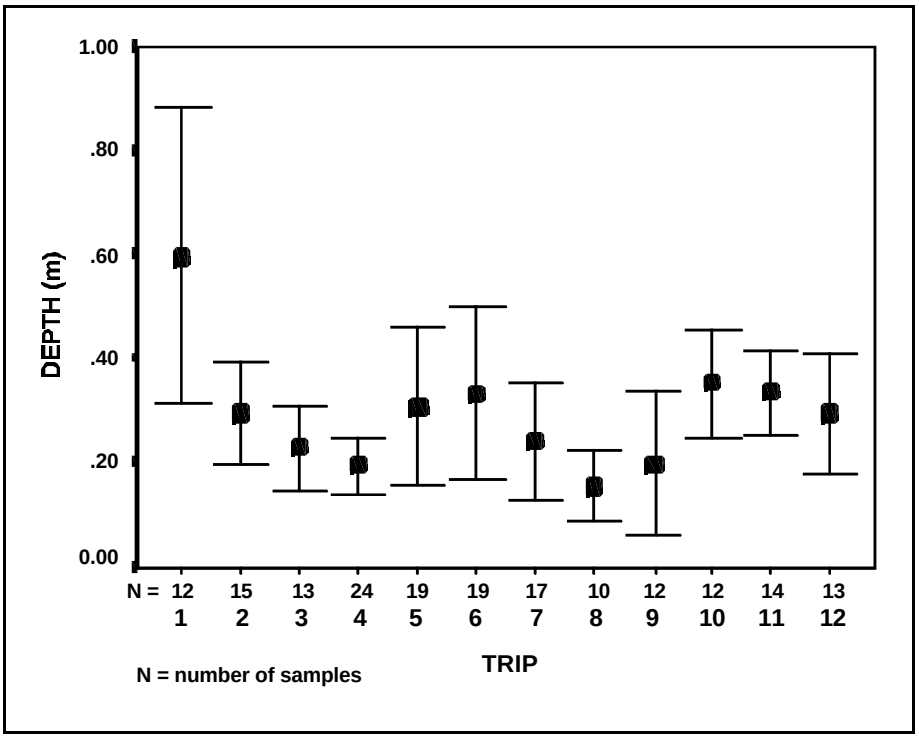

Figure 7.3. Mean Water Depth (±1 SE) in San Juan River Backwaters over the 1995-97 Period by Sampling Trip

treatments has been established. This is considered to be a moderately conservative analysis that is less sensitive to unequal sample sizes (Zar 1984). No significant differences in mean depth were detected between trips (P>0.05). However, there appeared to be generally greater, although highly variable, backwater depths during the first trip than in subsequent trips, particularly those that occurred prior to the following runoff (trips 2-4) (Table 7.1). As previously indicated, this first trip followed the highest volume of runoff experienced during the study and preceded a relatively moderate monsoon season (Figure 7.1). Although no pre-1995 runoff backwater data exists for this study, modeling studies would again predict that backwater flushing should have occurred that year (Bliesner 1999b). No flushing was evident in 1996 (trip 5) following a below average runoff and there appeared to be reduced and less variable backwater depth thereafter to the following late winter period (trip 8) (Figure 7.3). The degree of flushing following runoff in 1997 could not be assessed as post-runoff sampling in August (trip 10) and September (trip 11) occurred during elevated flows due to storms (Table 7.1). Thus, at those times, sampling actually occurred in recently formed backwaters not present during base flow conditions. Nevertheless, when comparing the late or post-monsoon period between all three years during base flow conditions (trips 3, 7, and 12), there were no differences detected (P>0.05). Backwaters averaged approximately 0.2-0.3 m at each of those times (Figure 7.3). Therefore, the severity of the monsoons appeared to have little effect on overall backwater depth by the end of the season when comparing between years.

When averaged across all sampling trips, there were no significant differences detected in water depth between reaches (P>0.05; Dunnett C) (Figure 7.4). Although there was some trend toward deeper backwaters in the lower two reaches, greater depths in Reach 1 was likely contributed to by changes in the elevation of Lake Powell over the study period. Mean water depth was less than 0.5 m in all reaches for the entire study period, particularly so in upstream reaches.

Backwaters sampled within the low gradient pikeminnow nursery area of the Colorado River were significantly deeper (~0.55 m) than those sampled throughout the San Juan River (~0.3 m) when averaged for trips 5 through 12 (P<0.005; Independent samples t-test) (Figure 7.5). During trips 9 through 12, backwaters in the Colorado were again deeper than in the San Juan, averaging 0.9 and 0.3 m, respectively (P<0.05; Dunnett C), while those in the Green River were intermediate (~0.5 m) and not significantly different from either of the other systems (P>0.05) (Figure 7.6). It should be emphasized the presence or absence of storms and the magnitude thereof played a major role in the depths of backwaters measured during this last series of trips in all of the rivers sampled.

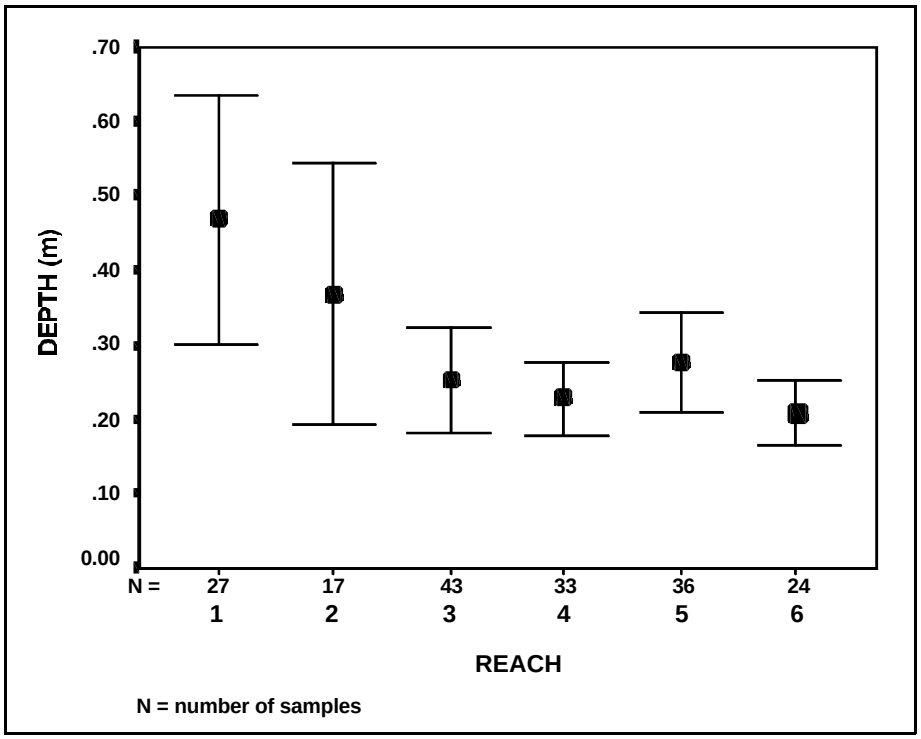

Figure 7.4. Mean Water Depth (±1 SE) in San Juan River Backwaters over the 1995-97 Period by Geomorphic Reach

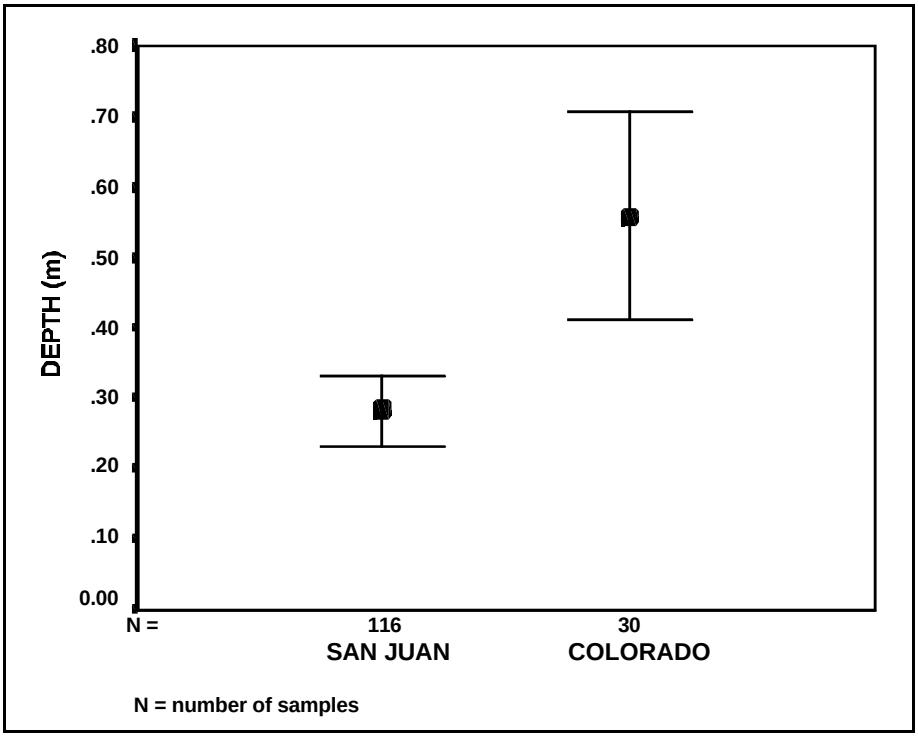

Figure 7.5. **Mean Water Depth (±1 SE) in San Juan and Colorado River Backwaters over the 1996-97 Period for Sampling Trips 5 Through 12**

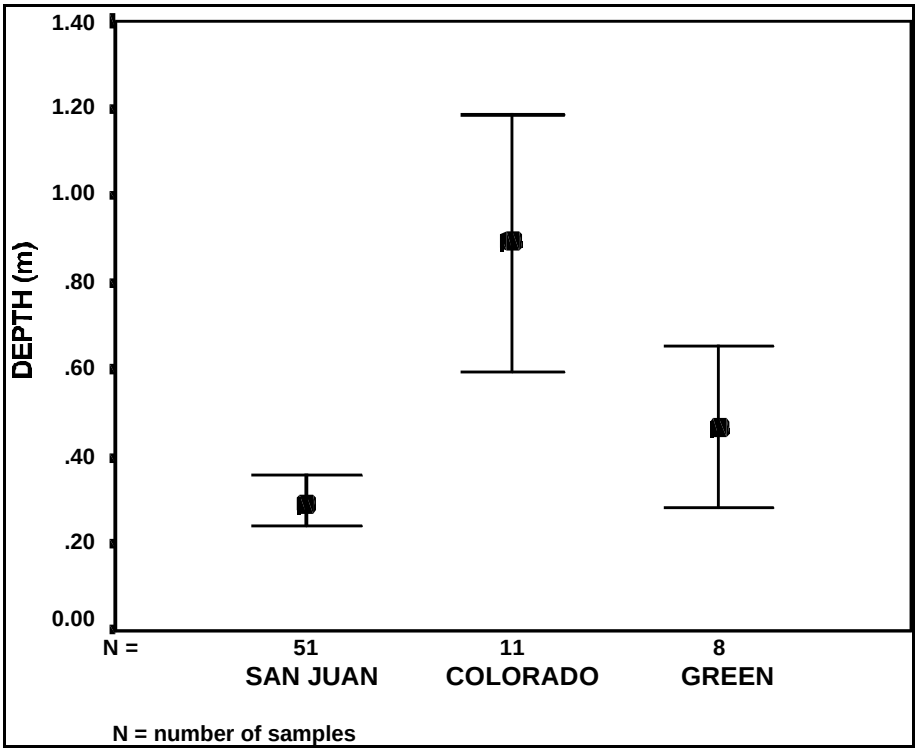

Figure 7.6. **Mean Water Depth (±1 SE) in San Juan, Colorado, and Green River Backwaters over the April to October 1997 Period for Sampling Trips 9 through 12**

Total Suspended Solids

Elevated concentrations (>200 mg/L) of total suspended solids (TSS) were observed during trips 2, 6, 8, 10, and 11 (Figure 7.7), all of which occurred during or immediately following storms (Figure 7.1). The highest concentration (~4,500 mg/L) was observed during trip 2 in September, 1995, when sampling occurred during a large storm. The lowest concentrations (<75 mg/L) occurred during trips 1, 3, and 4 under base flow conditions. Mean TSS concentrations following runoff in 1996 and 1997 during trip 5 (~150 mg/L) and trip 10 (~250 mg/L), respectively, were significantly greater ($P<0.05$; Dunnett C) than those detected following runoff in 1995 during trip 1 (~25 mg/L) (see Table 7.1). No storms occurred during or prior to trip 1 in 1995, while storms did occur during the post-runoff trips in 1996 and 1997 (Figure 7.1).

There was no relationship between discharge and TSS (Figure 7.8). Higher magnitude storms with respect to discharge did not produce higher levels of TSS. For example, intermediate discharges of about 1,500 cfs (Table 7.1) during trip 2 in September, 1995, produced very high TSS concentrations in excess of 4,000 mg/L, whereas discharges of about 3,000 cfs during trips 10 and 11 in 1997 resulted in only moderately high TSS levels of 250 to 500 mg/L (Figure 7.7).

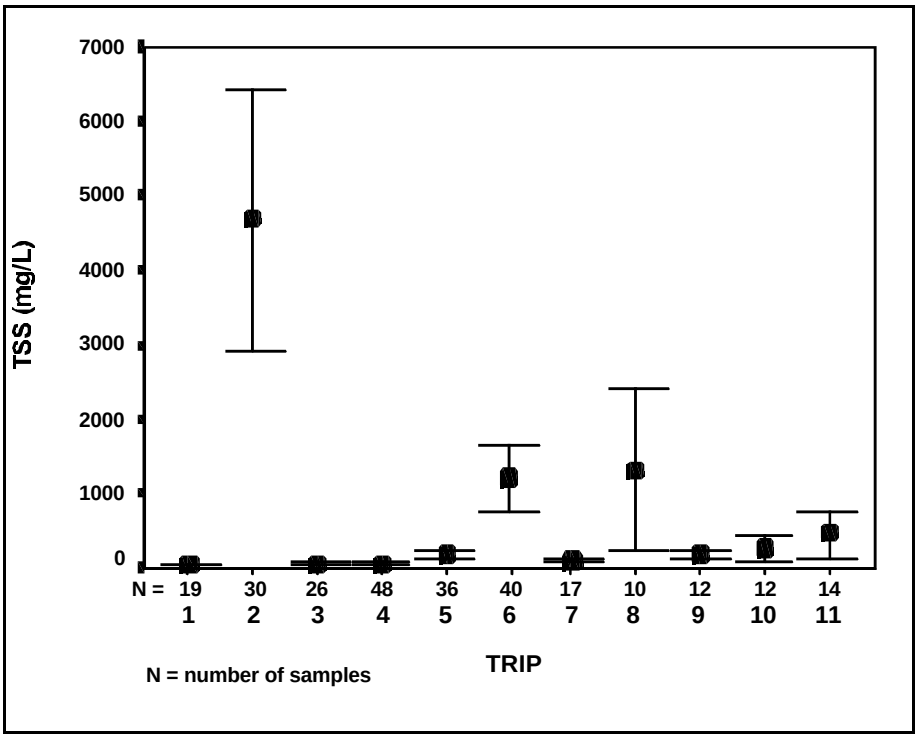

Figure 7.7. Mean Total Suspended Solids (±1 SE) in San Juan River Backwaters over the 1995-97 Period by Sampling Trip

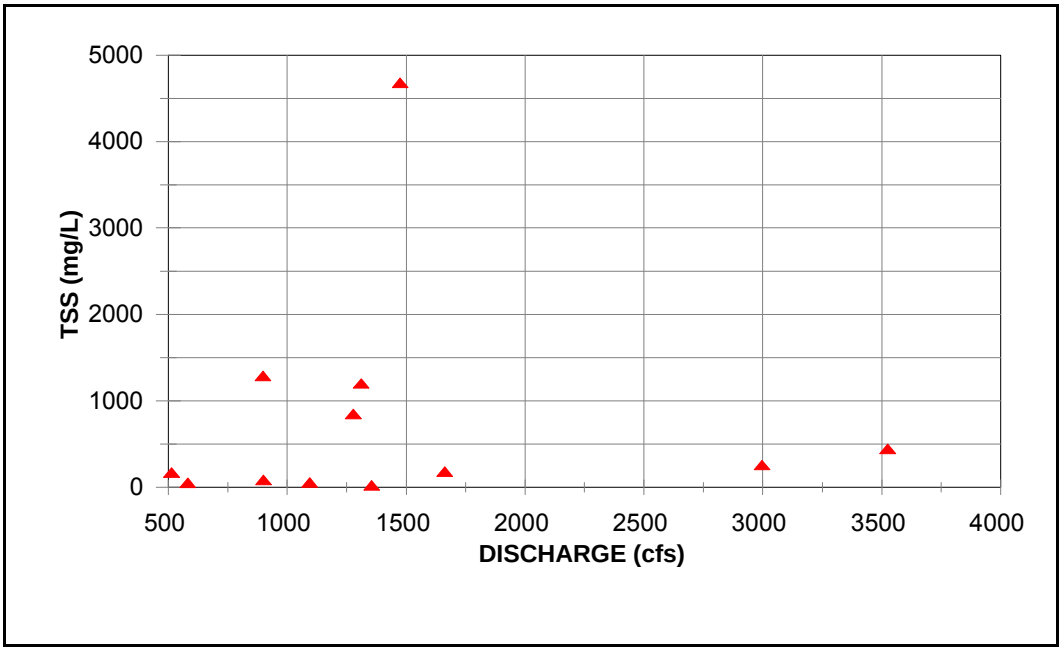

Figure 7.8. The Relationship Between Discharge and Total Suspended Solids in San Juan River Backwaters over the 1995-97 Period for Trips 1 through 12

TSS concentrations tended to be lowest in Reaches 5 and 6 overall and greater, although more variable, in downstream reaches; however, no differences were significant (Figure 7.9) ($P>0.05$; Dunnett C). The higher and more variable concentrations in the lower reaches was due primarily to the storm during trip 2 (Figure 7.1), which occurred after sampling in Reaches 5 and 6 had been nearly completed.

TSS levels were significantly greater in San Juan than Colorado River backwaters during trips 5 through 11 ($P<0.001$; Independent samples t-test; equal variance not assumed) (Figure 7.10). They averaged approximately 600 mg/L in the San Juan River and 100 mg/L in the Colorado River, and were considerably less variable in the Colorado. Inspection of the results by trip indicated that TSS levels were higher in San Juan backwaters during trips 5 ($P<0.001$; Independent samples t-test), 6 ($P<0.001$), 8 ($P<0.05$), and 9 ($P<0.005$) (Figure 7.11). Examination of the hydrographs for the San Juan (Figure 7.1) and Colorado Rivers (Figure 7.2) reveals that storms occurred during or immediately prior to those trips on the San Juan, but not on the Colorado. Storms occurred during or prior to sampling during trips 10 and 11 in both rivers when there was no significant difference in TSS levels detected ($P>0.36$; Independent samples t-test).

There was no difference in TSS concentrations between the San Juan, Colorado, and Green Rivers during trips 9, 10, and 11 when samples were obtained in all three systems ($P>0.66$; One-way ANOVA). Storms were prevalent in all three drainages over this period (Figures 7.1 and 7.2) when concentrations averaged about 250 mg/L.

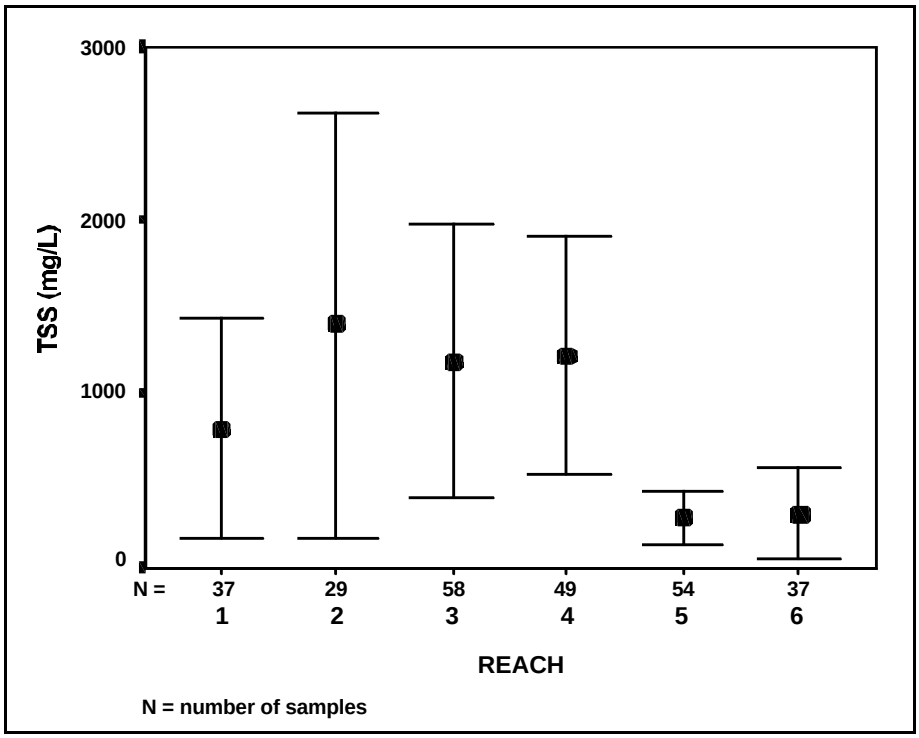

Figure 7.9. Mean Total Suspended Solids (±1 SE) in San Juan River Backwaters over the 1995-97 Period by Geomorphic Reach.

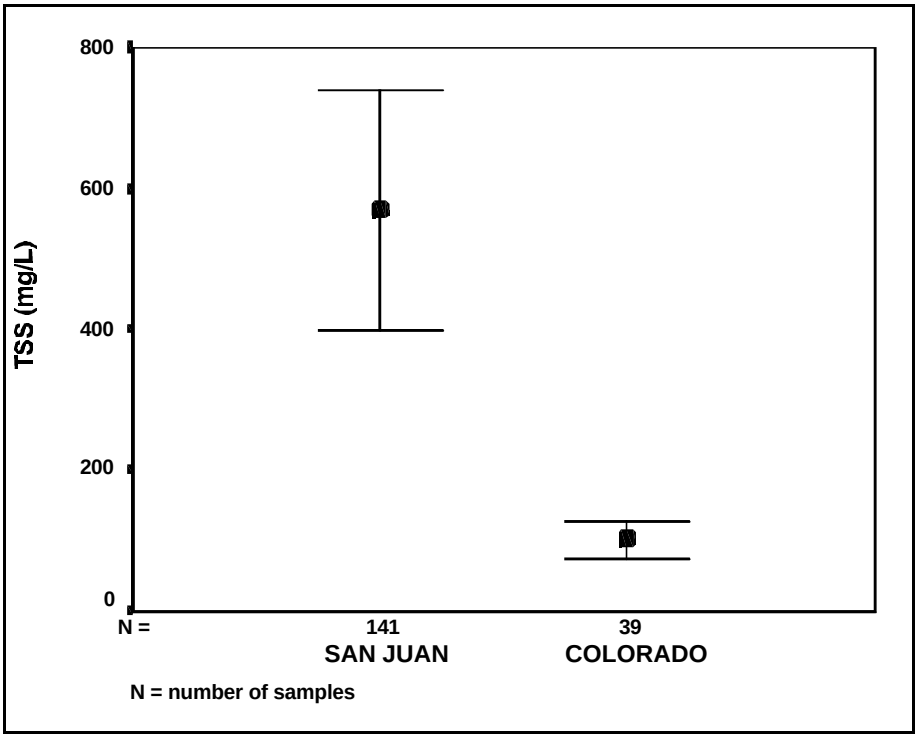

Figure 7.10. Mean Total Suspended Solids (±1 SE) in San Juan and Colorado River Backwaters over the 1996-97 Period for Sampling Trips 5 through 11

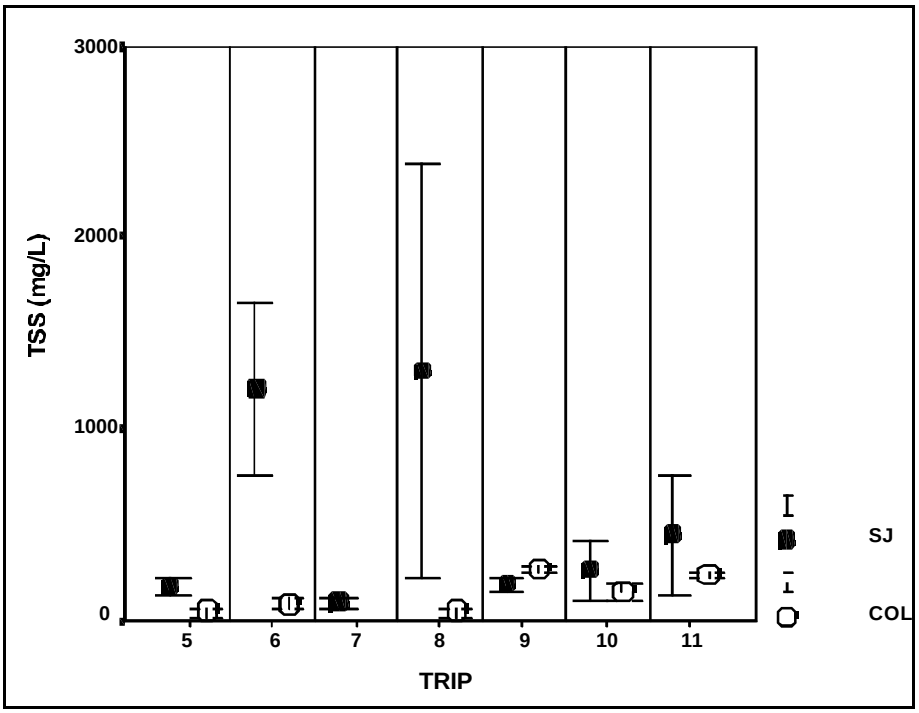

Figure 7.11. Mean Total Suspended Solids (±1 SE) in San Juan and Colorado River Backwaters over the 1996-97 Period by Sampling Trip

Temperature

The maximum summer temperatures observed in San Juan River backwaters averaged about 27°C and occurred during the July and August trips (Figure 7.12, Table 7.1). There was no difference between the temperatures observed during the August trips (1, 6, and 10) between years (P>0.05; Dunnett C). Hence, storms appeared to have little influence on backwater temperatures or such effects may have been obscured by climactic conditions. The coolest temperatures during the study were observed during the December, 1996 trip and averaged about 4° C. Many of the backwaters encountered at that time were partially or completely frozen. There were no temperature differences observed by reach when averaged across all trips (P>0.70; Tukey's HSD), although there appeared to be a slight depression in the canyon-bound Reach 1 (Figure 7.13).

A comparison of backwaters in the Colorado and San Juan rivers indicated that temperatures matched fairly closely through time (Figure 7.14). San Juan River backwaters were warmer than Colorado backwaters only during trips 8 (P<0.05) and 9 (P<0.005; Independent samples t-test) in February and April, 1997, respectively. When comparing all three rivers during trips 9-12, no significant differences in backwater temperature were found (P>0.05; Tukey's HSD), although temperatures in Colorado River backwaters were nearly less than those in the San Juan (P=0.07) (Figure 7.15).

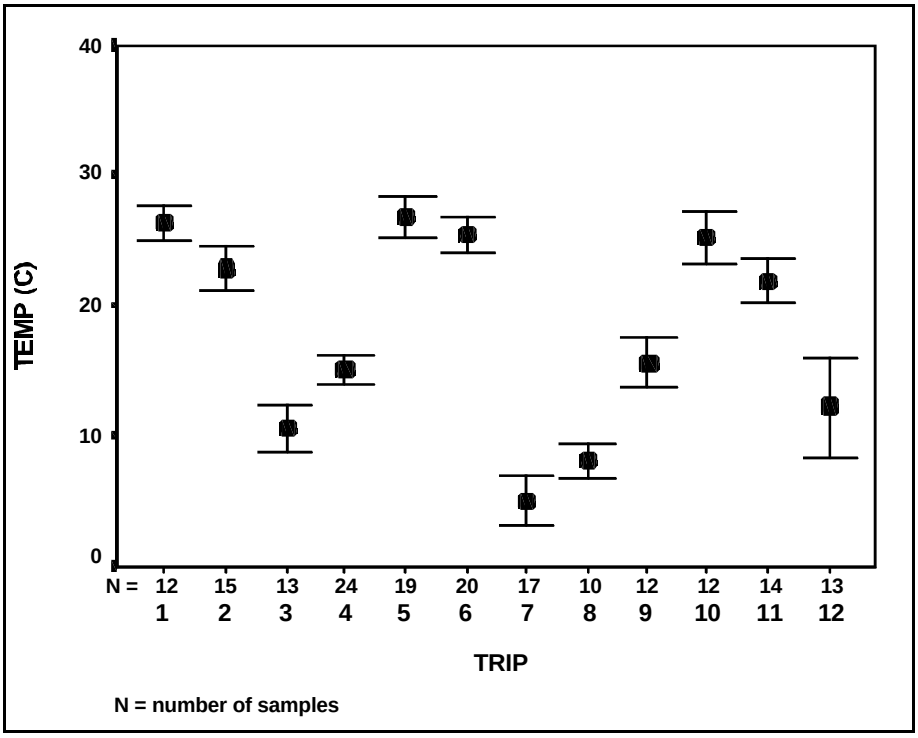

Figure 7.12. Mean Temperature (±1 SE) in San Juan River Backwaters over the 1995-97 Period by Sampling Trip

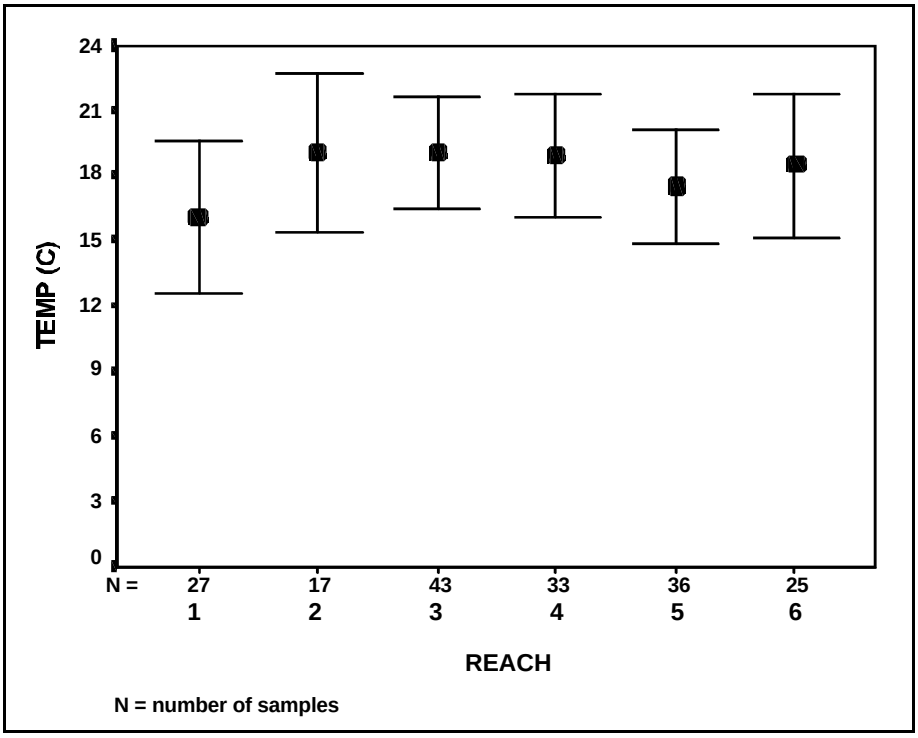

Figure 7.13. Mean Temperature (±1 SE) in San Juan River Backwaters over the 1995-97 Period by Geomorphic Reach

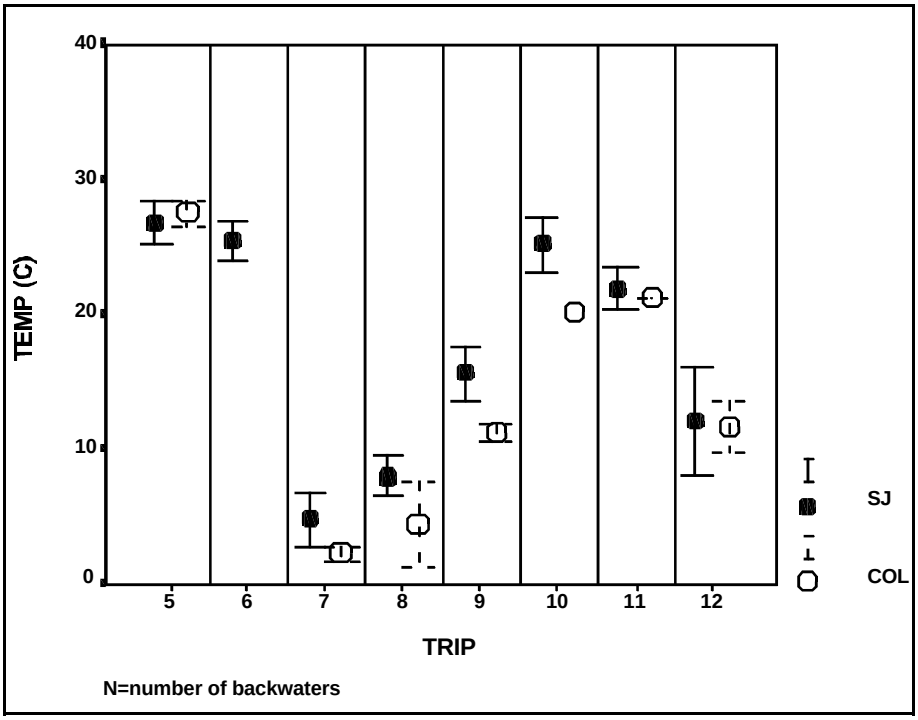

Figure 7.14. Mean Temperature (±1 SE) in San Juan and Colorado River Backwaters over the 1996-97 Period by Sampling Trip

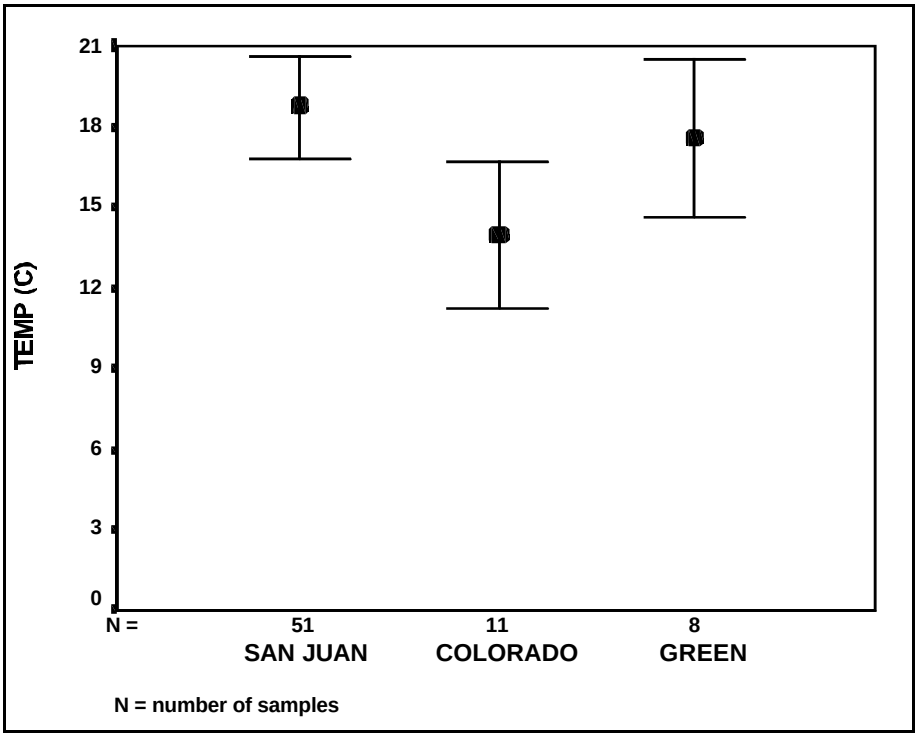

Figure 7.15. Mean Temperature (±1 SE) in San Juan, Colorado, and Green River Backwaters over the April to October 1997 Period for Sampling Trips 9 through 12

Dissolved Oxygen

Dissolved oxygen concentrations were generally highest in San Juan River backwaters during the cooler months of November to April (trips 3, 4, 7, and 9) and lowest during the warmer months of July to September (trips 2, 5, 6, and 10) (Figure 7.16). They ranged from a mean of 2.7 mg/L during August, 1997 (trip 10) to a high of 9.7 mg/L during December, 1996 (trip 7). Temperatures did not differ significantly between years during August trips (P>0.05; Dunnett C), nor did storms appear to consistently affect oxygen levels. For example, dissolved oxygen levels dropped significantly following a storm which occurred during trip 2 from unperturbated conditions observed during trip 1 (P<0.05). However, there was no difference found in oxygen levels between trip 5 which preceded a storm and trip 6 which occurred during a storm a month later (P>0.05). Dissolved oxygen did not vary by reach when averaged for all trips combined (P>0.86; Tukey's HSD).

Colorado River backwaters were more oxygenated than those in the San Juan River during trip 5 in July, 1996 and trip 8 in February, 1997 (P<0.001; Independent samples t-test); otherwise, there were no differences found (P>0.30) (Figure 7.17). Over the same period of time (trips 9-12) in 1997, Colorado River backwaters had higher oxygen levels than San Juan River backwaters (P<0.05; Dunnett C), while those in the Green River were more variable and not significantly different from the other two rivers (P>0.05) (Figure 7.18).

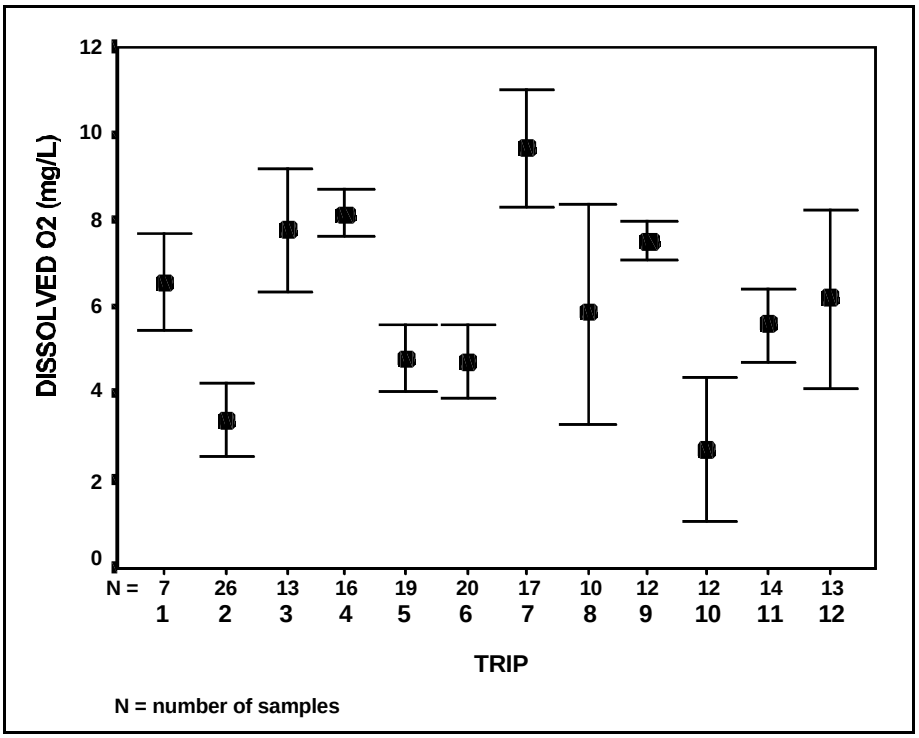

Figure 7.16. Mean Dissolved Oxygen (±1 SE) in San Juan River Backwaters over the 1995-97 Period by Sampling Trip

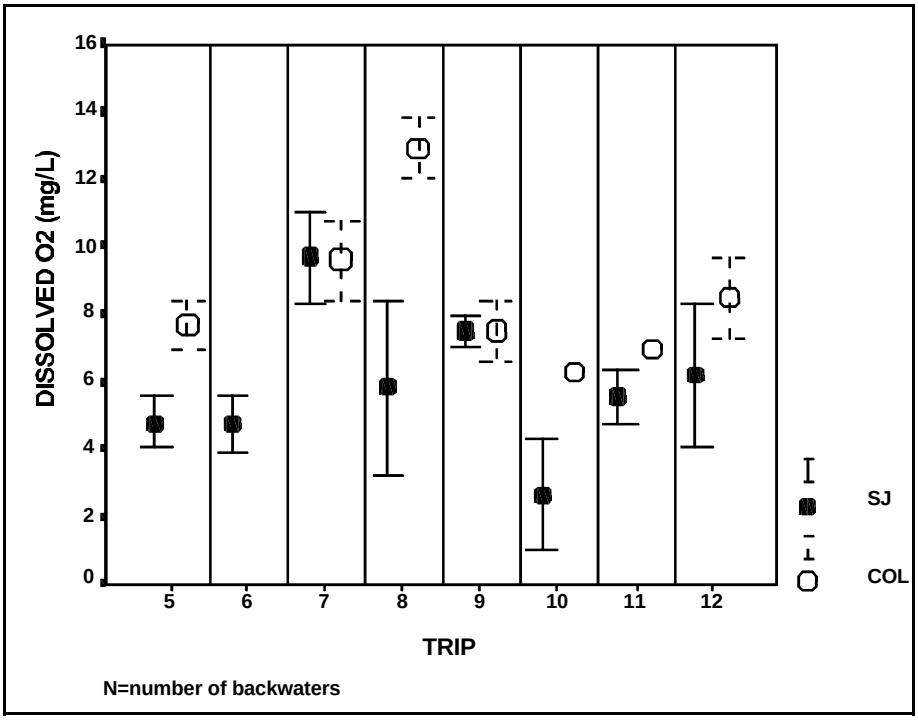

Figure 7.17. Mean Dissolved Oxygen (±1 SE) in San Juan and Colorado River Backwaters over the 1996-97 Period by Sampling Trip

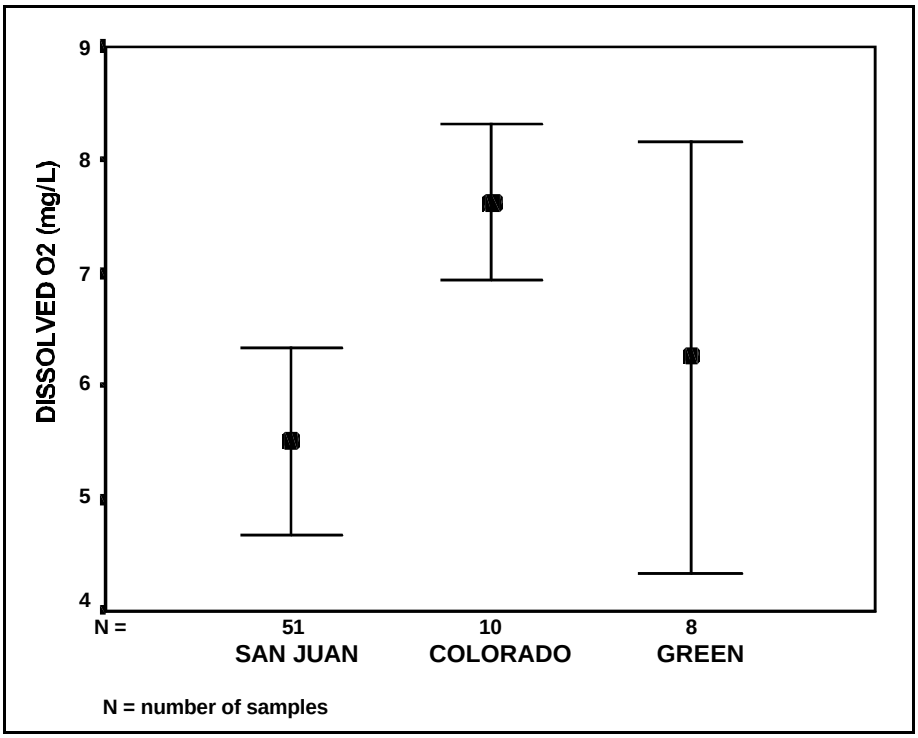

Figure 7.18. Mean Dissolved Oxygen (±1 SE) in San Juan, Colorado, and Green River Backwaters over the April to October 1997 Period for Sampling Trips 9 through 12.

Phytoplankton

Phytoplankton biomass was relatively low (<10 µg/L) during most of the San Juan River sampling trips (Figure 7.19). Periods of stability preceding sampling in 1995 and 1996 resulted in some increase in phytoplankton during trips 3 and 4 (see Table 7.1) over low, post-runoff levels observed during trip 1 in August, 1995 ($P<0.05$; Dunnett C). This trend is more distinguishable when examining a single backwater (RM 153) in Reach 5 sampled during the first four trips (Figure 7.20). The highest levels riverwide were observed during trip 8 in February, 1997 (Figure 7.19), although due to high variability it did not differ significantly from any other trips ($P>0.05$). Further analysis revealed that this high variability was due primarily to two backwaters sampled in Reach 1 (see Table 7.1), which ranged from about 10 to 70 µg/L, that were actually located in Lake Powell at RM -1. There was no difference between August trips from 1995 to 1997 ($P>0.05$), despite large differences in levels of total suspended solids between trips as noted above, which may affect production of phytoplankton by influencing light penetration. There were no differences in phytoplankton by reach when averaged across all trips ($P>0.05$) and Reach 1 was again found to be the most variable location (Figure 7.21).

A comparison of the San Juan to the Colorado River during trips 5 through 12 combined indicated that there was no difference between the two systems in phytoplankton biomass ($P>0.05$; Independent samples t-test) (Figure 7.22). Analysis of these data by trip indicated that phytoplankton was greater in Colorado River backwaters during trip 5 ($P<0.05$; Independent samples t-test), trip 6 ($P<0.001$), and trip 12 ($P<0.05$) (Figure 7.23). Total suspended solids were greater in the San Juan than the Colorado River during trips 5 and 6 due to storms, whereas no storms occurred on the Colorado. Phytoplankton was greater in the San Juan than the Colorado during trip 8 ($P<0.05$); however, much of this difference was again due to two backwaters in Reach 1 of the San Juan River that were actually located in Lake Powell and therefore not subject to riverine processes. There was no significant difference when these two habitats were eliminated from the analysis ($P=0.27$).

Phytoplankton in backwaters of the San Juan, Colorado, and Green Rivers was compared during trips 9 through 12 (Figure 7.24). Biomass was greater in the Green than the San Juan River ($P<0.05$; Tukey's HSD), but there were no other significant differences ($P>0.05$). Overall, phytoplankton was relatively low in backwaters sampled in all rivers (<3 µg/L) during this stormy period compared to, for example, levels of about 25 µg/L observed in the one backwater at RM 153 following six months of stable flows (Figure 7.20).

Zooplankton

Abundance of zooplankton, composed primarily of cladocerans, copepods, and rotifers, was an extremely variable measure of productivity in San Juan River backwaters (Figure 7.25). There was no apparent relationship between discharge during trips (Figure 7.2) and the number of zooplankton present in backwaters (Figure 7.25). For example, zooplankton density was relatively high and variable during trips 2 and 11 when storm events occurred, but not during trip 10 which also took place during a storm.

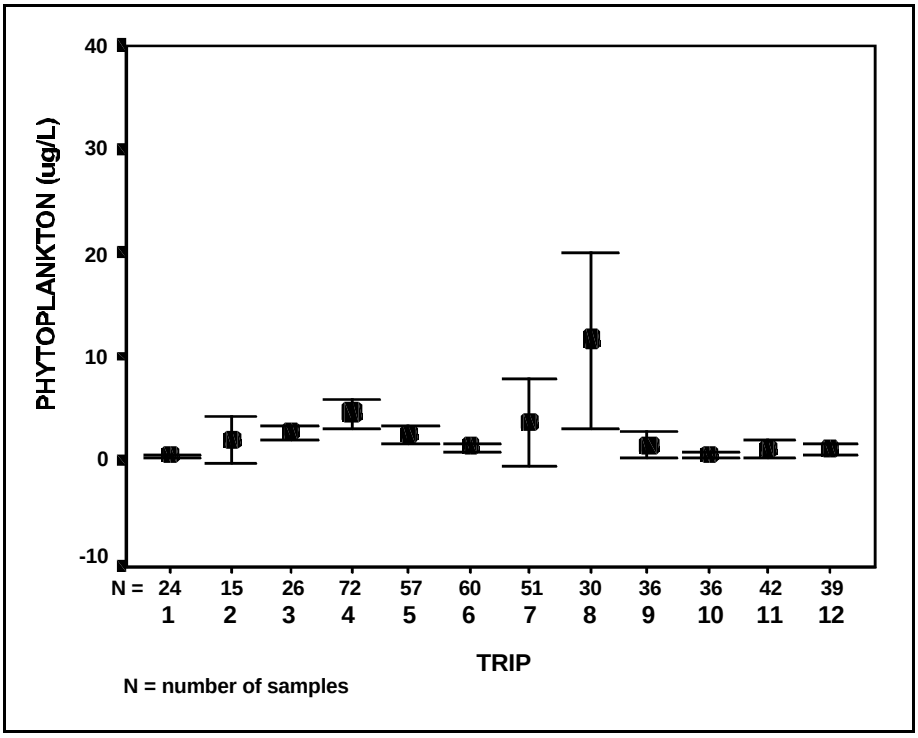

Figure 7.19. Mean Phytoplankton Biomass (±1 SE) in San Juan River Backwaters over the 1995-97 Period by Sampling Trip

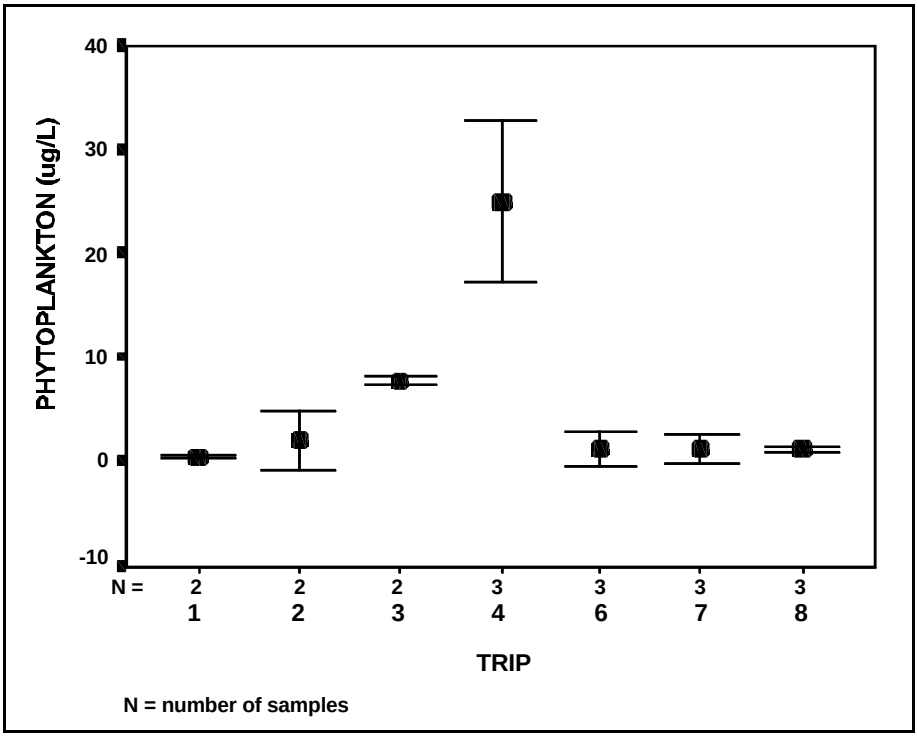

Figure 7.20. Mean Phytoplankton Biomass (±1 SE) in San Juan River Backwater at Rm 153 in Reach 5 by Sampling Trip

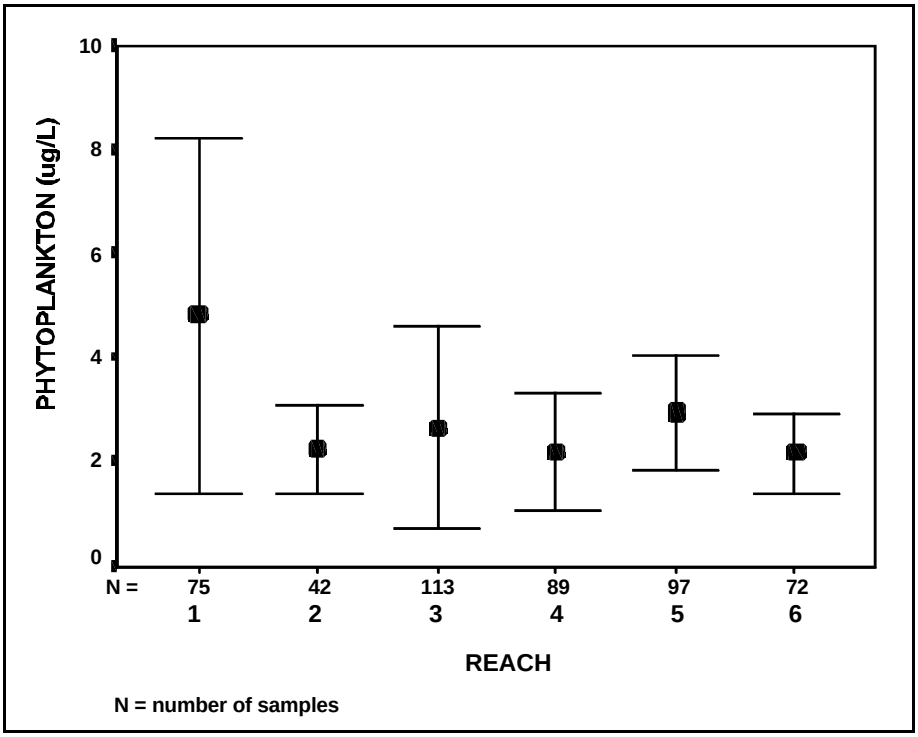

Figure 7.21. Mean Phytoplankton Biomass (±1 SE) in San Juan River Backwaters over the 1995-97 Period by Geomorphic Reach

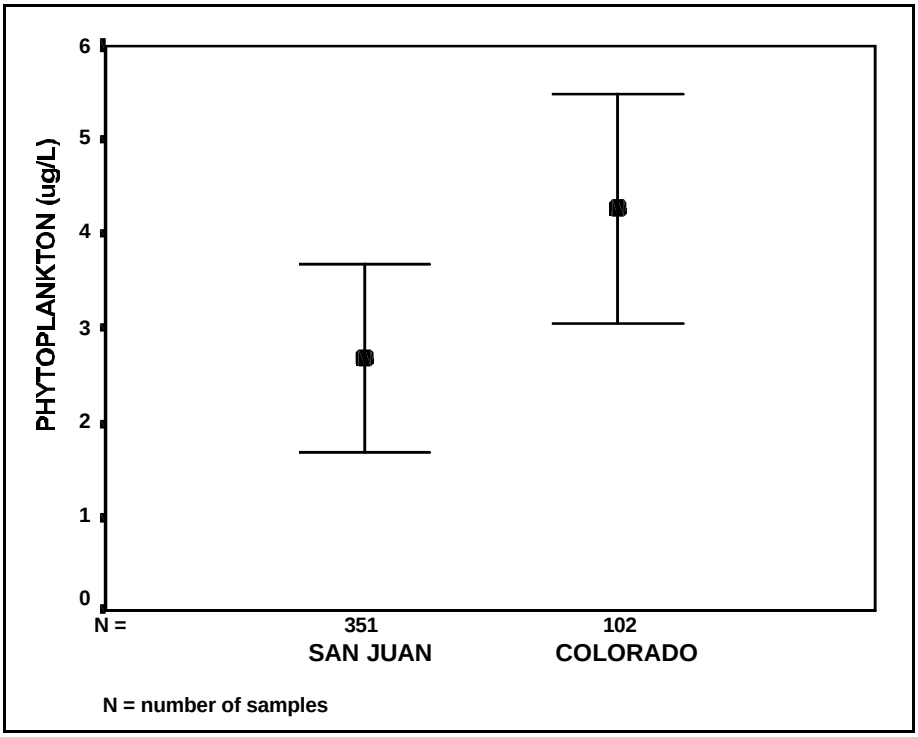

Figure 7.22. Mean Phytoplankton Biomass (±1 SE) in San Juan and Colorado River Backwaters over the 1996-97 Period for Sampling Trips 5 through 12

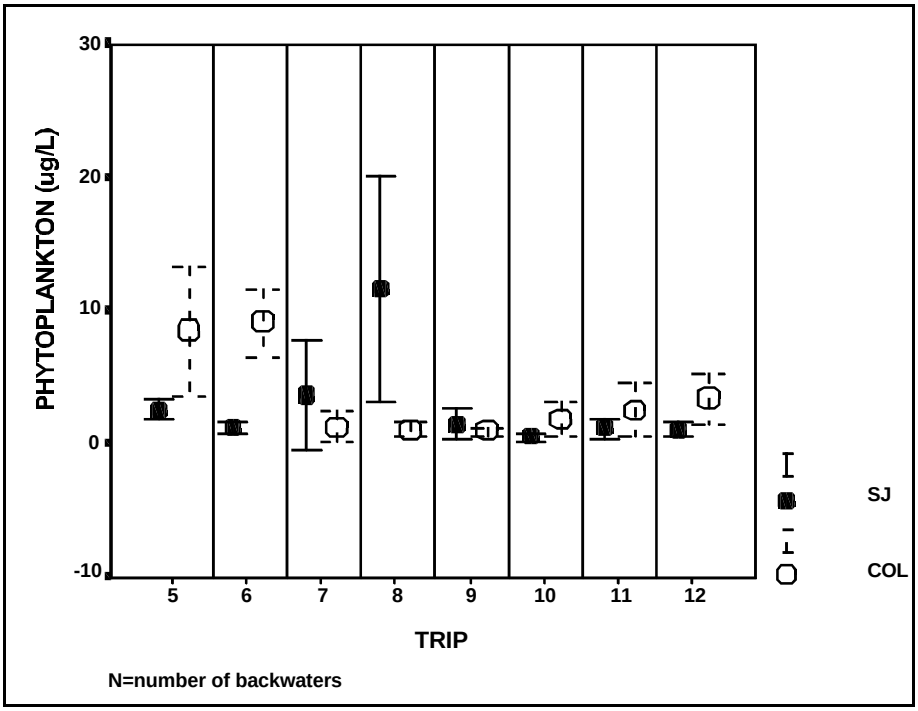

Figure 7.23. Mean Phytoplankton Biomass (±1 SE) in San Juan and Colorado River Backwaters over the 1996-97 Period by Sampling Trip

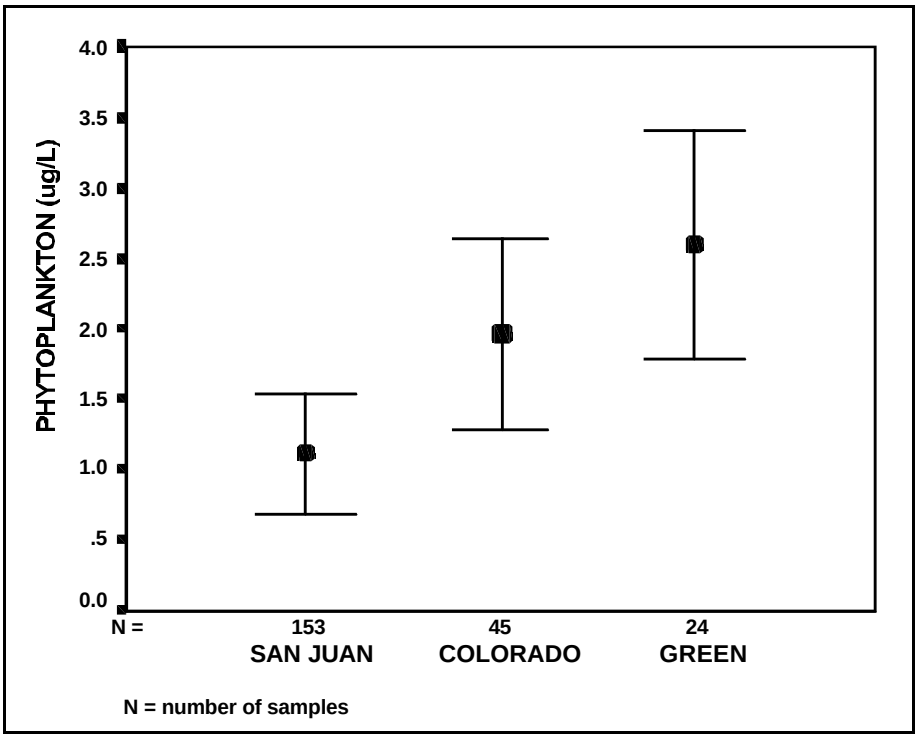

Figure 7.24. Mean Phytoplankton Biomass (±1 SE) in San Juan, Colorado, and Green River Backwaters over the April to October 1997 Period for Sampling Trips 9 through 12

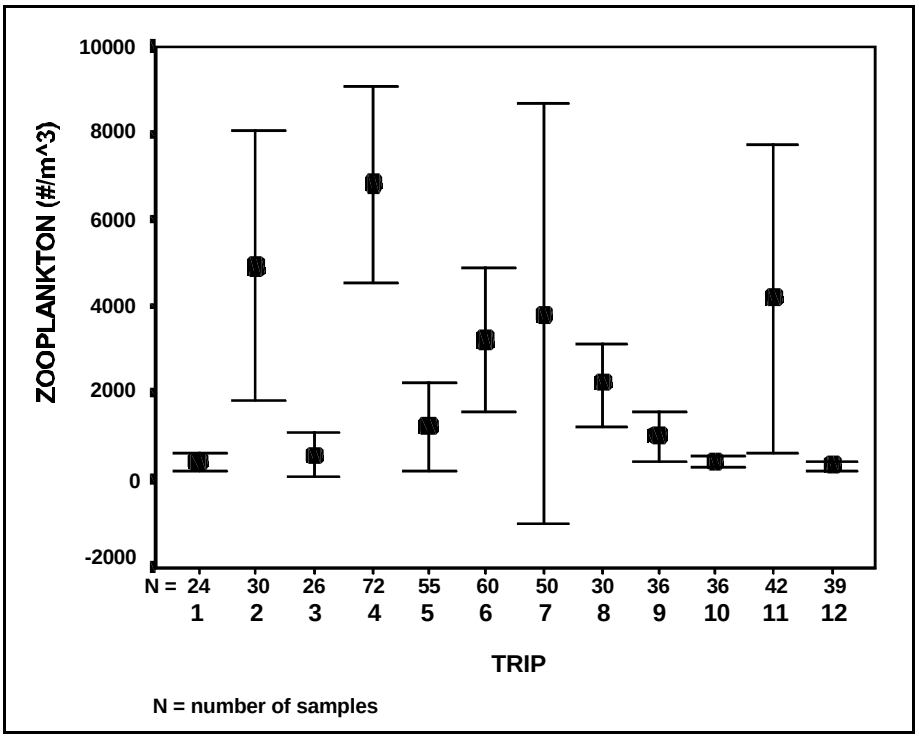

Figure 7.25. Mean Zooplankton Biomass (±1 SE) in San Juan River Backwaters over the 1995-97 Period by Sampling Trip

Most notably, however, there was a significant increase in zooplankton ($P<0.05$; Dunnett C) from the end of the monsoon period in 1995 to the pre-runoff sampling in 1996 (trip 4), while there was no change in zooplankton ($P>0.05$) from the end of the monsoon period in 1996 (trip 7) to the corresponding period the following spring (trip 9) (Figure 7.25). Again, the winter period from 1995-96 was characterized by stable base flows while the corresponding period during 1996-97 was relatively stormy (Figure 7.2). Therefore, stable flows appeared to result in increased numbers of zooplankton.

As stated previously, storms preceded post-runoff sampling in 1996 (trip 5) and 1997 (trip 10), but not in 1995 (trip 1). Abundance of zooplankton was relatively low (400 to 1,200 per m^3) and not significantly different between those sampling periods ($P>0.05$; Dunnett C) (Figure 7.25).

Thus, storms, or the lack thereof, appeared to have no discernible effect on the abundance of zooplankton in backwaters at those times. It is possible that regardless of whether or not storms have occurred previously, there are relatively few zooplankton in the backwaters so soon after runoff flows have abated. This has important implications for pikeminnow larvae potentially present in the backwaters at those times, which preferentially feed on zooplankton at this small size. However, it

should be emphasized that it is not known whether zooplankton are limited in abundance during this period in relation to the dietary needs of these larval fishes.

There were no spatial differences in the abundance of zooplankton in backwaters of the San Juan River between reaches when averaged across all trips (P>0.05; Dunnett C) (Figure 7.26), although there appeared to be some spatial patterns at certain times. For example, during trip 1 when all eight geomorphic reaches were sampled, there were relatively greater numbers of zooplankton in Reach 7, and particularly, Reach 8 (Figure 7.27). It was suspected that this increased abundance in these reaches was due largely to export of zooplankton from Navajo Reservoir. The single backwater sampled in Reach 8 was approximately one mile downstream of the reservoir (Figure 1.1). However, due to high variability, there were no differences in zooplankton abundance between reaches even in this case (P>0.05; Dunnett C). During trip 2, zooplankton was again high and variable in Reach 8; however, there were somewhat high levels in downstream reaches at that time as well (Figure 7.28). A storm event that occurred after sampling in Reach 5 (Figure 7.2) may have resulted in some downstream displacement of zooplankton. Regardless, there were still no significant differences amongst reaches (P>0.05; Dunnett C).

Density of zooplankton in the San Juan and Colorado River backwaters over trips 5 through 12 did not differ (P=0.71; Independent samples t-test), with both rivers averaging about 2,000±1,000 individuals per m^3 (Figure 7.29). A comparison of the two rivers through time indicated fairly similar patterns, although Colorado backwaters contained greater numbers of zooplankton during trip 10 (P<0.001; Independent samples t-test) and trip 12 (P<0.05) (Figure 7.30). Storms occurred during or prior to these trips in both rivers (Figures 7.1 and 7.2), so it is possible that differences in the stage-discharge relationship between the two locations was a factor in this disparity. Stage in the Colorado River within the study area is less sensitive to changes in discharge than is the San Juan River. Over trips 9 through 12 combined, there was no difference between the abundance of zooplankton in backwaters of the Colorado and the San Juan Rivers, although this difference was nearly significant (P=0.09; Tukey's HSD) (Figure 7.31). Zooplankton abundance in the Green River was not significantly different from the other two rivers (P>0.24).

Periphyton

Temporal variations in levels of periphyton, a measure of primary production, are indicated in Figure 7.32 for all sampling trips (refer to Table 7.1 for numbering of trips). Again, these data include only Reaches 1 through 6 as only these reaches were sampled during every sampling period. The first three trips, occurring before, during, and after the 1995 monsoon season (see Figure 7.2), show a significant decline (P<0.05; Dunnett C) in periphyton between the first sampling after runoff in August and the next trip in September, which occurred during a storm. Nearly two months later, periphyton levels remained low and unchanged (Figure 7.32) even though only one relatively minor storm had occurred in the interim (Figure 7.2). Following nearly six months of stable discharge, periphyton levels increased dramatically (P<0.05) by the next sampling period in April (trip 4). Further analysis of the data collected during trips 1 and 4, when periphyton levels were relatively high, indicated that there was a distinct and consistent longitudnal pattern. Generally higher levels were observed in upstream reaches, particularly 7 and 8, during trip 1 in August (Figure 7.33).

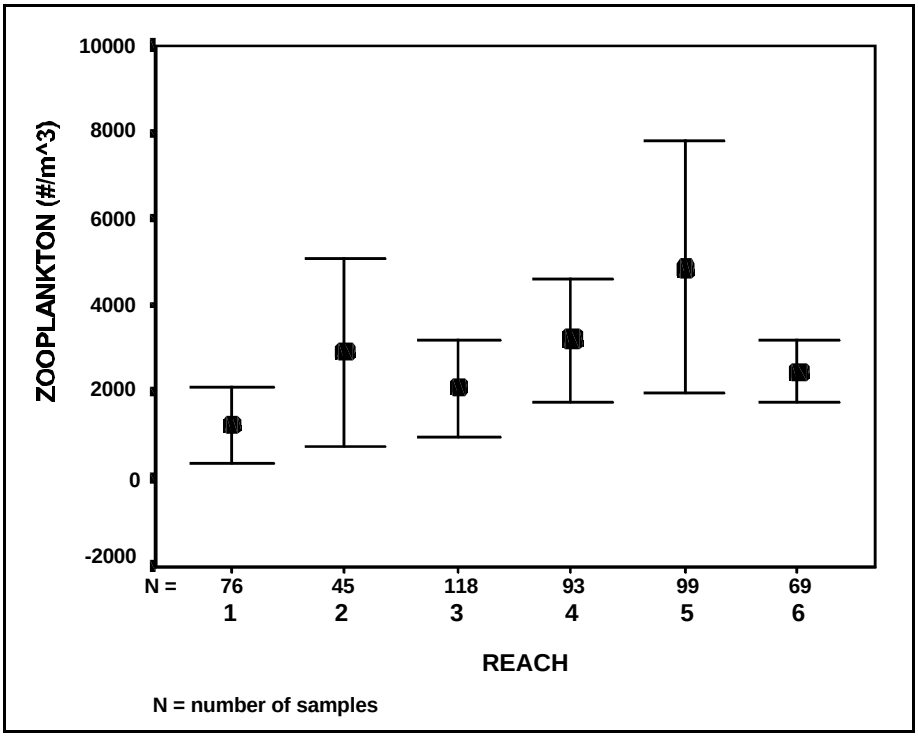

Figure 7.26. Mean Zooplankton Biomass (±1 SE) in San Juan River Backwaters over the 1995-97 Period by Geomorphic Reach

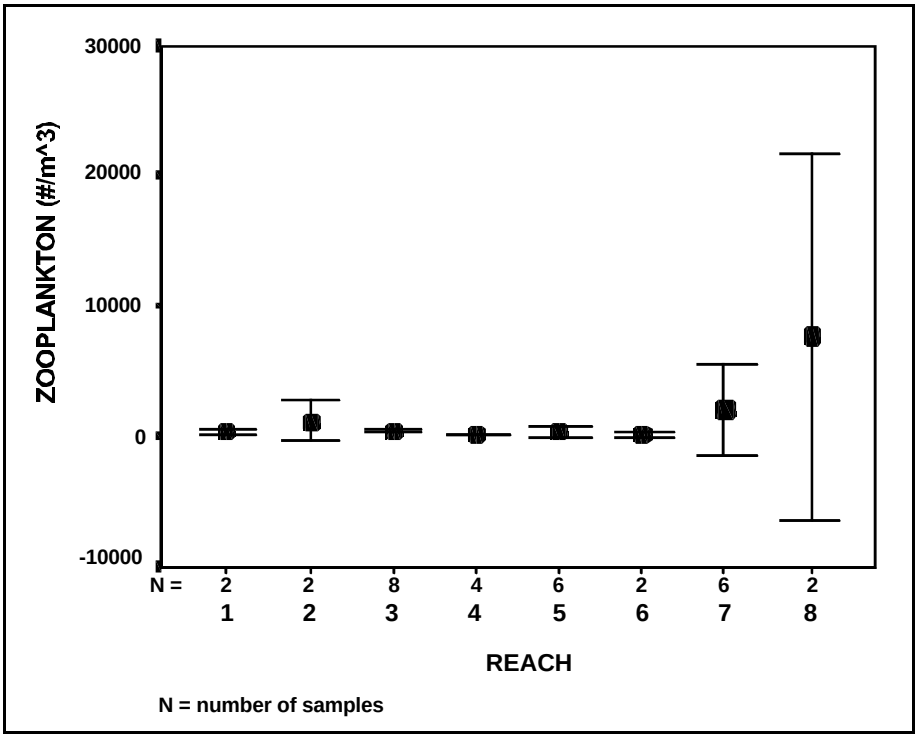

Figure 7.27. Mean Zooplankton Biomass (±1 SE) in San Juan River Backwaters During Trip 1 in August, 1995 by Geomorphic Reach

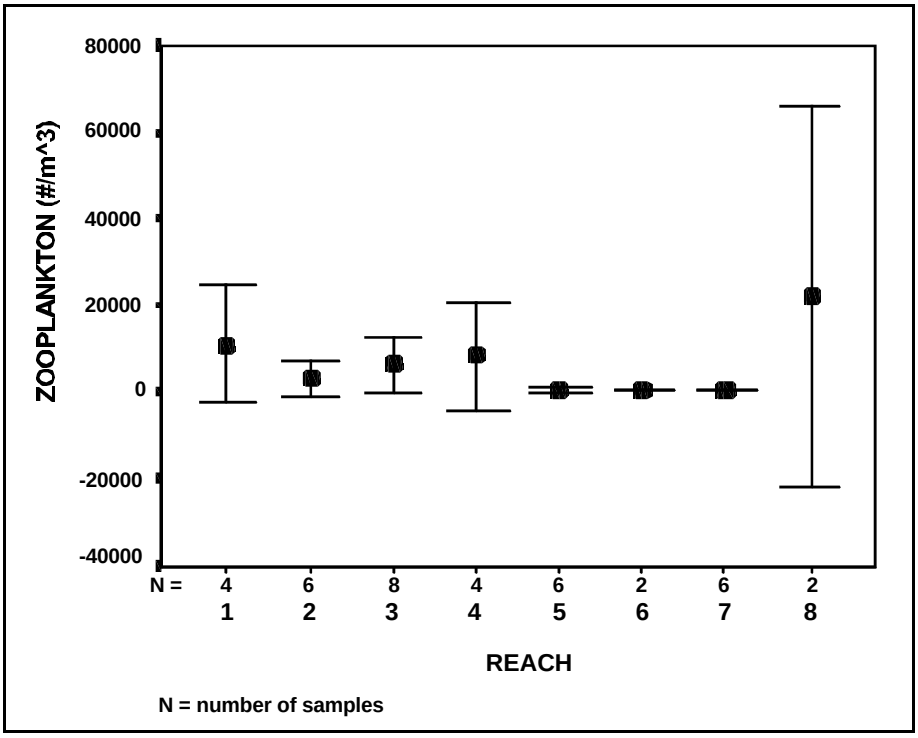

Figure 7.28. Mean Zooplankton Biomass (±1 SE) in San Juan River Backwaters During Trip 2 in September, 1995 by Geomorphic Reach

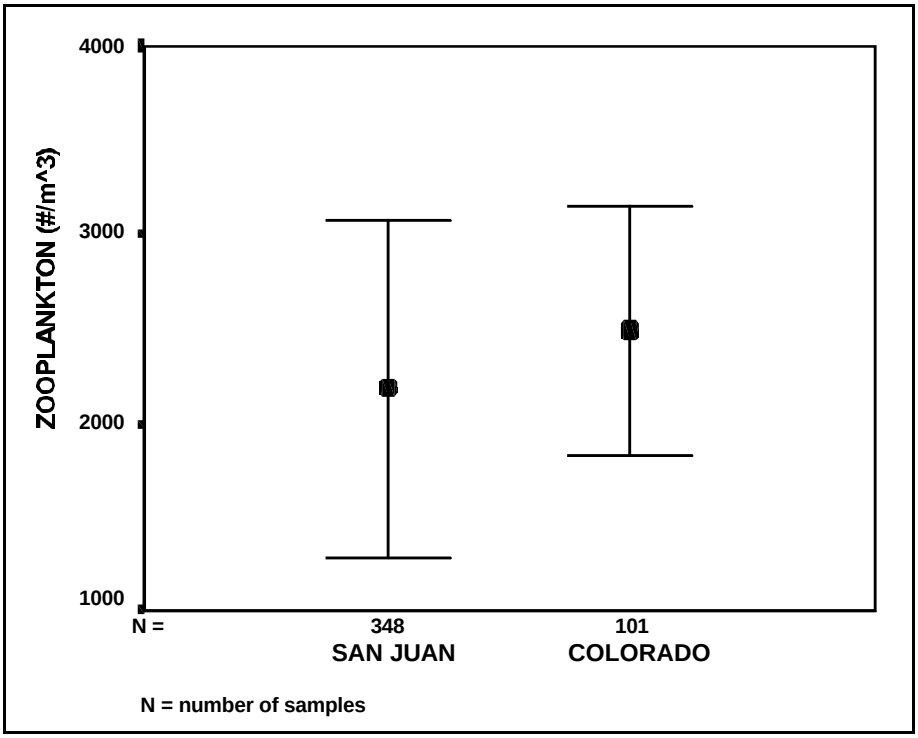

Figure 7.29. Mean Zooplankton Biomass (±1 SE) in San Juan and Colorado River Backwaters over the 1996-97 Period for Sampling Trips 5 Through 11

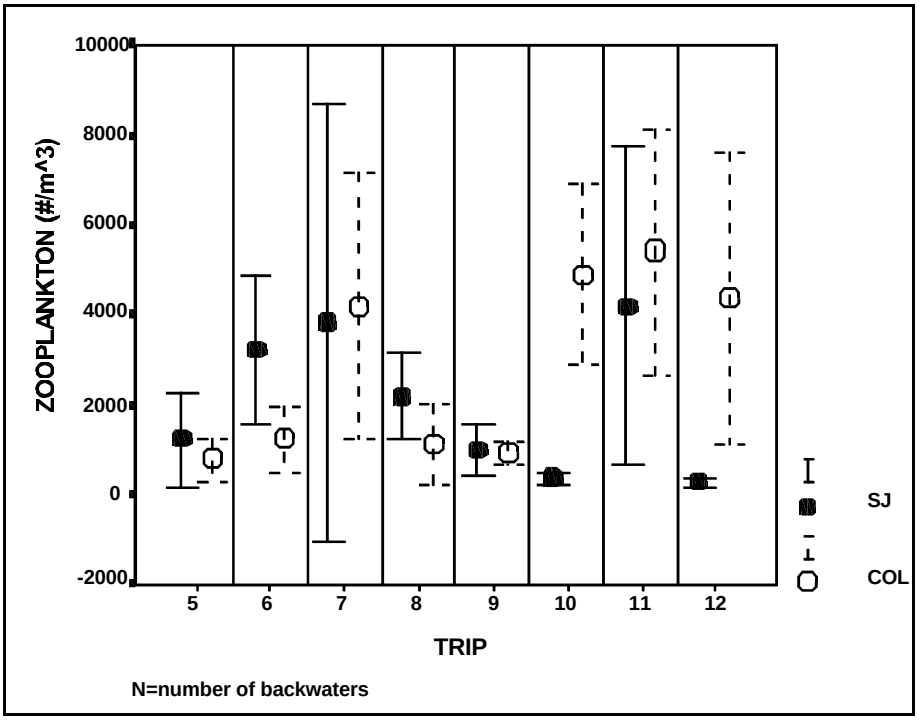

Figure 7.30. Mean Zooplankton Biomass (±1 SE) in San Juan and Colorado River Backwaters over the 1996-97 Period by Sampling Trip

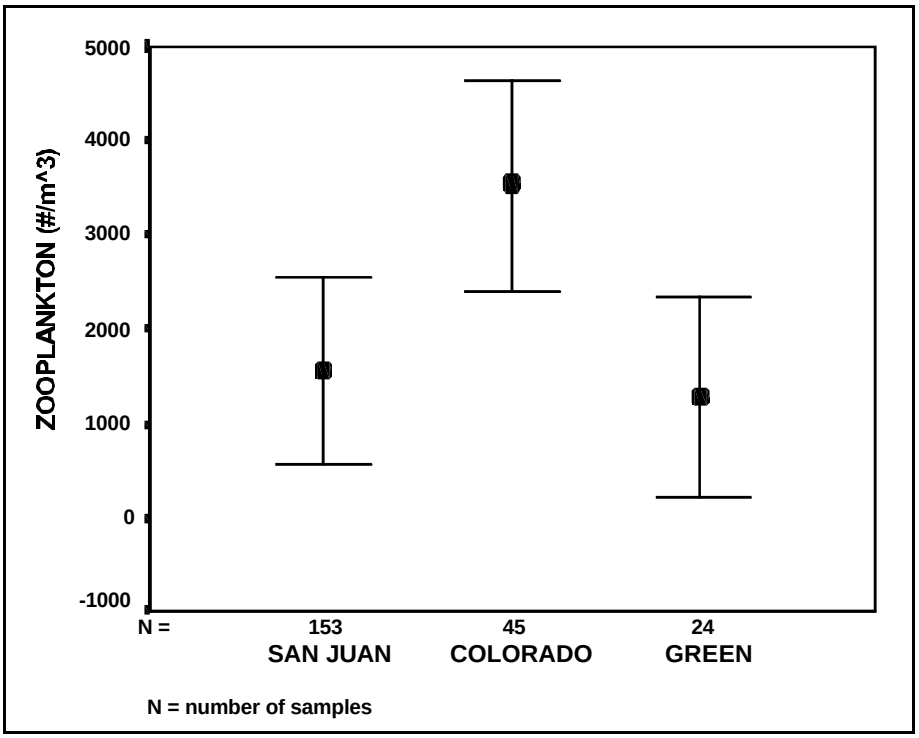

Figure 7.31. Mean Zooplankton Biomass (±1 SE) in San Juan, Colorado, and Green River Backwaters over the April to October 1997 Period for Sampling Trips 9 through 12

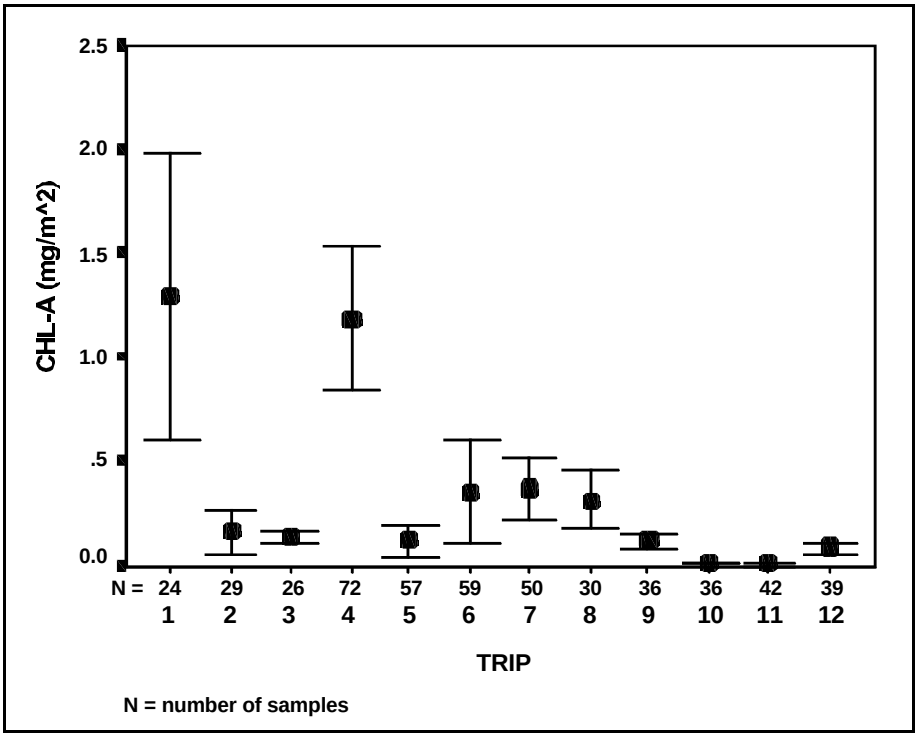

Figure 7.32. Mean Periphyton Biomass (±1 SE) in San Juan River Backwaters over the 1995-97 Period by Sampling Trip

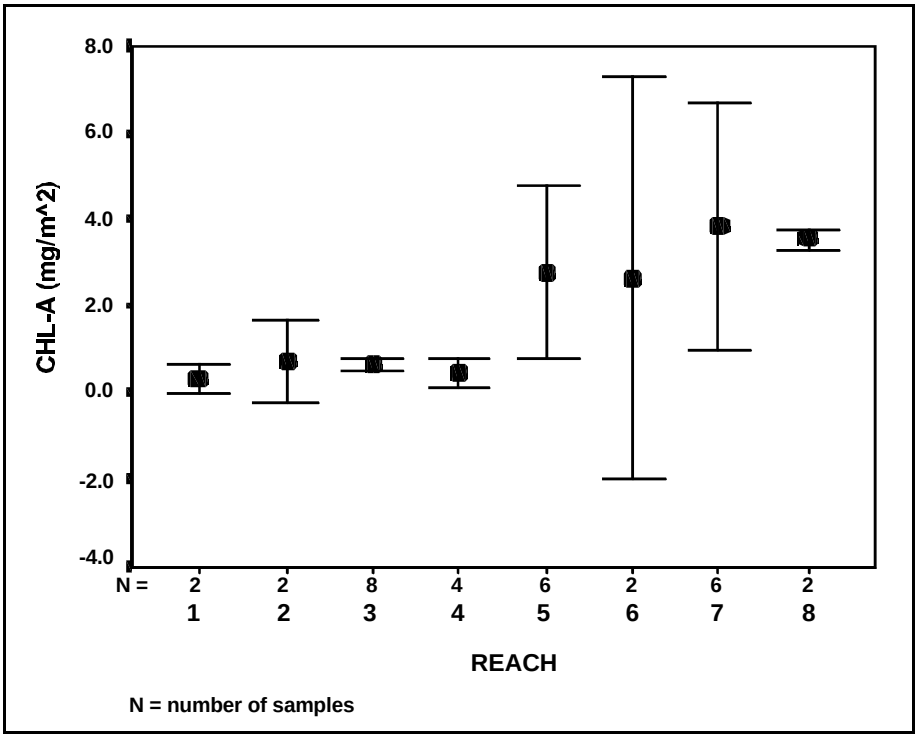

Figure 7.33. Mean Periphyton Biomass (±1 SE) in San Juan River Backwaters During Trip 1 in August, 1995 by Geomorphic Reach

However, due to high variability in the data and low sample sizes, these differences were not significant (P>0.05). During trip 4 the following April, the longitudnal trend was more pronounced with Reaches 5 and 6 having the highest levels (Figure 7.34). Reach 5 was significantly greater (P<0.005) than Reaches 1 and 2, while Reach 6 was significantly greater than Reaches 1 through 4 (P<0.005). Periphyton was low in all reaches with no significant differences between reaches during trips 2 and 3 in September and November, 1995, respectively.

Following the below-average runoff in 1996, periphyton levels were significantly reduced in July (trip 5) from the pre-runoff levels observed in April (P<0.05; Dunnett C) (Figure 7.32). Those levels were also significantly lower than the corresponding post-runoff, pre-storm levels observed the previous year (trip 1) (P<0.05), which followed a substantially greater volume of runoff (Figure 7.2). Also, as stated previously, total suspended solid concentrations during trip 1 were significantly less than during trip 5 and the lowest recorded during the study (Figure 7.8). Periphyton biomass remained low over the next four trips (6-9) in August and December, 1996, and February and April, 1997 with no significant differences between trips (P>0.05). Between the August, 1996 and April, 1997 trips at least six storms producing discharges in excess of 1,500 cfs were recorded, three of which occurred between August and December (Figure 7.1). Above average rainfall in the spring produced discharge spikes in excess of 4,000 cfs prior to the April trip. Thus, a comparison of the winter period of 1996 between trips 7 and 9 and the same period in 1995 (trip 3 to 4) reveals an interesting difference between the two years. While there was a significant increase in periphyton riverwide the first season during stable winter discharges, there was no change in biomass density over the same period the following year when storms prevailed.

During the last monsoon season studied in 1997 (trips 10-12), backwaters were universally low in periphyton throughout the river with no significant differences temporally (P>0.05; Dunnett C) (Figure 7.32). Indeed, sampling during trips 10 and 11 occurred during large storms (Table 7.1, Figure 7.1) and so the backwaters sampled had only recently become inundated. Hence, there was no post-runoff, pre-storm sample obtained during the 1997 monsoon season for valid comparison to the previous two years. Inspection of the hydrograph reveals that there were few, brief periods available during the monsoon season in 1997 for sampling at base flow conditions (Figure 7.1). Sampling during the last trip, one month after cessation of the monsoons, indicated that periphyton levels in the backwaters had not improved.

Periphyton density in San Juan backwaters was compared to those in the Colorado and Green Rivers for correspondingly sampled time periods. First, the San Juan and Colorado backwater results were compared for trips 5 through 12 when both rivers were sampled. When averaged across all trips, the Colorado backwaters had significantly greater levels of periphyton (Figure 7.35) than the San Juan River (P<0.001; Independent samples t-test; equal variance not assumed (Zar 1984)). Testing individual trips revealed that there were significant differences between the two rivers only during trips 5 (July, 1996), 6 (August, 1996), and 10 (August, 1997) (P<0.005; Independent samples t-test), but that trips 5 and 6 accounted for most of the difference. Figure 7.36 illustrates the temporal differences between the two systems. Generally, the results would indicate that the Colorado River backwaters did not appear to be perturbated during trips 5 and 6, when periphyton biomass was

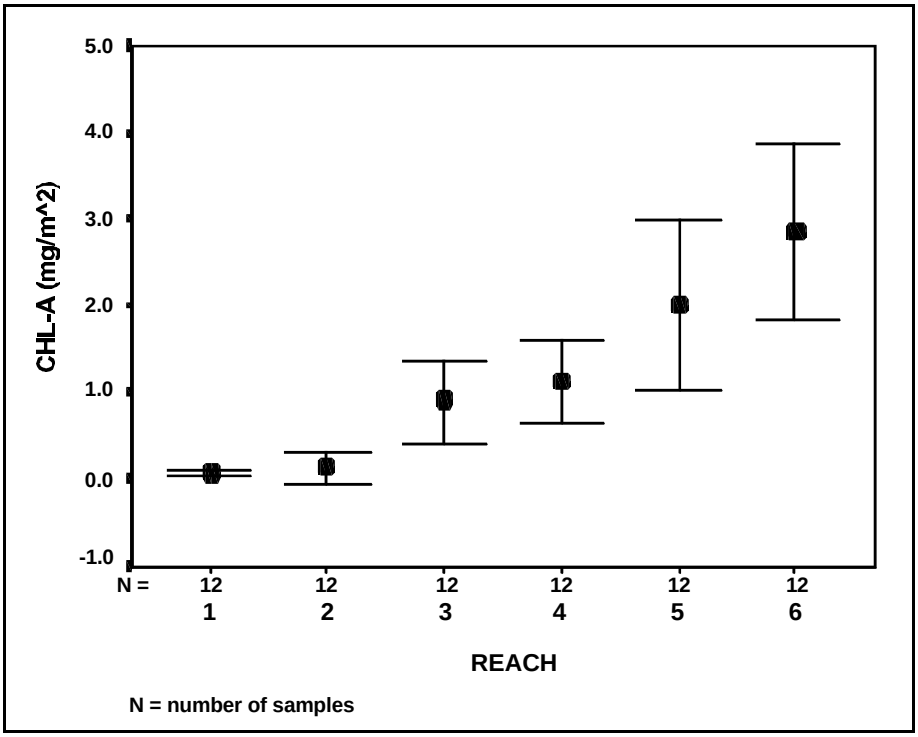

Figure 7.34. Mean Periphyton Biomass (±1 SE) in San Juan River Backwaters During Trip 4 in April, 1996 by Geomorphic Reach

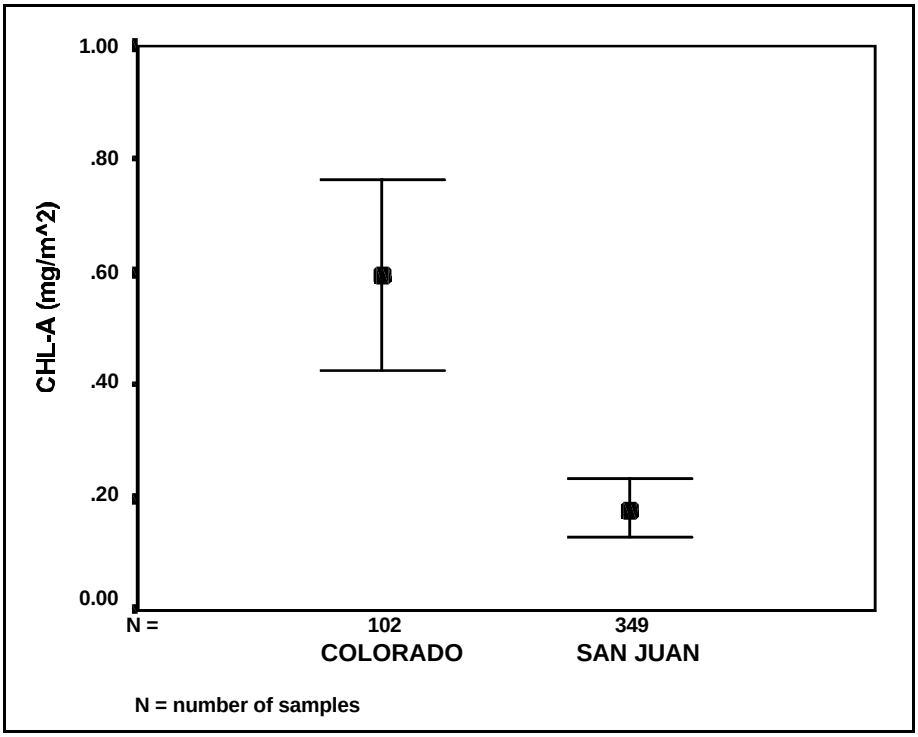

Figure 7.35. Mean Periphyton Biomass (±1 SE) in San Juan and Colorado River Backwaters over the 1996-97 Period for Sampling Trips 5 Through 12

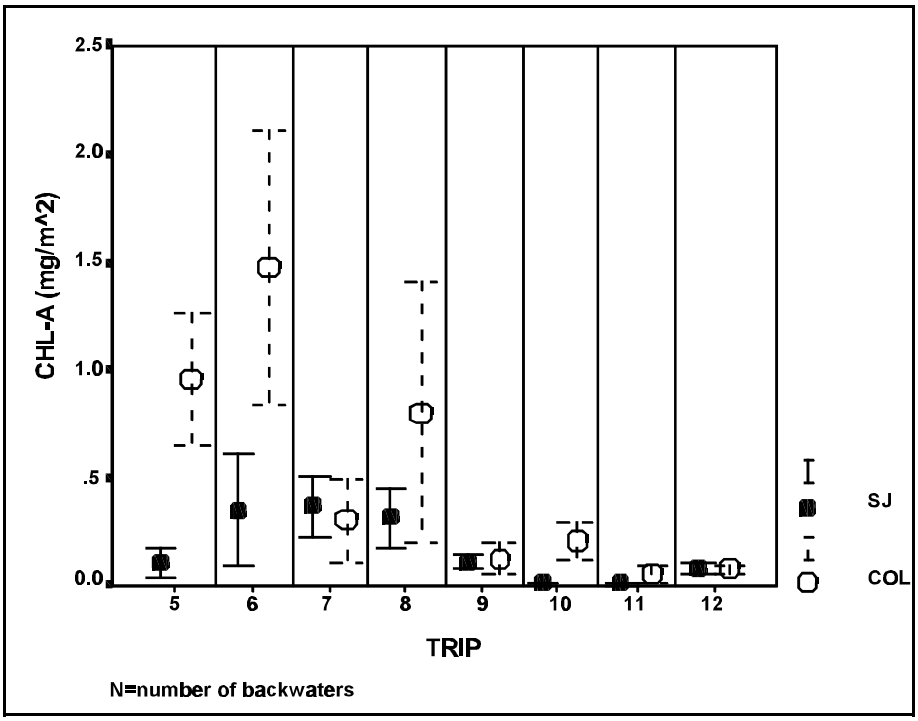

Figure 7.36. Mean Periphyton Biomass (±1 SE) in San Juan and Colorado River Backwaters over the 1996-97 Period by Sampling Trip

relatively high and significantly greater than the San Juan River, but that backwaters in both rivers appeared to be perturbated to some degree in every trip thereafter as evidenced by low periphyton. The San Juan, Colorado, and Green rivers were compared for trips 9-12 when sampling occurred in all three rivers. Over this time period (April-October, 1997), periphyton was significantly greater in the Colorado backwaters than both the San Juan ($P<0.001$; Independent samples t-test) and the Green Rivers ($P<0.005$) (Figure 7.37). However, the San Juan and Green River backwaters were not significantly different from each other ($P>0.98$). Mean periphyton was relatively low in all rivers (<0.2 mg/m^2) when averaged across all four trips, suggesting that backwaters in all systems appeared to be perturbated to some extent.

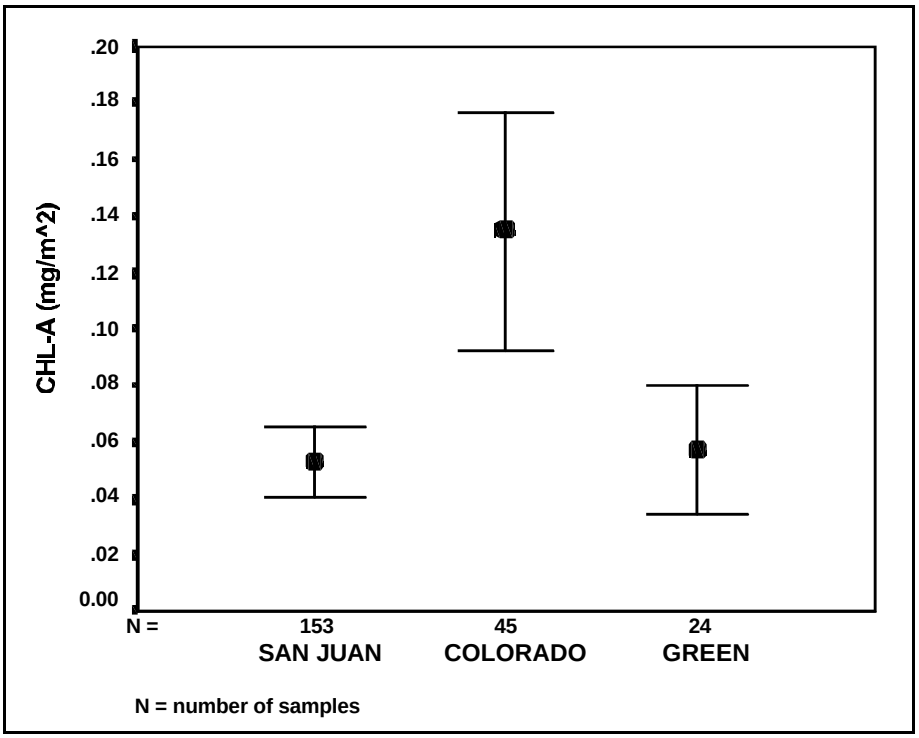

Figure 7.37. Mean Periphyton Biomass (±1SE) in San Juan, Colorado, and Green River backwaters over the April- October 1997 Period for Sampling Trips 9 through 12

Benthic Invertebrates

The biomass of benthic invertebrates in backwaters, primarily composed of chironomid and, to a lesser degree, ceratopogonid larvae, was relatively low during most trips on the San Juan River with the notable exception of trip 4 in April, 1996 (Figure 7.38) which followed an extended period of stable flows (Figure 7.1). Benthic invertebrate biomass was significantly greater during trip 4, than during nearly every other trip ($P<0.05$; Dunnett C). The greater abundance of invertebrates during trip 4, following stable flows, contrasted sharply with relatively low levels observed during a similar period the subsequent year in February (trip 8) and April, 1997 (trip 9) which followed a stormy period (Figure 7.1). The increase in invertebrate abundance during trip 4 was apparent to some degree in every reach sampled (Figure 7.39), although only in Reaches 1, 4, and 5 were these increases significant ($P<0.05$; Independent samples t-test).

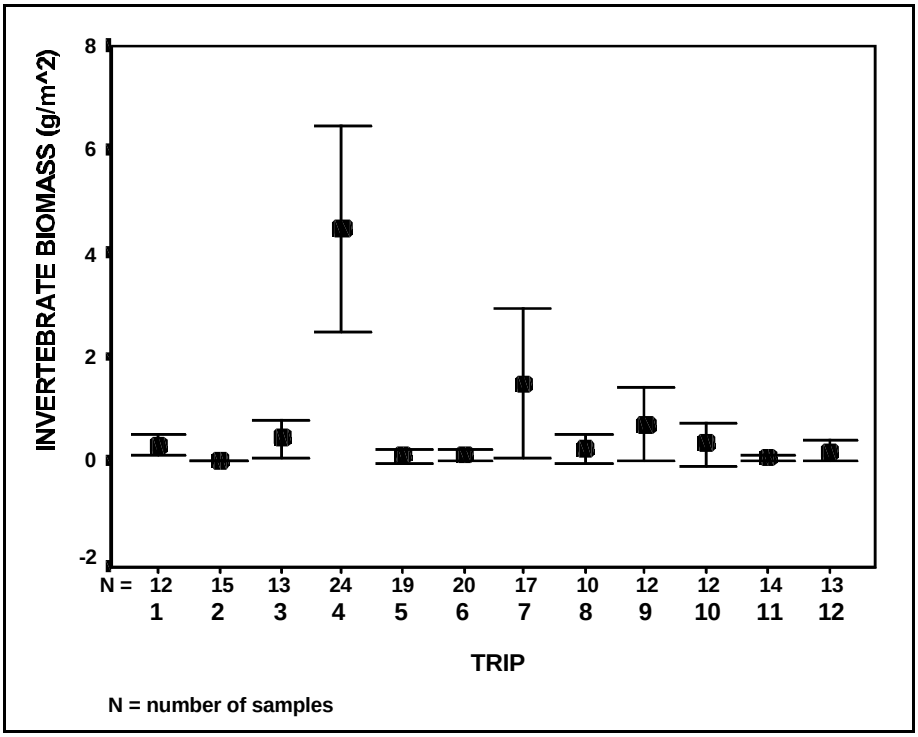

Figure 7.38. Mean Benthic Invertebrate Biomass (±1 SE) in San Juan River Backwaters over the 1995-97 Period by Sampling Trip

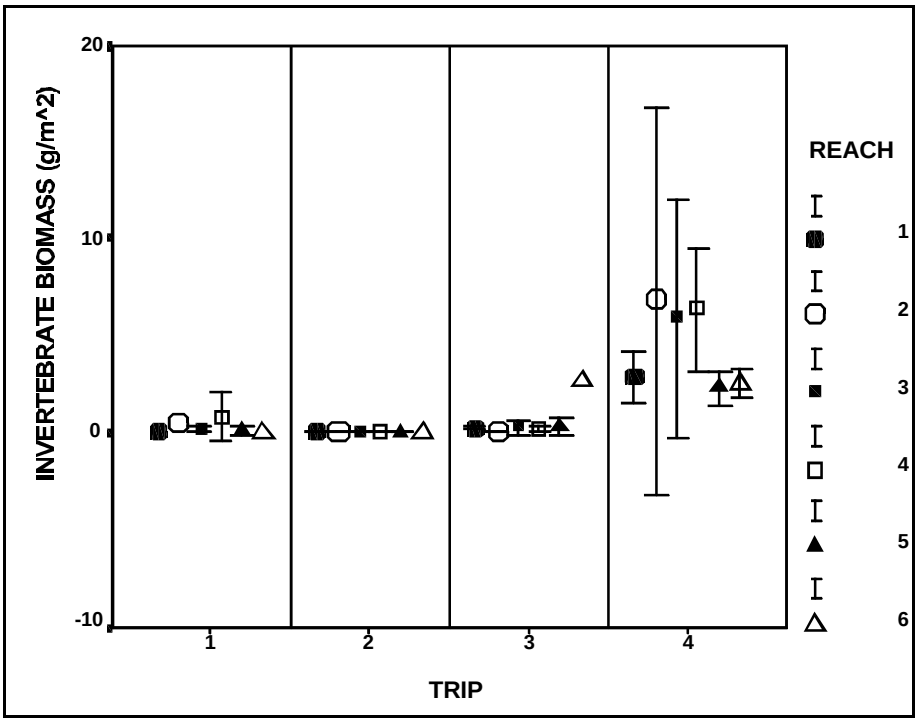

Figure 7.39. Mean Benthic Invertebrate Biomass (±1 SE) in San Juan River Backwaters During Trips 1 through 4 by Geomorphic Reach

Trips 4 and 7 were examined more closely to determine whether spatial trends existed during the comparatively higher invertebrate densities observed at those times. No significant differences existed by reach during either trip 4 (Figure 7.39) or trip 7 (Figure 7.30) ($P>0.05$; Dunnett C). During trip 4, there was some trend toward higher invertebrate biomass in all reaches over those during trip 3 in Reaches 2, 3, and 4 (Figure 7.39). Curiously, invertebrate abundance remained relatively low and near zero in Reaches 1, 5, and 6. During trip 7, although no differences existed between reaches, invertebrates appeared to be more abundant, although more variable upstream in Reaches 5 and 6 (Figure 7.40). Backwaters in downstream reaches were nearly devoid of invertebrates, suggesting perhaps that negative impacts associated with prior storms may have been more severe and widespread in those reaches. When averaged across all 12 trips, there were no significant differences between reaches ($P>0.05$; Dunnett C) (Figure 7.41).

Over trips 5 through 12, encompassing the period of July, 1996, to October, 1997, there was no difference in benthic invertebrate biomass between the San Juan and Colorado River backwaters ($P=0.84$; Independent samples t-test) (Figure 7.42). Both rivers averaged approximately 0.4 ± 0.2 g/m^2 over this period. Comparisons over time revealed that only during trip 6 did backwaters in the two rivers differ, with Colorado River backwaters having greater invertebrate biomass ($P<0.05$; Independent samples t-test) (Figure 7.43). One-way ANOVA indicated that there were no differences ($P=0.71$) between benthic invertebrate abundance in the San Juan, Colorado, and Green Rivers when averaged over the commonly sampled period encompassing trips 9 through 12 (Figure 7.44). Backwaters in all three rivers averaged about 0.2 g/m^2, with the most variability found in the less intensively sampled Green River.

Detritus

Benthic detritus in San Juan River backwaters was generally a highly variable parameter with few differences noted through time when Reaches 1-6 were averaged (Figure 7.45). Dunnett's C-test indicated that backwater detritus during trip 8 (February, 1997) was significantly less than trips 4 (April, 1996), 11 (September, 1997), and 12 (October, 1997) ($P<0.05$). No other differences were detected. There was no spatial pattern apparent when all trips were averaged (Figure 7.46) (Dunnett C; $P>0.05$), although levels of detritus appeared to increase slightly in Reach 1, the lowest gradient reach.

Detrital biomass was compared in the San Juan and Colorado Rivers, averaged across trips 5 through 12 when both rivers were sampled, and no significant differences were found ($P=0.58$; Independent samples t-test) (Figure 7.47). Temporal variation between the two rivers was fairly similar (Figure 7.48), with somewhat higher levels observed during later trips. Only on two occasions, trip 10 ($P<0.05$; independent samples t-test; equal variance not assumed) and trip 12 ($P<0.001$), did detritus levels differ between the two rivers, but one river was not consistently higher than the other. Detritus levels between all three rivers were compared for trips 9 through 12 combined (Figure 7.49) and no significant differences were found ($P>0.23$; Tukey's HSD).

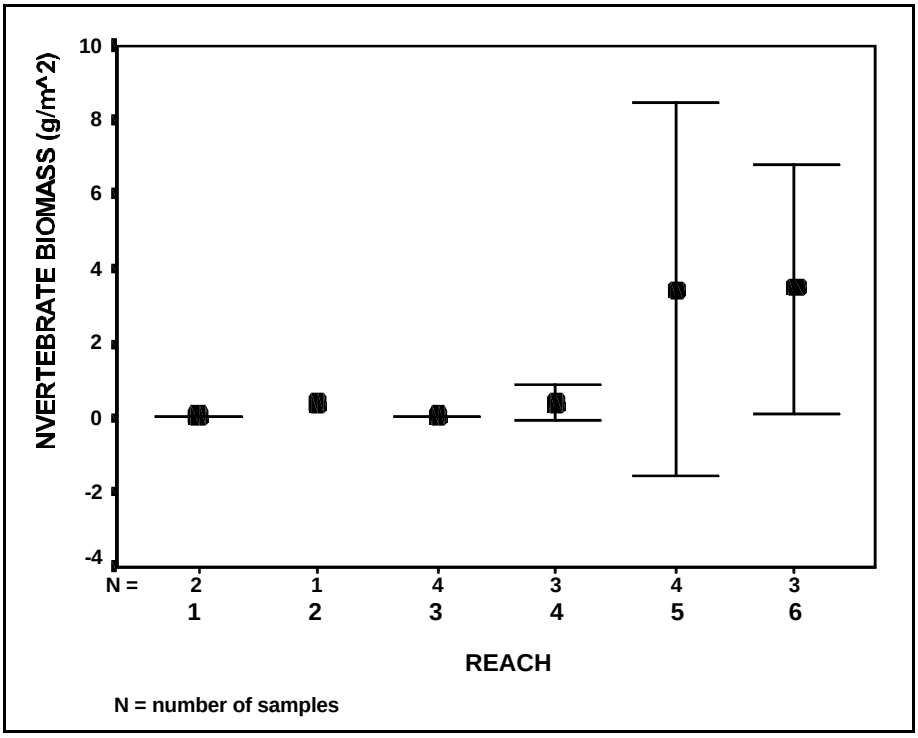

Figure 7.40. Mean Benthic Invertebrate Biomass (±1 SE) in San Juan River Backwaters During Trip 7 in December, 1996 by Geomorphic Reach

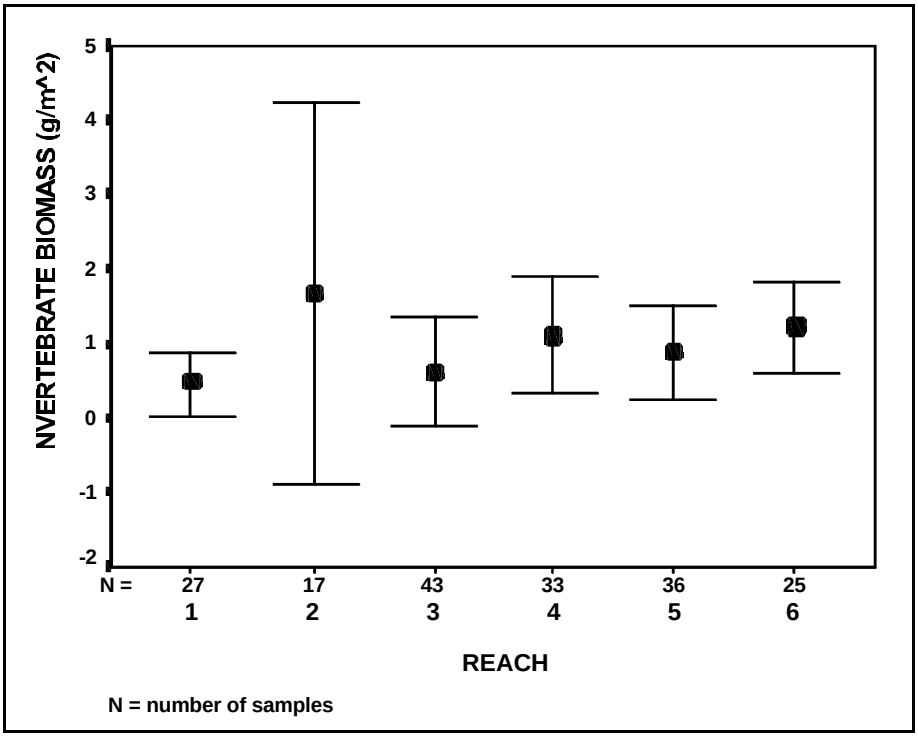

Figure 7.41. Mean Benthic Invertebrate Biomass (±1 SE) in San Juan River Backwaters over the 1995-97 Period by Geomorphic Reach

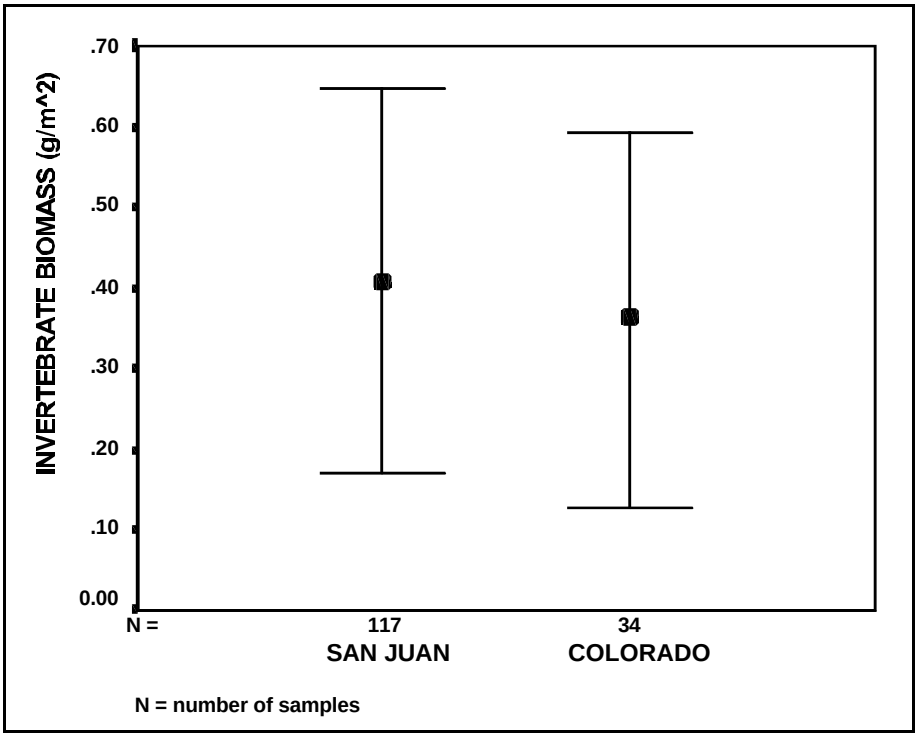

Figure 7.42. Mean Benthic Invertebrate Biomass (±1 SE) in San Juan and Colorado River Backwaters over the 1996-97 Period for Sampling Trips 5 Through 12

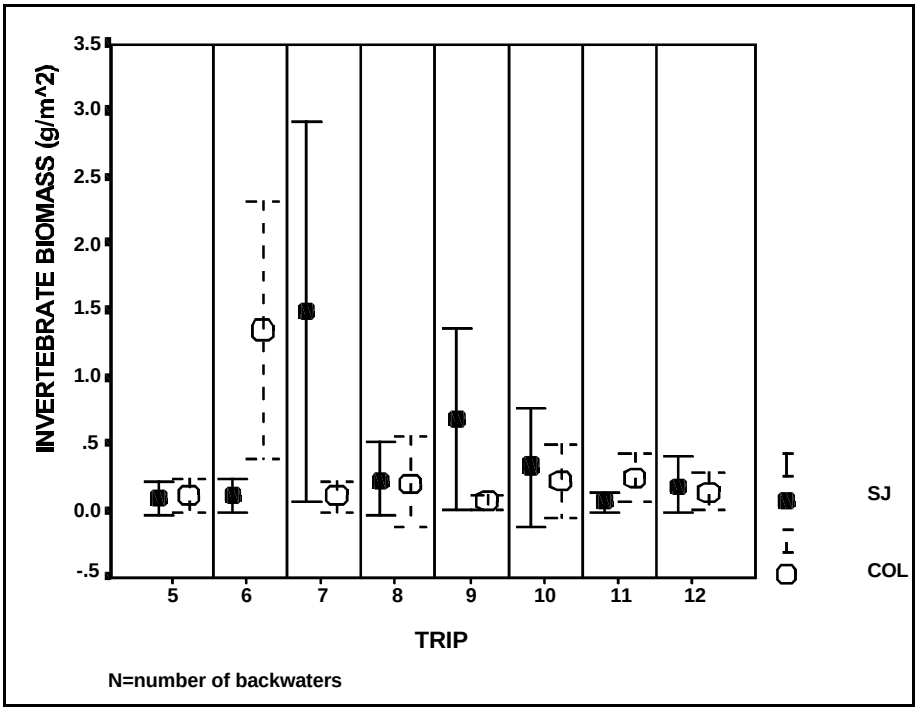

Figure 7.43. Mean Benthic Invertebrate Biomass (±1 SE) in San Juan and Colorado River Backwaters over the 1996-97 Period by Sampling Trip

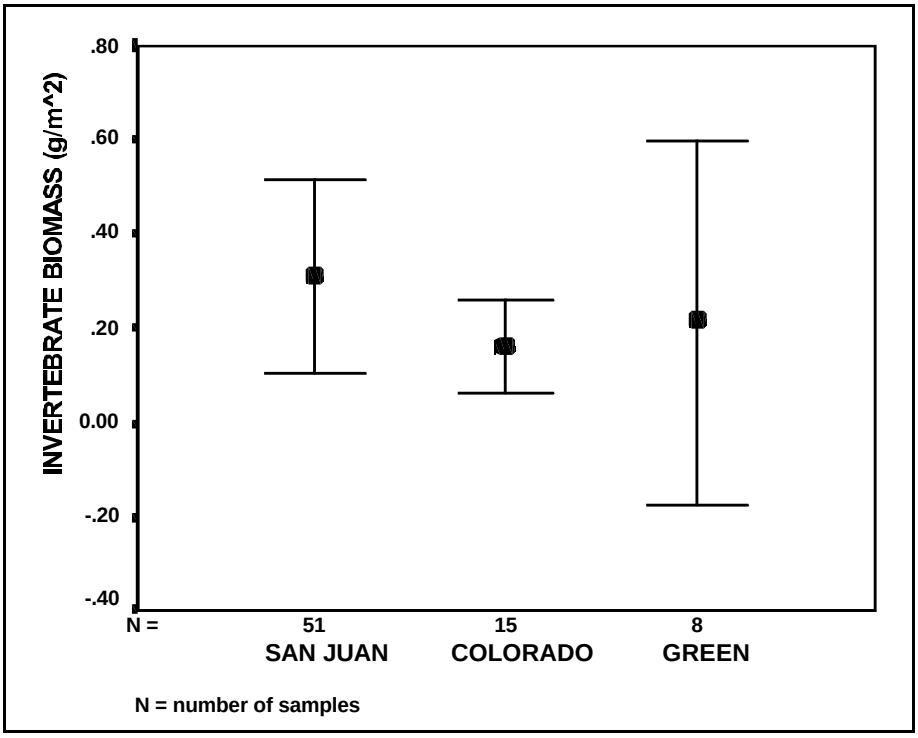

Figure 7.44. Mean Benthic Invertebrate Biomass (±1 SE) in San Juan, Colorado, and Green River Backwaters over the April to October 1997 Period for Sampling Trips 9 through 12

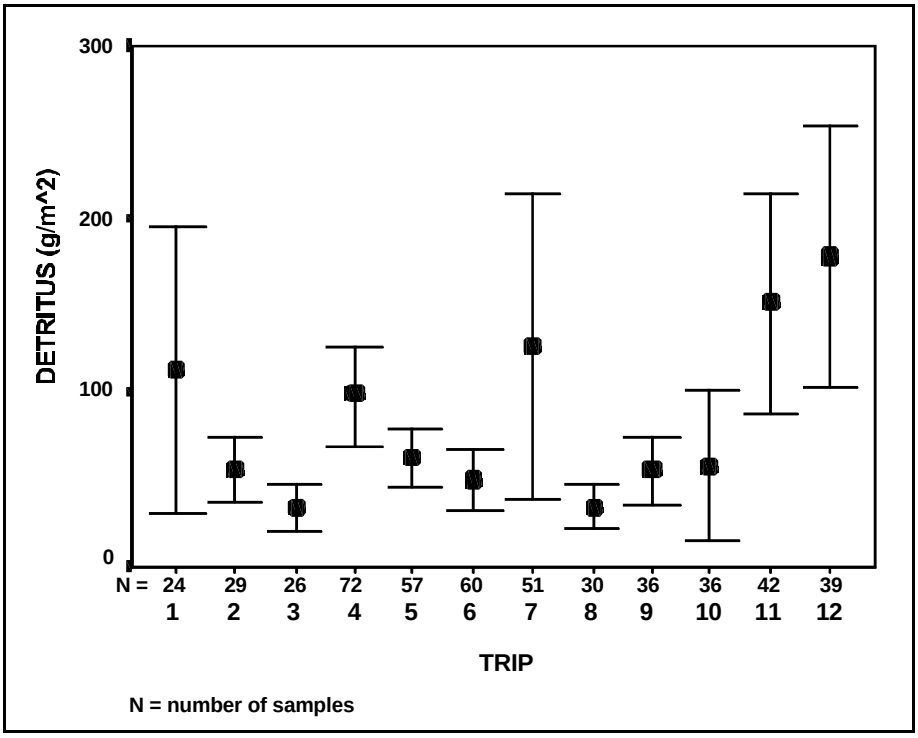

Figure 7.45. Mean Detrital Biomass (±1 SE) in San Juan River Backwaters over the 1995-97 Period by Sampling Trip

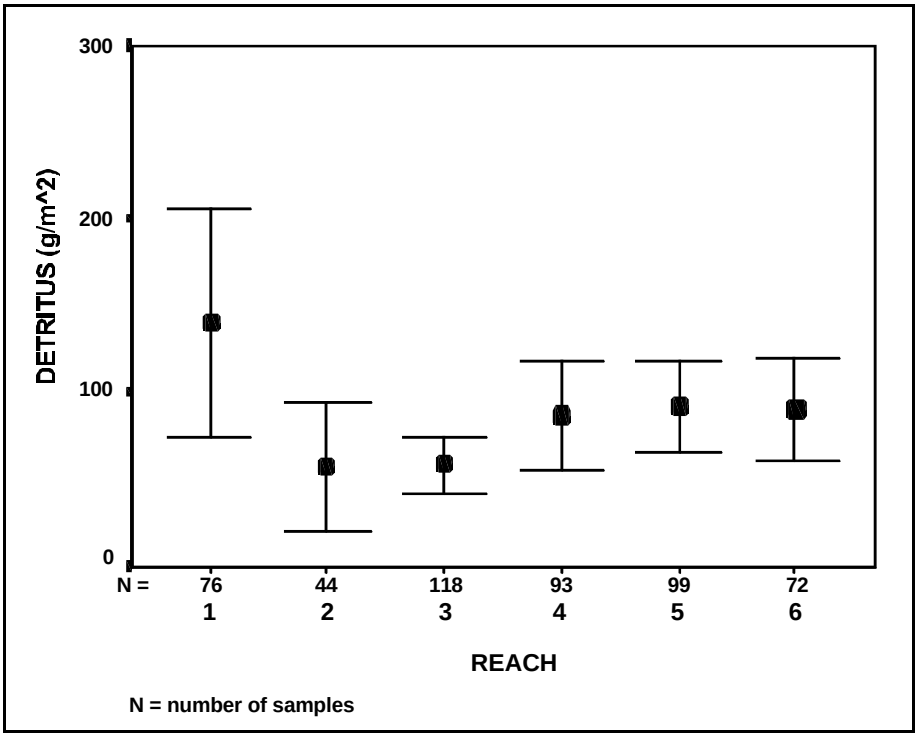

Figure 7.46. Mean Detrital Biomass (±1 SE) in San Juan River Backwaters over the 1995-97 Period by Geomorphic Reach

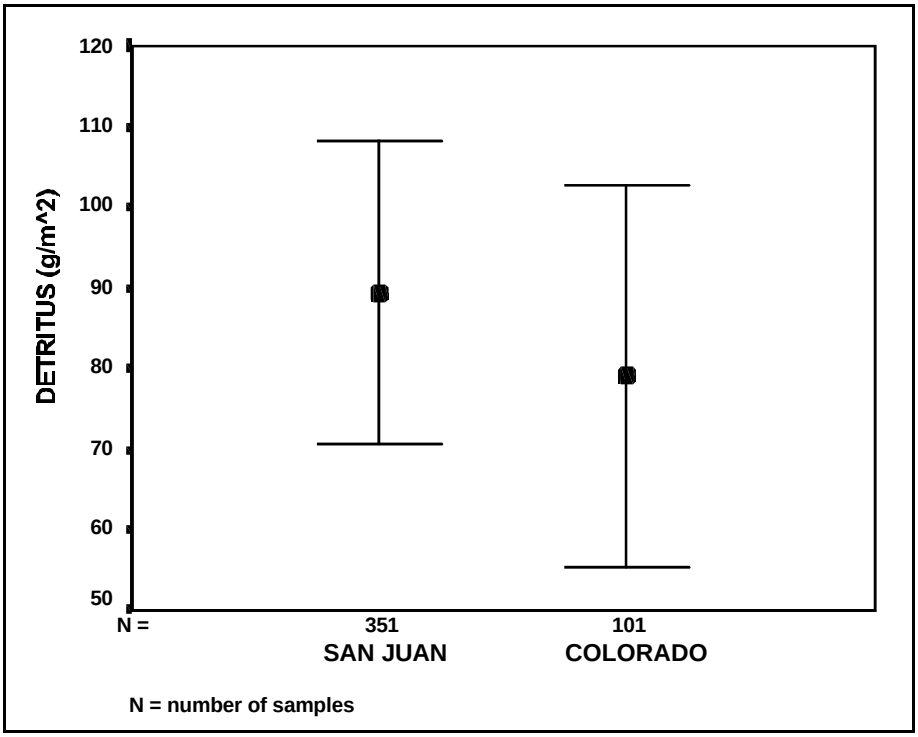

Figure 7.47. Mean Detrital Biomass (±1 SE) in San Juan and Colorado River Backwaters over the 1996-97 Period for Sampling Trips 5 through 12

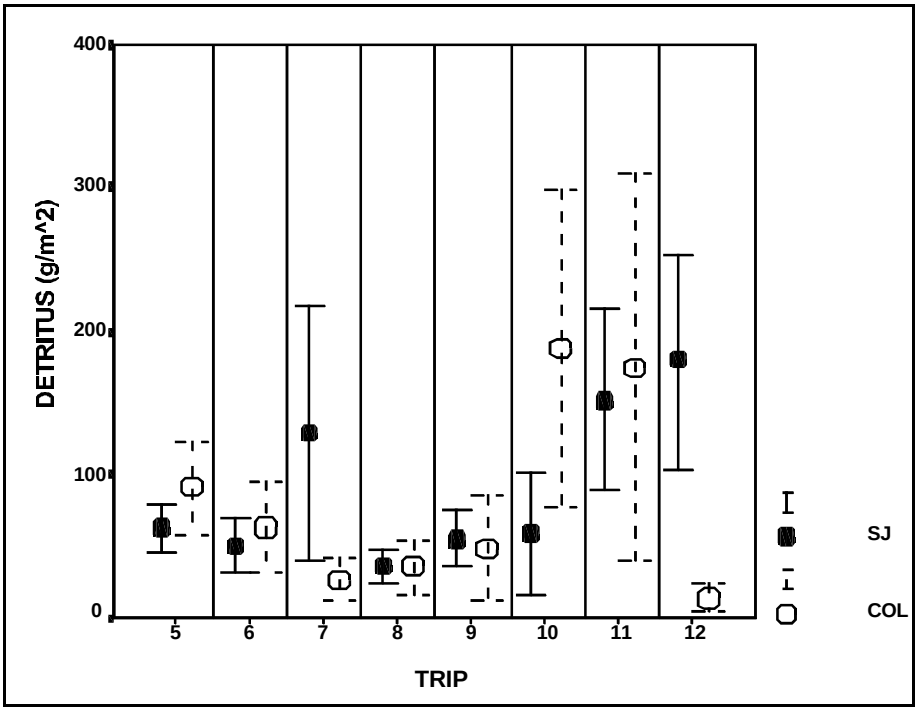

Figure 7.48. Mean Detrital Biomass (±1 SE) in San Juan and Colorado River Backwaters over the 1996-97 Period by Sampling Trip

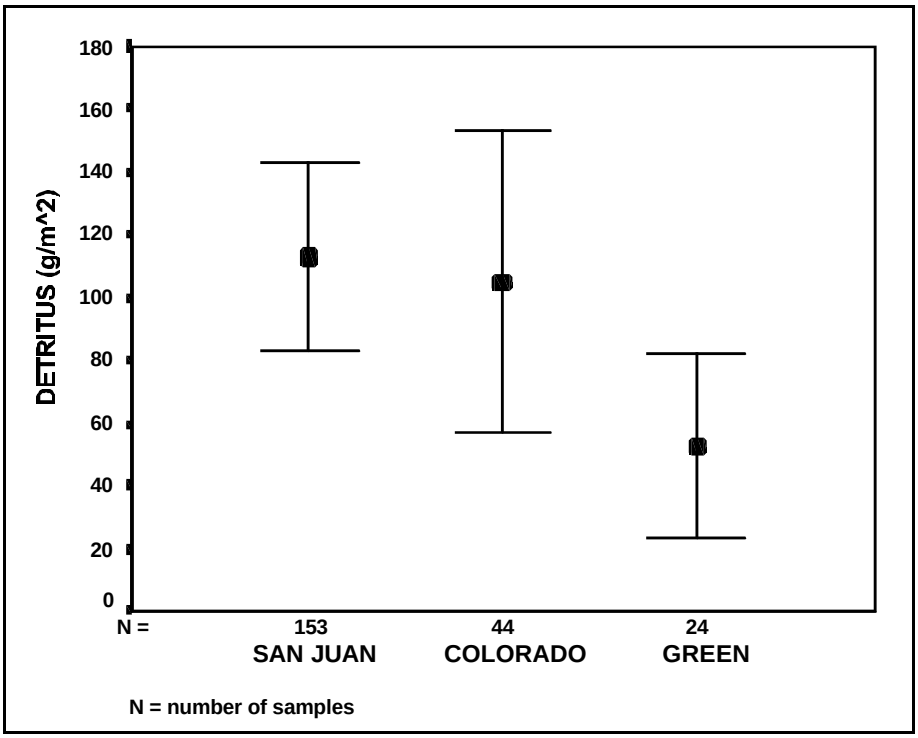

Figure 7.49. Mean Detrital Biomass (±1 SE) in San Juan, Colorado, and Green River Backwaters over the April to October 1997 Period for Sampling Trips 9 through 12

DISCUSSION

During this investigation, the impacts of storms on several parameters indicative of the quality of backwaters in the San Juan River was observed. These parameters included phytoplankton, periphyton, and benthic invertebrate biomass. Production of these organisms was relatively low during or immediately following storm events. Conversely, productivity increased following a prolonged period of stable flows lasting five to six months. Stable flows on the order of a month or two appeared to be insufficient to result in significant increases in these parameters. When productivity was relatively high, only periphyton demonstrated a consistent longitudnal pattern, with biomass decreasing steadily downstream.

Backwater depth declined to about the same levels (0.2-0.3 m) each year after the monsoon season, apparently irrespective of the frequency or magnitude of storms. Backwater depth was highest at about 0.6±0.2 m immediately after runoff in 1995, which was the highest volume of runoff experienced during the study, suggesting some flushing of backwaters. Depths declined to the following spring to about 0.2±0.1 m and remained fairly steady thereafter to the end of the study, although changes in river stage due to storms influenced backwater depths on several occasions. Concurrently, during the period following the 1995 runoff to the following spring, the percentage of ultra fine sediment (<0.063 mm) in these habitats increased river-wide from roughly 0% to 75% (Figure 7.50), an effect that was evident in all six reaches (Figure 7.51). This suggests that accumulation of these fine sediments in the backwaters contributed to the observed decrease in mean depth. Incomplete flushing was apparent after the below average runoff in 1996 (Figure 7.50). Subsequently, percentages remained relatively high ($40%) to the end of the study in October, 1997, which constituted a rather stormy period. At least 10 storms in excess of 1,500 cfs (mean daily average) occurred over this time interval (Figure 7.2).

Other measures within backwaters were less consistent with regard to response to storms or the lack thereof. For example, zooplankton abundance increased following the period of stable flows during the fall to spring period of 1995-96, but displayed similarly “high” levels during or immediately following some storms on other occasions. There appeared to be some downstream displacement of zooplankton to lower reaches during at least one storm. Some backwaters in the lower portions of Reach 8 (Figure 1.1) may be a source of zooplankton at these times. These backwaters experience more stable flow regimes due to the lower number of tributaries located upstream and zooplankton populations within are likely augmented by limited downstream drift of zooplankton from Navajo Reservoir. Backwaters located in the upper portion of Reach 8 have no tributaries upstream and thus are not susceptible to flushing except in some instances during elevated releases from Navajo Dam.

Benthic detritus likewise increased over the prolonged period of stable flows, but was highly variable temporally with no consistent effect by storms. Storms did not appear to affect the temperature nor the amount of oxygen in backwaters. Dissolved oxygen seemed to be most influenced by temperature, with the highest levels generally occurring during the colder periods and the lowest during the warmer months.

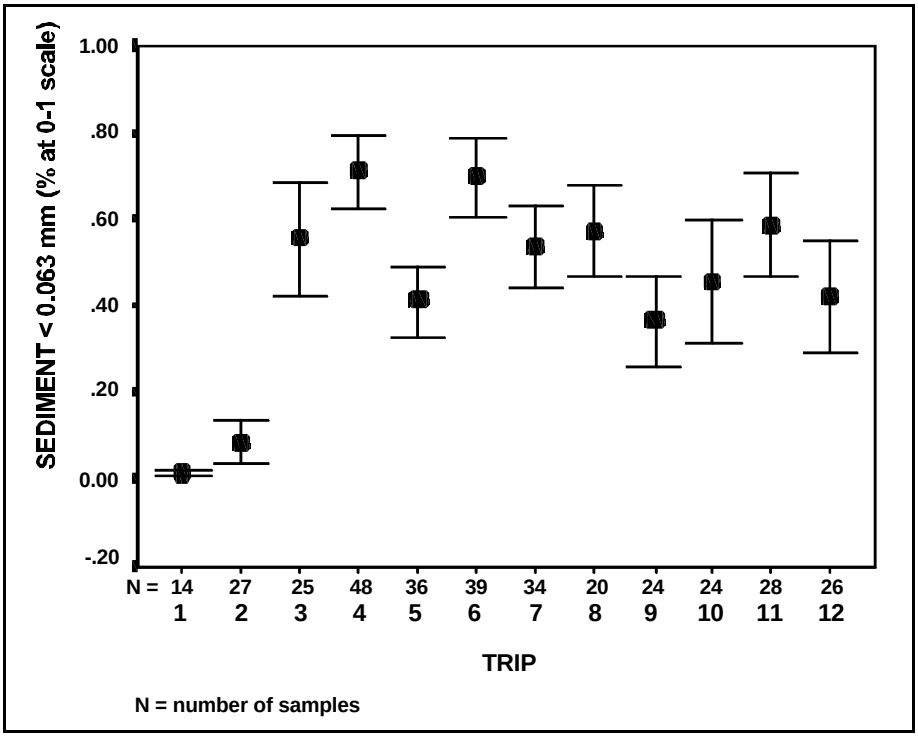

Figure 7.50. Mean Percentage (±1 SE) Dry Weight of Sediment <0.063 mm in San Juan River Backwaters over the 1995-97 Period by Trip

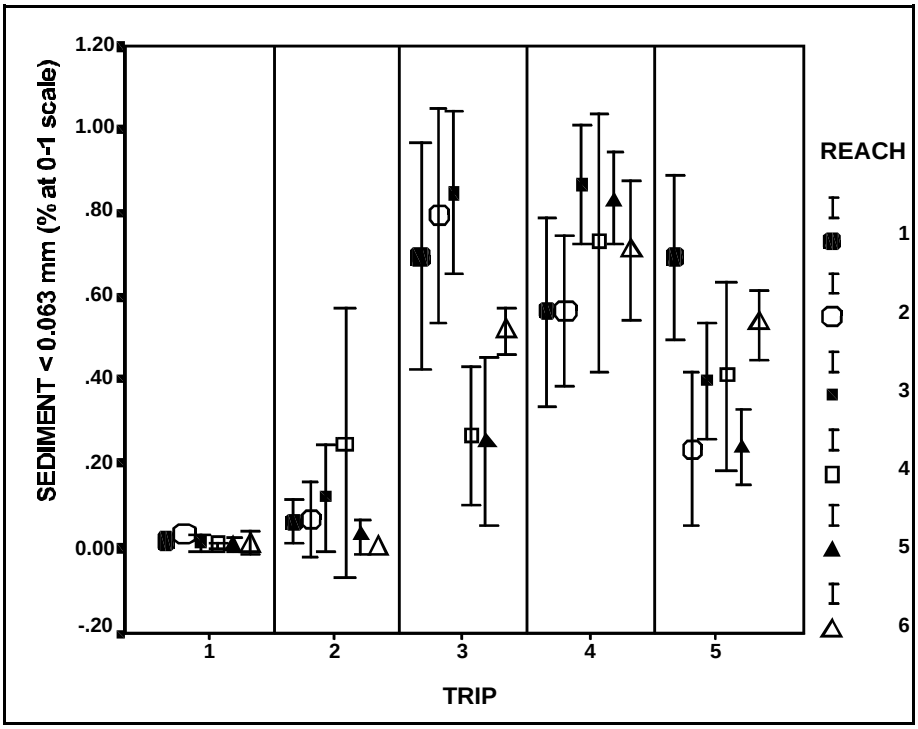

Figure 7.51. Mean Percentage (±1 SE) Dry Weight of Sediment <0.063 mm in San Juan River Backwaters over the Period of August, 1995 to July, 1996 During Trips 1 through 5 by Geomorphic Reach

Comparisons with the Colorado River over the period from July, 1996 to October, 1997, indicated that Colorado River backwaters within the area between Moab and Potash, Utah were generally deeper and less turbid than those in the San Juan River. Backwaters in the Colorado were several Celsius degrees cooler than in the San Juan and dissolved oxygen was greater in the Colorado backwaters (-9 mg/L) on average than those in the San Juan (-6 mg/L). Production-wise, periphyton was the only parameter that was significantly greater in Colorado backwaters. Reduced turbidity in Colorado backwaters may have contributed to higher periphyton biomass through increased light penetration improving rates of photosynthesis. Cooler temperatures combined with higher primary production likely contributed to higher oxygen levels in Colorado River backwaters. Oxygen levels in San Juan backwaters were rarely reduced to the point where the existence of most fishes would be compromised, although red shiners were observed gulping air at the water surface in a number of backwaters during several sediment-laden storms.

The two key potential food organisms for young pikeminnow, zooplankton and benthic invertebrate biomass, were essentially equal between the two rivers over the time period indicated above. However, considering that the first two months after runoff (August and September) are probably the most critical for young pikeminnow, over the 1996-97 time period Colorado River backwaters contained greater numbers of zooplankton during August, 1997. Although storms occurred in both drainages during that trip (Figures 7.1 and 7.2), the magnitude of the storm in the Colorado River was only about twice base flow, while in the San Juan River it was about six times the average base flow. Also, the discharge-stage relationship in this section of the Colorado River is such that approximately twice the incremental increase in discharge is required to produce the same increase in stage as in the San Juan River. Therefore, it is very possible that most if not all of the backwaters sampled in the Colorado at that time were not flushed during the storm, while those in the San Juan River were flushed. Biomass of zooplankton and benthic invertebrates is usually lower in recently flushed than non-flushed backwaters (Kennedy and Tash 1979). This disparity between the two rivers may be a critical factor in the survival potential for larval pikeminnow which would be less likely to be exposed to physical displacement in the Colorado backwaters and should also have more zooplankton and invertebrates on which to feed.

Benthic invertebrates (primarily chironomid larvae) were significantly greater in Colorado River backwaters during the August, 1996 sampling, but not at any other time. San Juan River backwaters were perturbated by a storm event at the time of sampling, while Colorado River backwaters were not. However, a prolonged period of stable flows over the 1996-97 winter period failed to produce an increase in the biomass of invertebrates in Colorado River backwaters such as that observed in the San Juan River during the 1995-96 winter period. This apparent contradiction is difficult to explain, although it should be emphasized that the Colorado data set encompassed only one such period. It is interesting to note that catch rates of pikeminnow yoy in this reach of the Colorado River were the highest in the fall of 1996 that they have been observed since 1986 (McAda 1996). It could be speculated that predation by these fishes on invertebrates may have reduced their abundance to some degree, although this possibility seems unlikely. The reason for the lack of increase in benthic invertebrates over the stable flow period in the Colorado is not known, but it is possible that low sample sizes coupled with larger-sized backwaters and the characteristic patchiness of benthic invertebrate distribution may have been a contributing factor.

Comparisons between the San Juan, Colorado, and Green Rivers during 1997 revealed few differences in any measures. During the period from August to October, all three rivers experienced storm perturbations that generated relatively low levels of productivity. The most important parameter with respect to the diet of young pikeminnow, benthic invertebrate abundance, did not differ between these three systems over this period. These results illustrated that while less susceptible to perturbations from storms, backwaters in the lower Colorado and Green Rivers are certainly not immune to their effects.

In the final analysis, however, the ultimate determinant of the relative suitability of backwaters per se may be river gradient. Although backwaters in the lower Colorado and Green Rivers where pikeminnow yoy are relatively abundant may be less susceptible to the negative effects of perturbations on primary and secondary productivity and the physical quality of those habitats than those throughout the San Juan River, these differences may be immaterial if the opportunity for drifting pikeminnow larvae in the San Juan River to settle into these habitats is too low to provide adequate recruitment to the adult population due to high gradient. Hopefully, once the spawning adult population is large enough, sufficient numbers of larvae can be retained throughout the river and survive in substantial quantities to allow for a self-sustaining population to become established. In that event, it should be an important next step to determine whether these storm events have significant negative effects on survival and growth of these young fishes. Should this be the case, range management options may exist to ameliorate these effects. For example, the huge amounts of sediment and a portion of the water that are introduced into the river by these storms is largely contributed to by the poor condition of riparian and range areas and the unstable banks of many tributaries that have developed as a result of heavy overgrazing in the basin since the latter half of the 19th century (Bliesner 1999a). Fencing of sensitive riparian zones and improvements in grazing practices are some management strategies that could be implemented to reduce these impacts.

SUMMARY AND CONCLUSIONS

1) Storms reduced the biomass of phytoplankton, periphyton, and benthic invertebrates (chiefly chironomids) in San Juan River backwaters.

2) Periods of relative stability in discharge (i.e., reduction in frequency and/or intensity of storms) on the order of months during the fall-to-spring period resulted in increased production of phytoplankton, zooplankton, periphyton, benthic invertebrates, and detritus in San Juan River backwaters. However, storms also increased the abundance of zooplankton and detritus in some river reaches on certain occasions.

3) Periphyton was the one parameter that displayed a clear longitudnal pattern following stable flows in the San Juan River, with biomass steadily declining downstream.

4) Backwater depth riverwide in the San Juan River was relatively high following the higher magnitude runoff in 1995, but declined to lower levels thereafter during a two-year period characterized by frequent storms.

5) Reductions in backwater depth in the San Juan River over the study period coincided with increased amounts of ultra-fine sized sediment accumulation in the backwaters.

6) Backwater depth riverwide declined to about the same average levels (0.2-0.3 m) following all three monsoon seasons studied from 1995 to 1997, apparently regardless of storm intensity during the monsoon period.

7) Dissolved oxygen in San Juan River backwaters was inversely related to water temperature, but was rarely reduced to less than 3 mg/L in even the warmest backwaters.

8) Colorado River backwaters within the Moab to Potash reach tended to be deeper, less turbid, cooler, and more oxygenated than San Juan River backwaters over the same time period.

9) Colorado River backwaters contained higher levels of periphyton over the same time period than San Juan River backwaters riverwide, while other biological parameters were similar on average.

10) During the monsoon period in 1997 when storms were prevalent, San Juan, Colorado, and Green River backwaters contained similarly low primary and secondary productivity, indicating physical disturbances to the backwaters throughout all three drainages.

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APPENDIX A:
COBBLE BAR SURFACE PLOTS

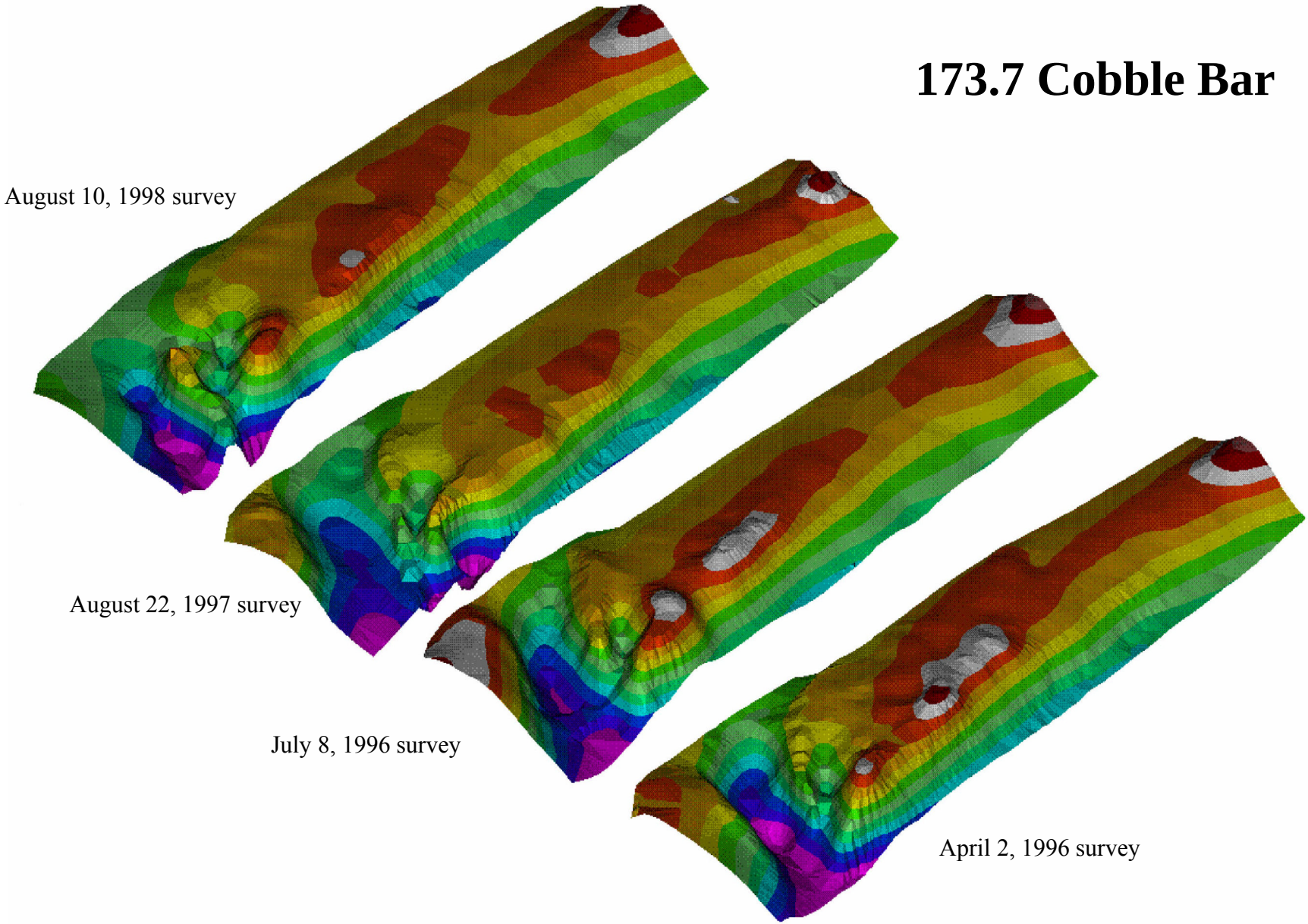

Figure A.1. Surface plots of cobble bar at RM 173.7 (1996-1998)

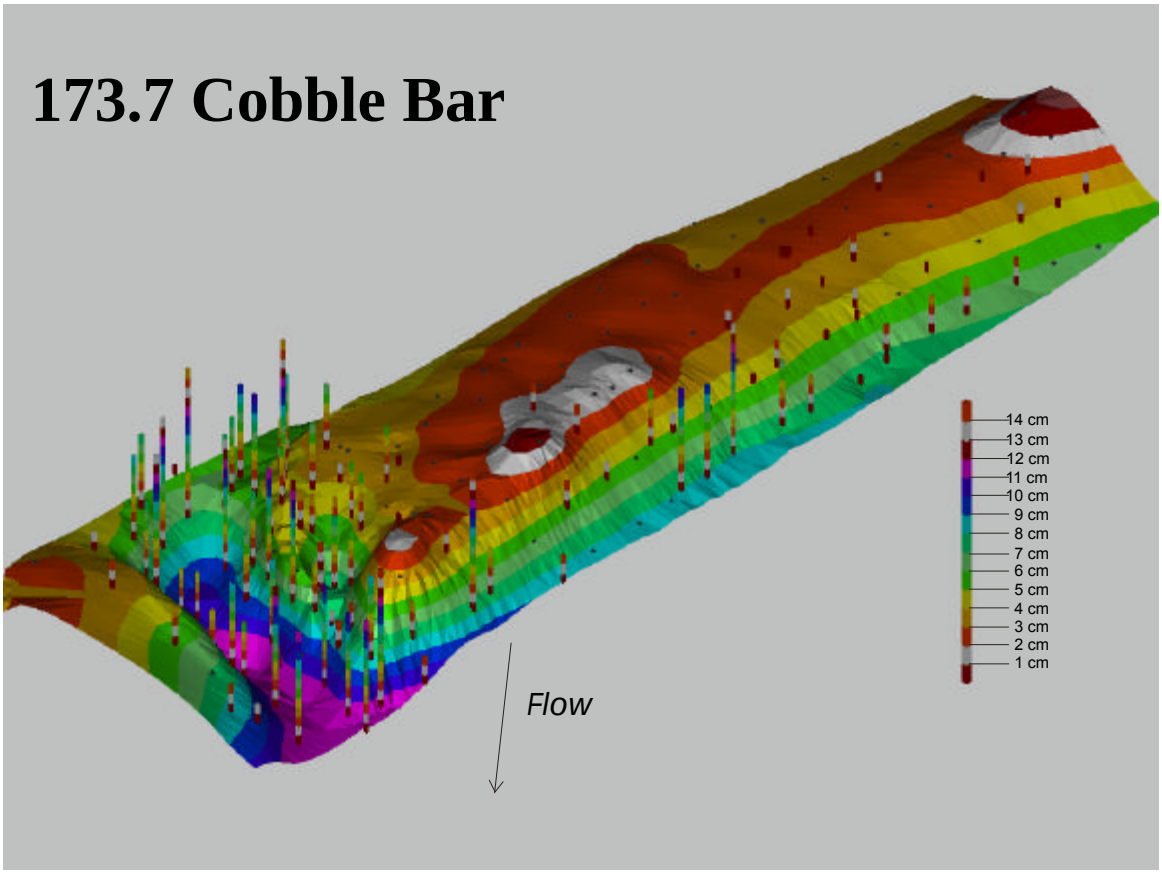

Figure A.2. April 2, 1996 survey with embeddedness markers.

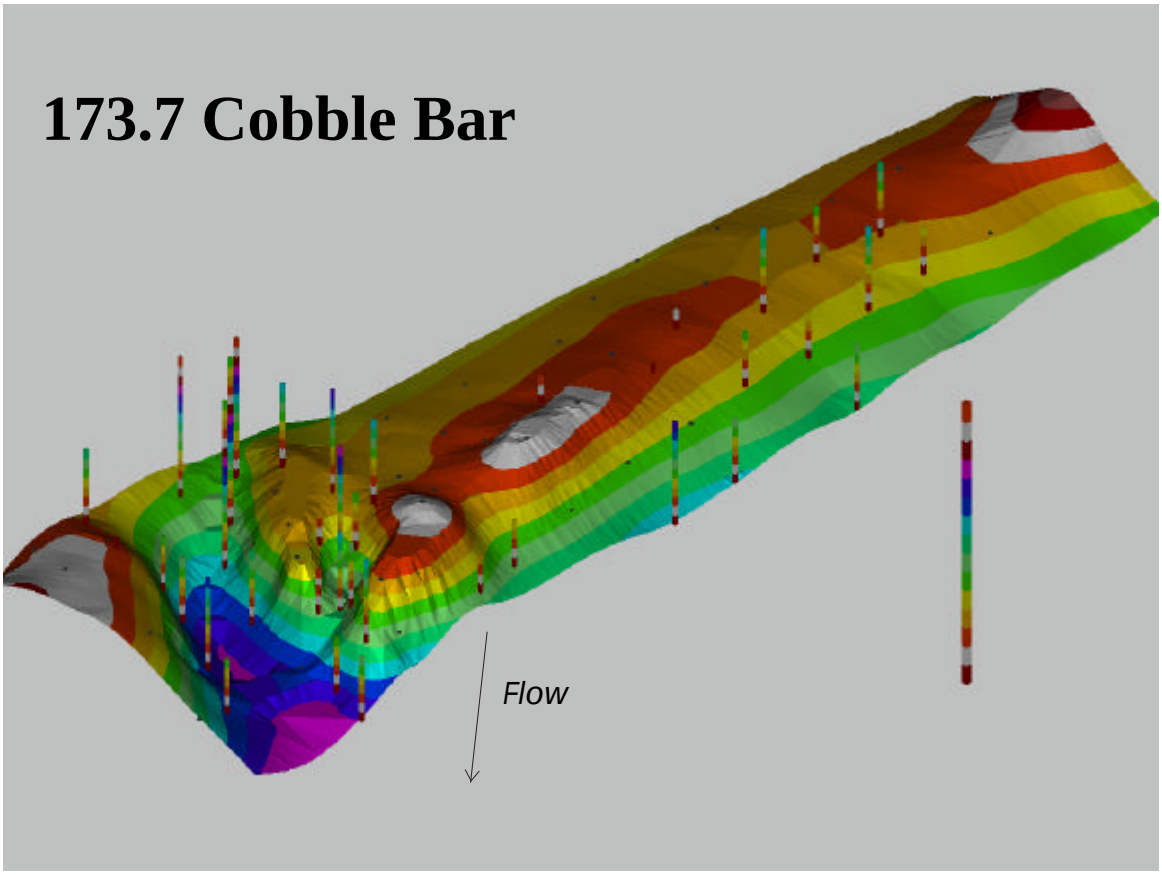

Figure A.3. July 8, 1996 survey with embeddedness markers.

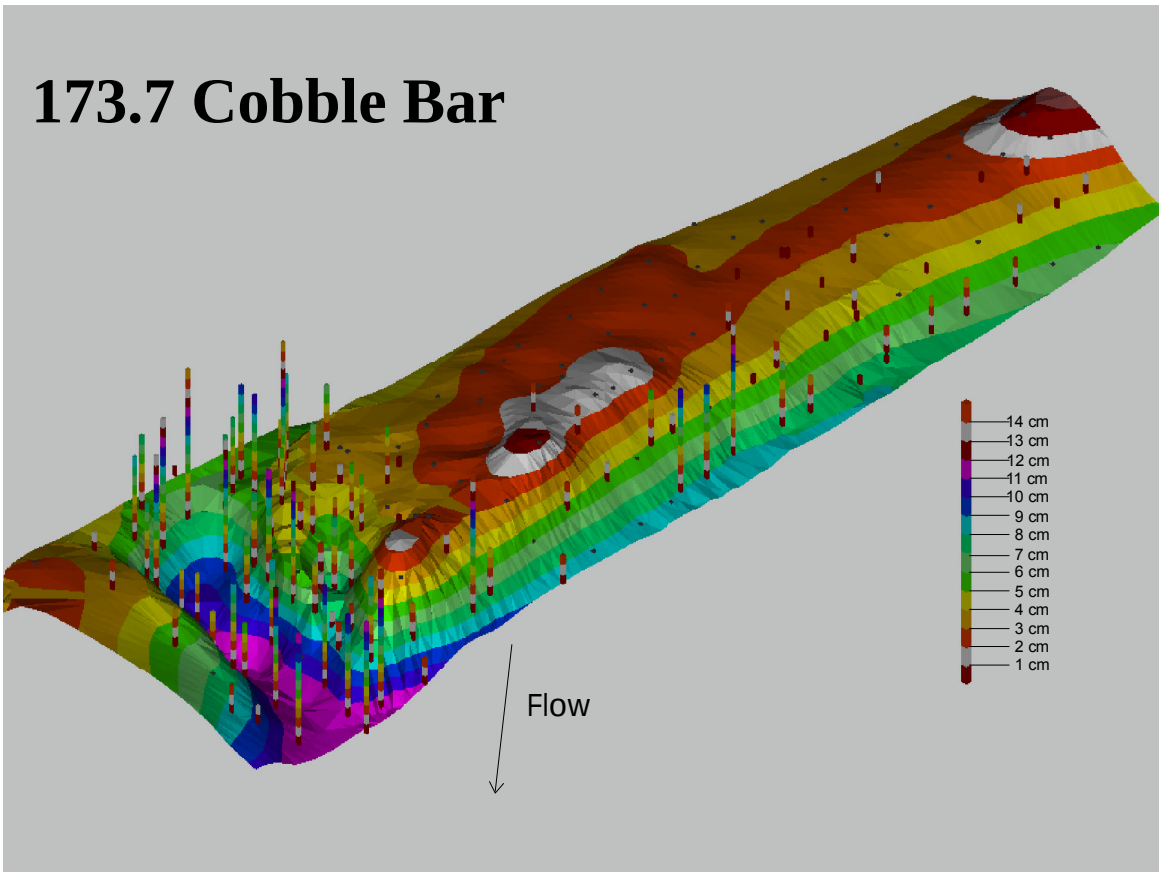

Figure A.2. April 2, 1996 survey with embeddedness markers.

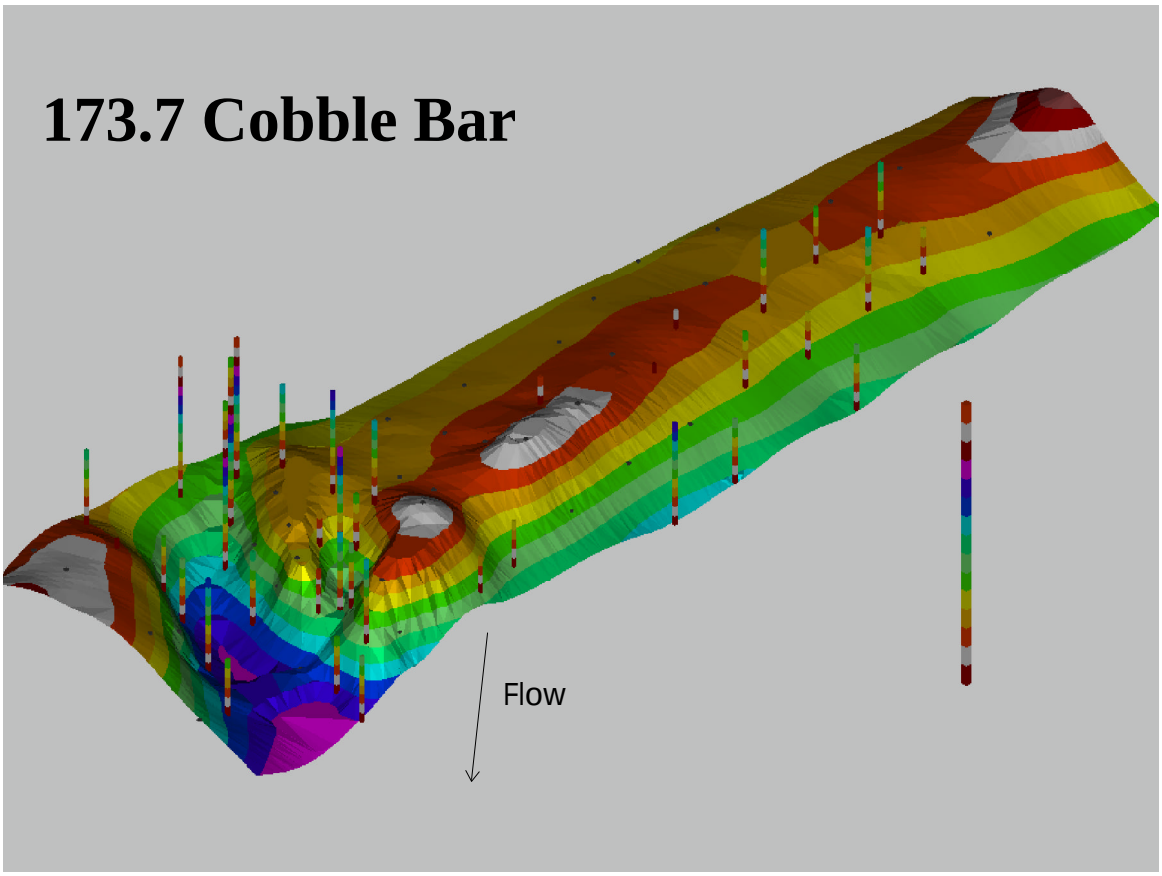

Figure A.3. July 8, 1996 survey with embeddedness markers.

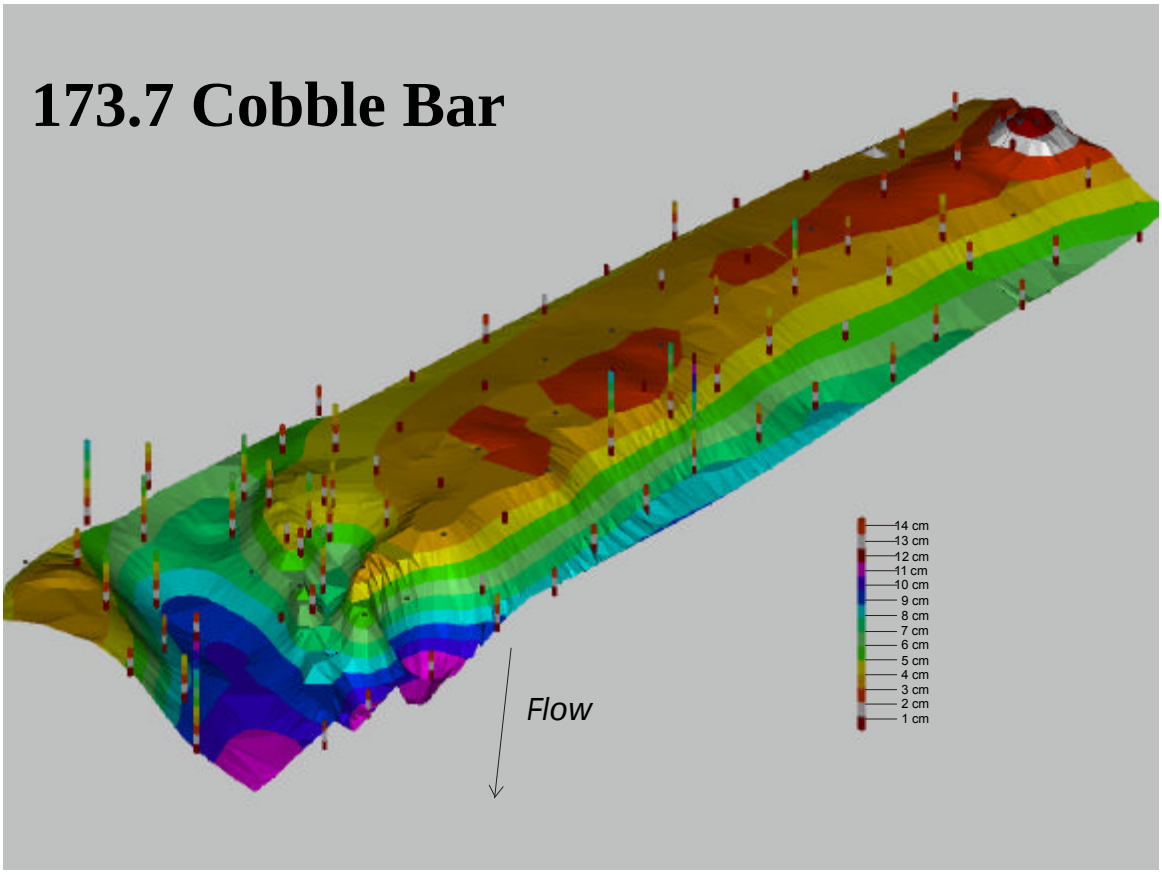

Figure A.4. August 22, 1997 survey with embeddedness markers.

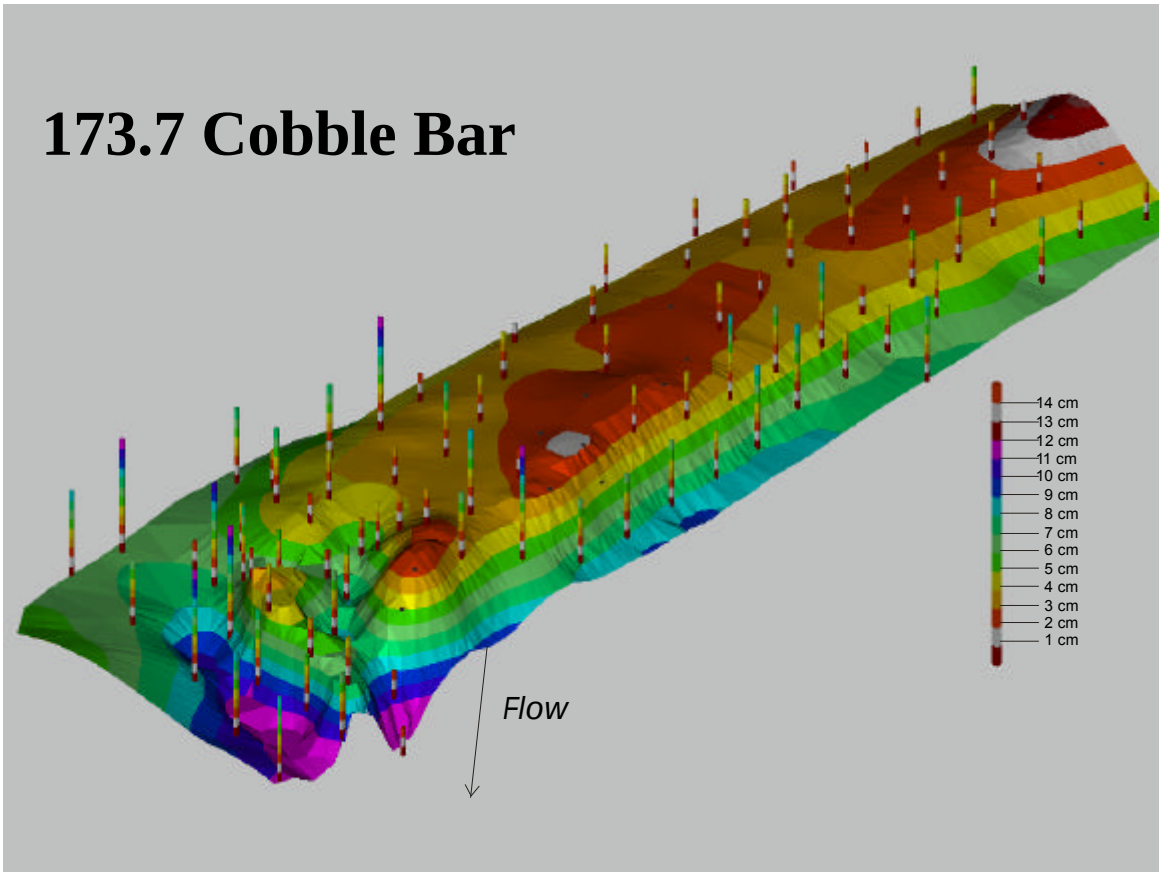

Figure A.5. August 10, 1998 survey with embeddedness markers.

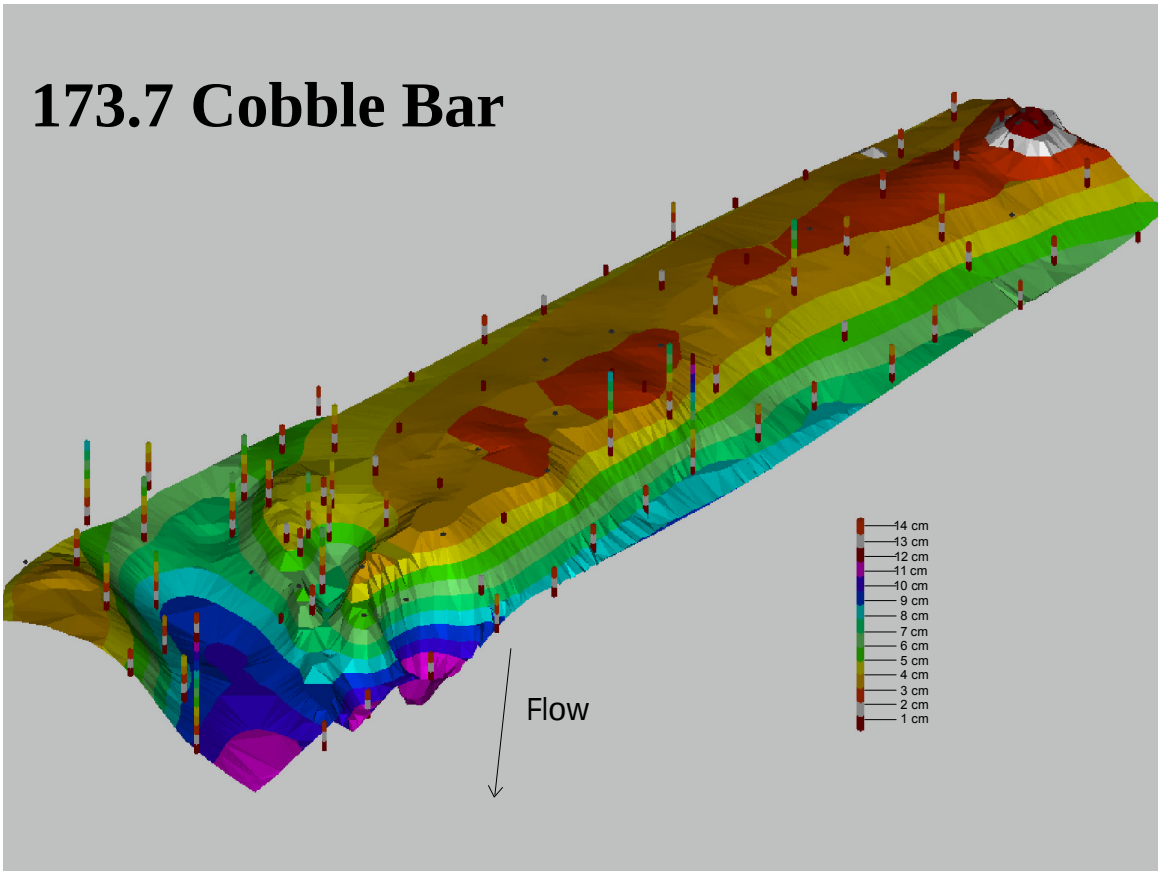

Figure A.4. August 22, 1997 survey with embeddedness markers.

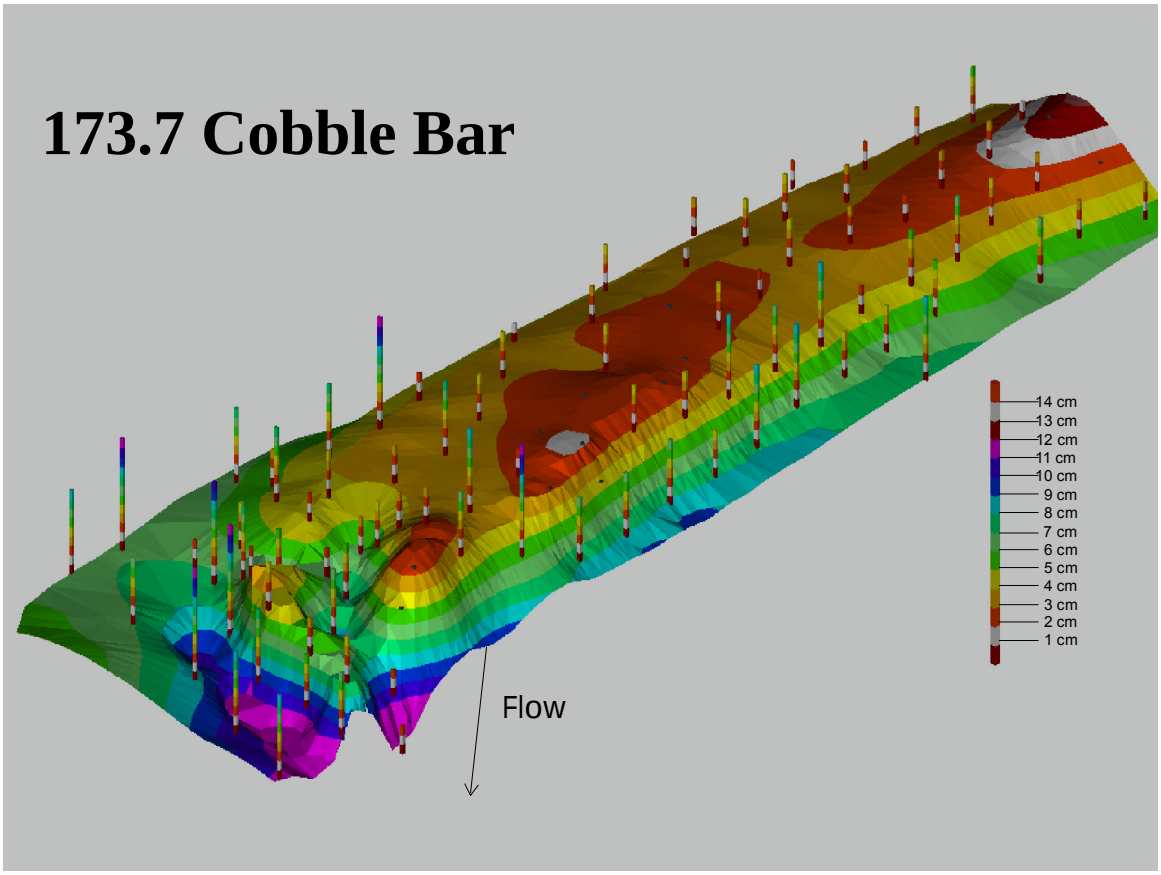

Figure A.5. August 10, 1998 survey with embeddedness markers.

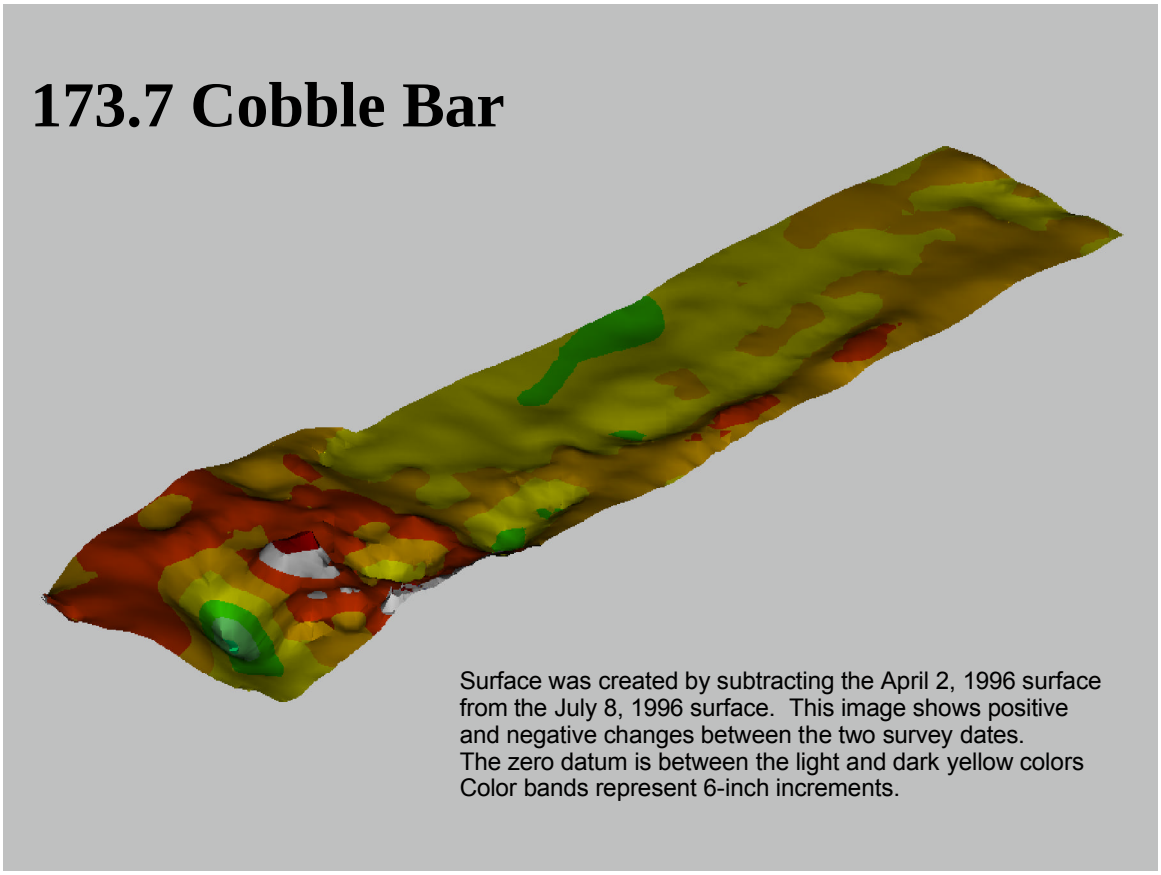

Figure A.6. This image shows positive and negtive changes between April 2, 1996 and July 8, 1996.

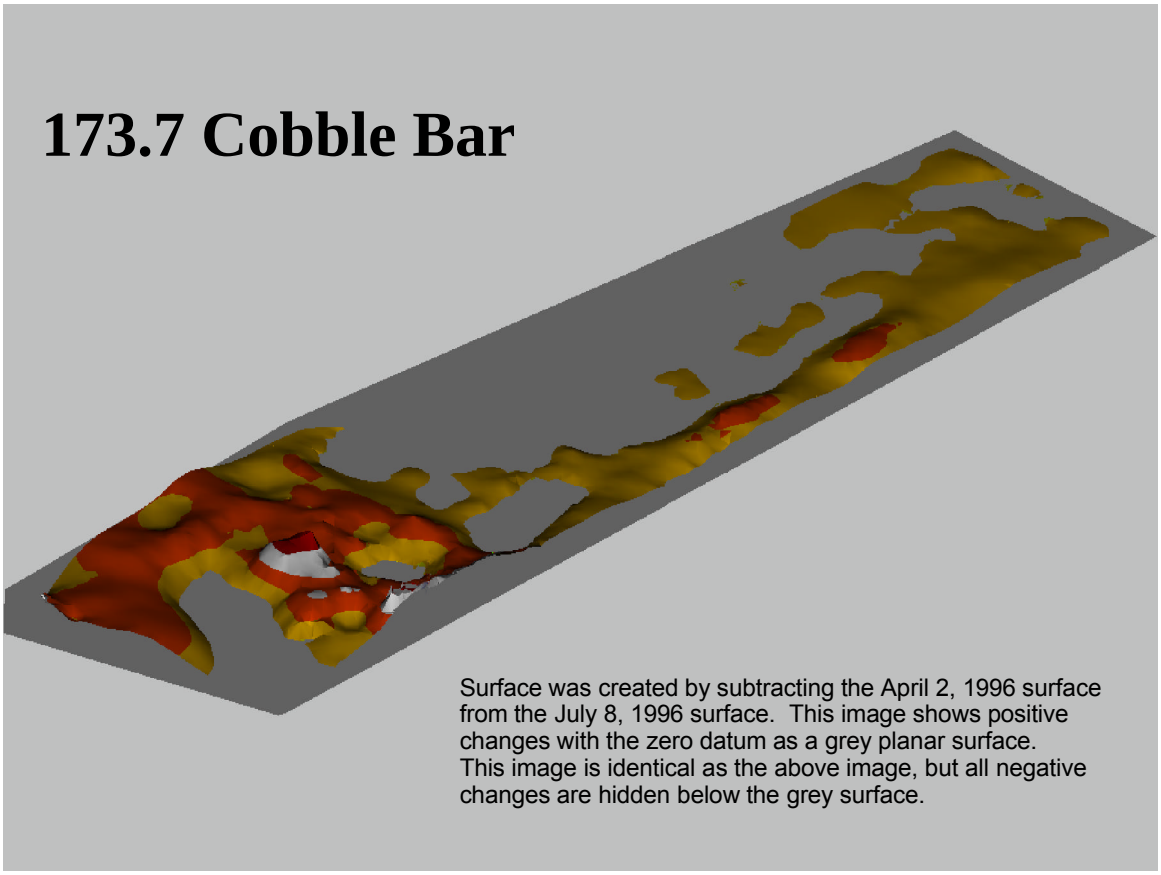

Figure A.7. This image shows positive changes with the zero datum as a grey planar surface.

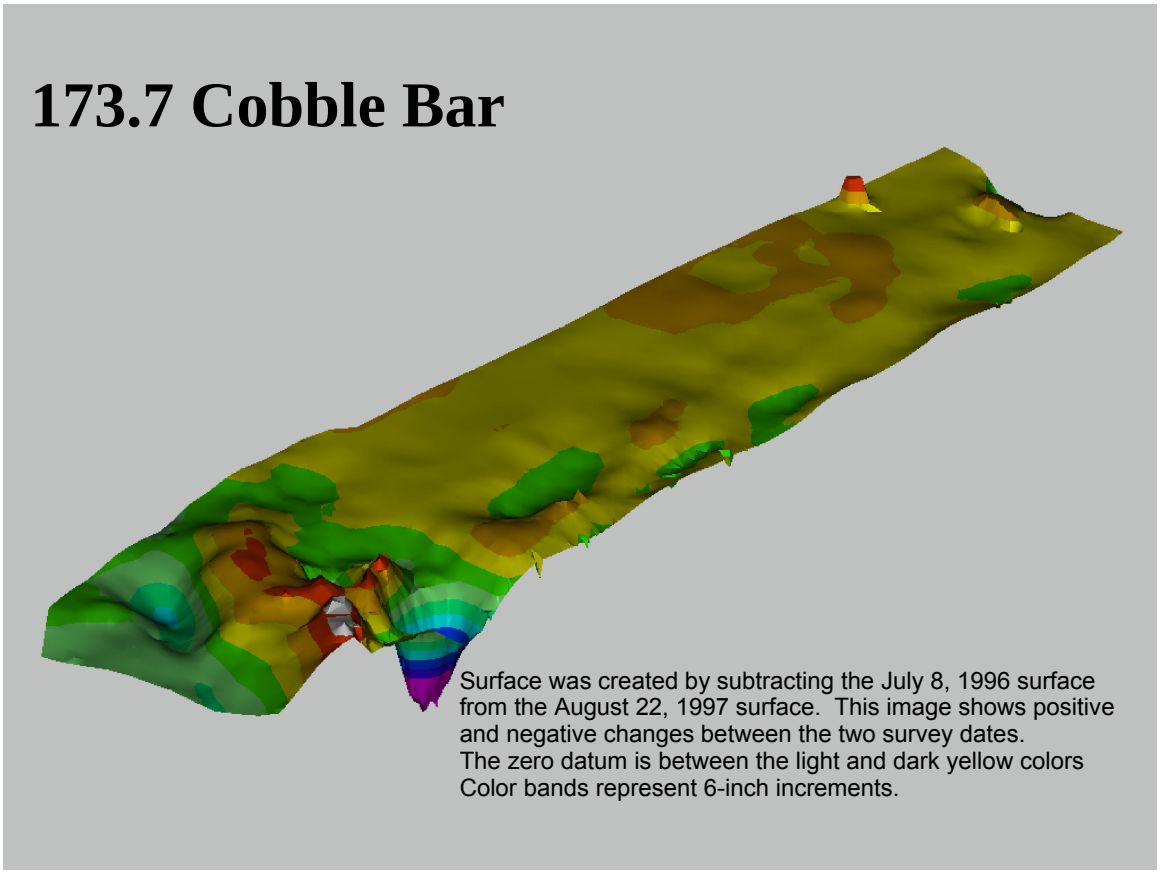

Figure A.8. This image shows positive and negtive changes between July 8, 1996 and August 22, 1997.

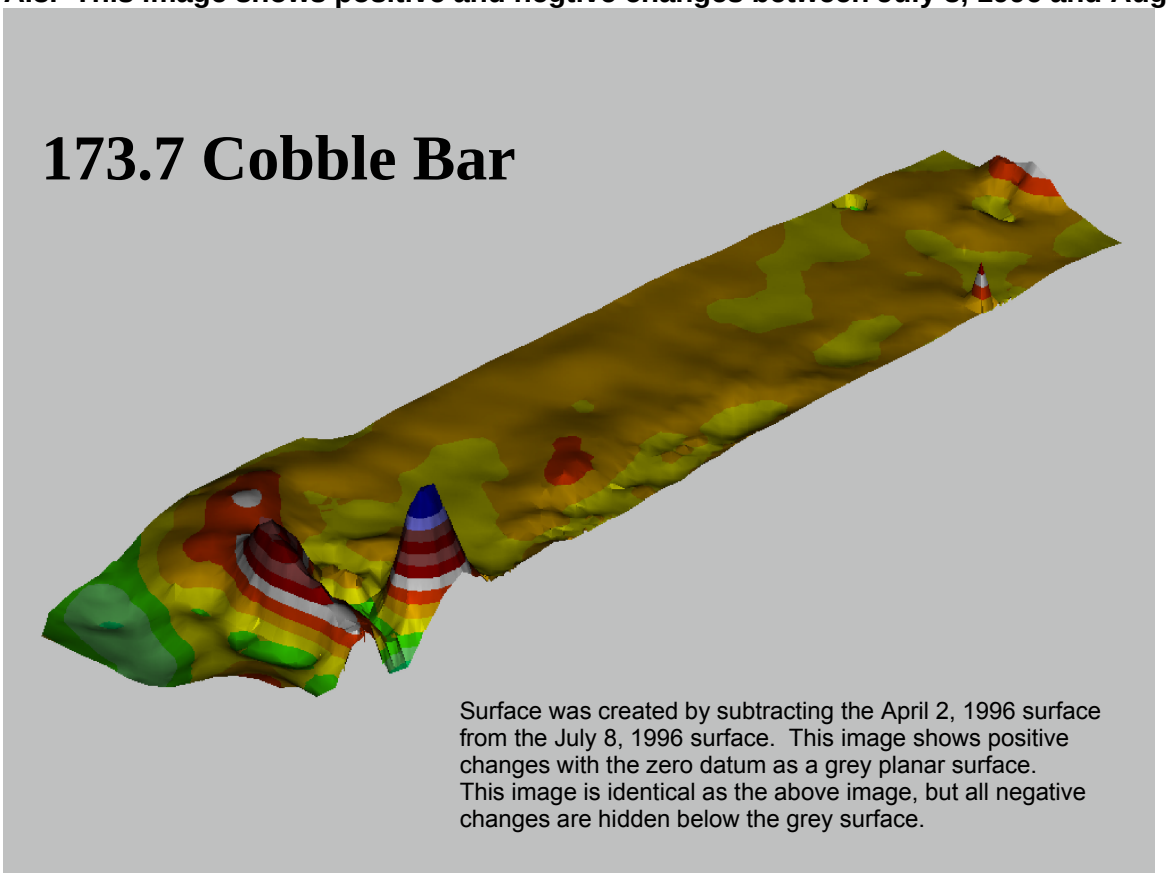

Figure A.9. This image shows positive and negative changes between August 22, 1997 and August 10, 1998.

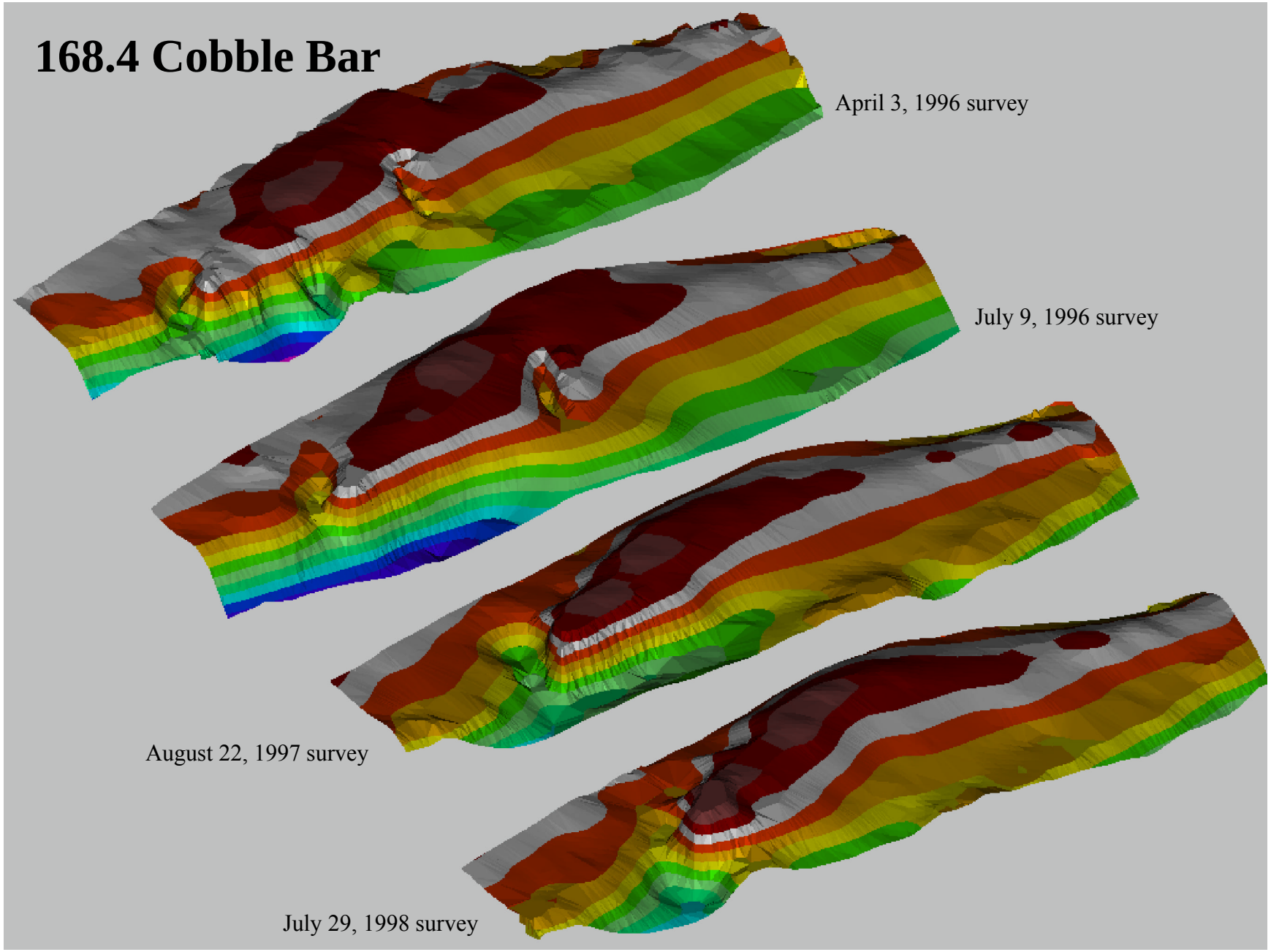

Figure A.10. Surface plots of cobble bar at RM 168.4.

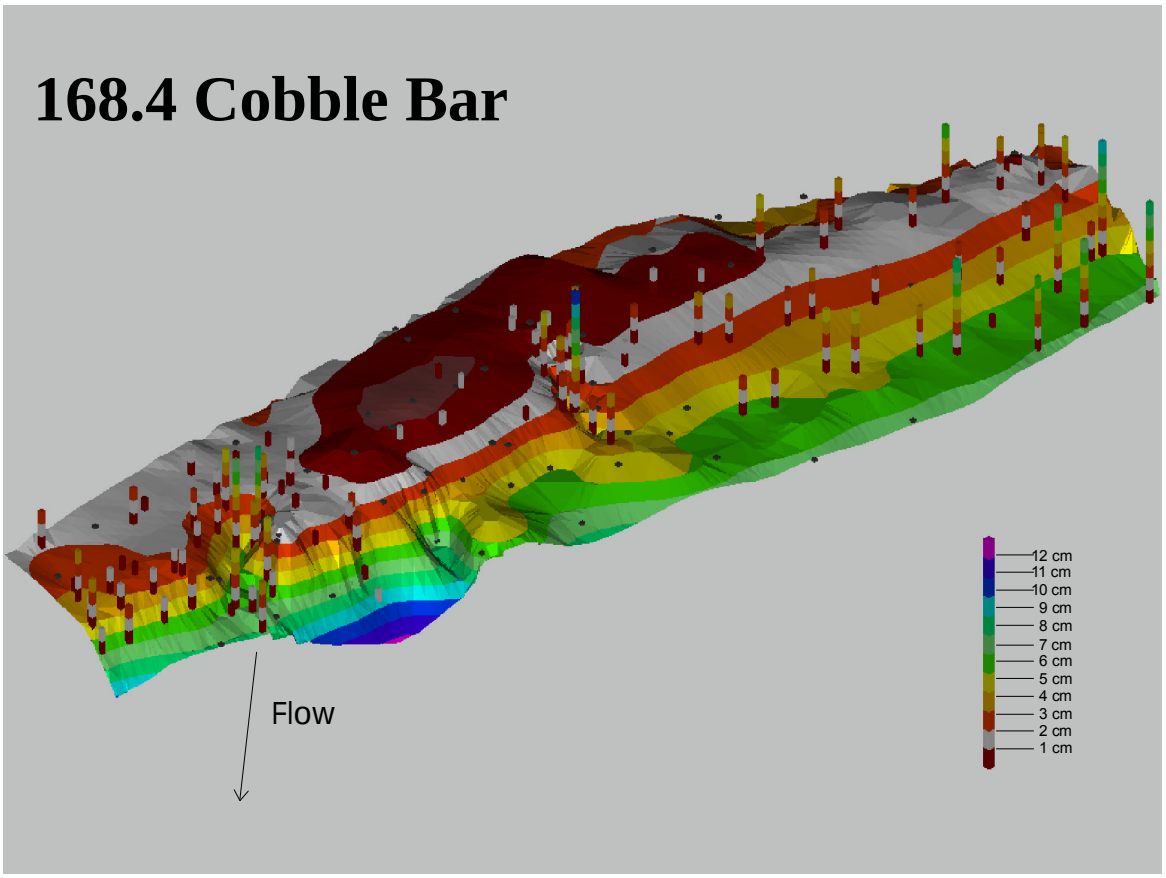

Figure A.11. April 3, 1996 survey with embeddedness markers.

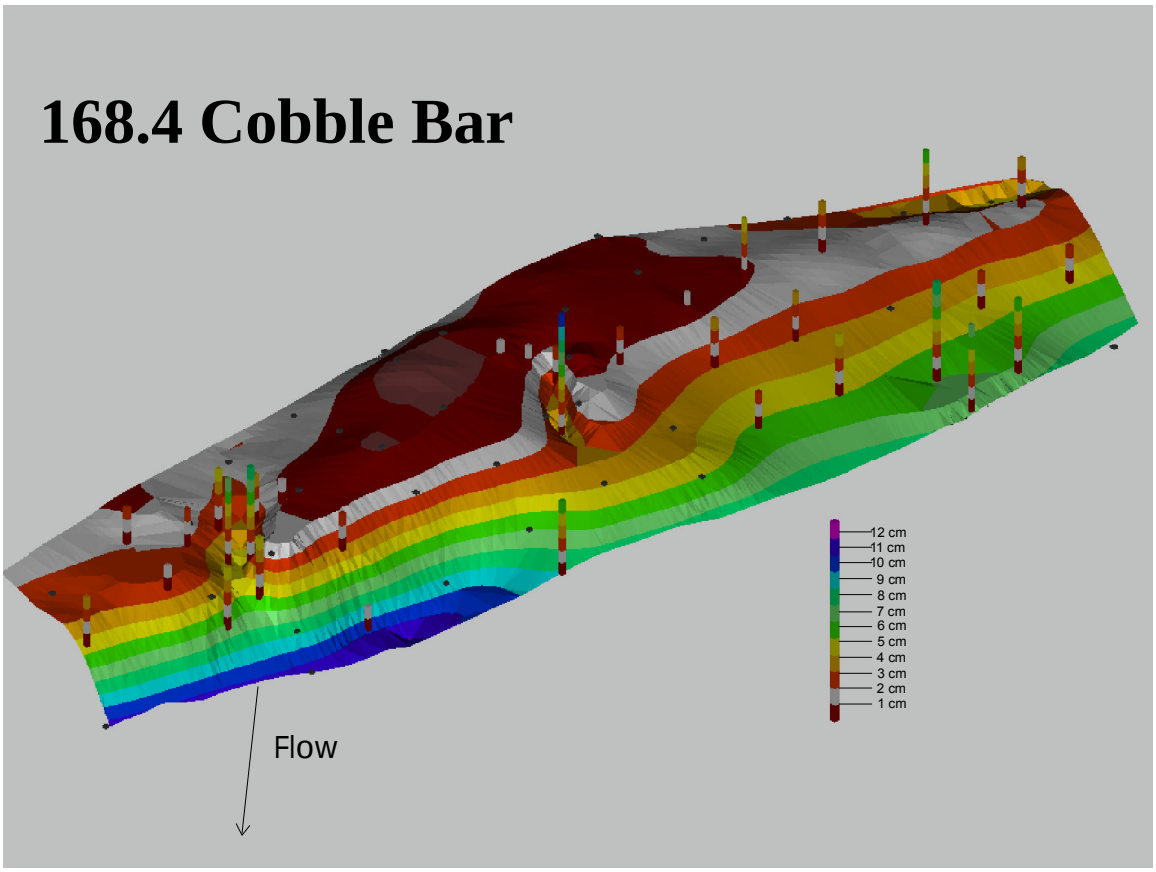

Figure A.12. July 9, 1996 survey with embeddedness markers.

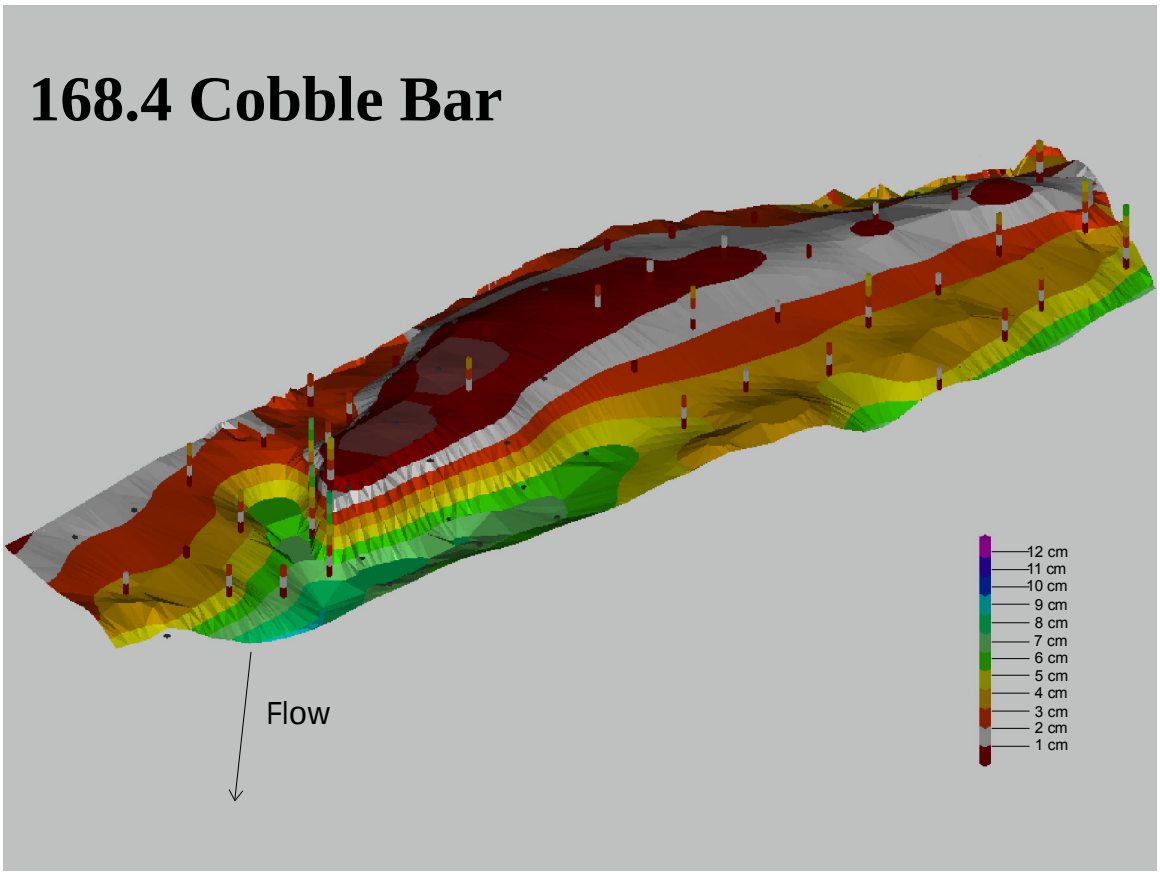

Figure A.13. August 22, 1997 survey with embeddedness markers.

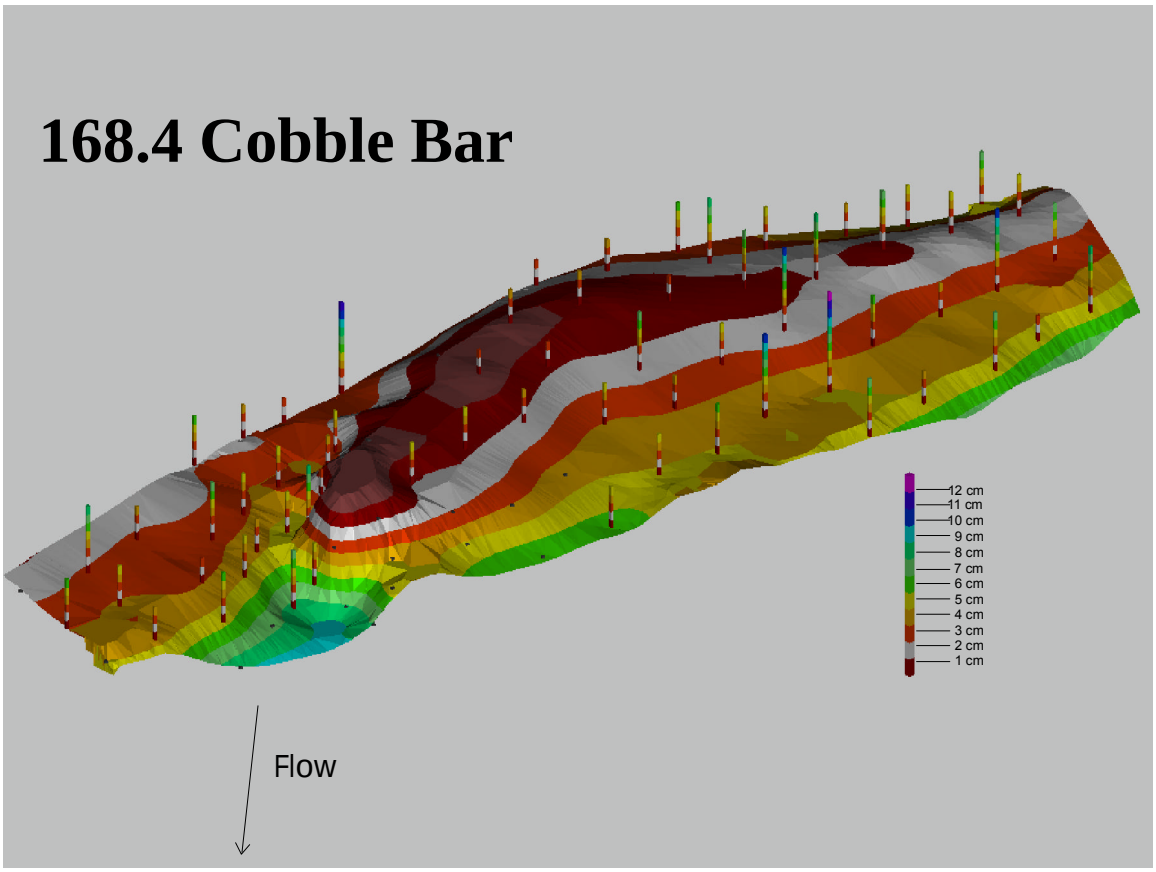

Figure A.14. July 29, 1998 survey with embeddedness markers.

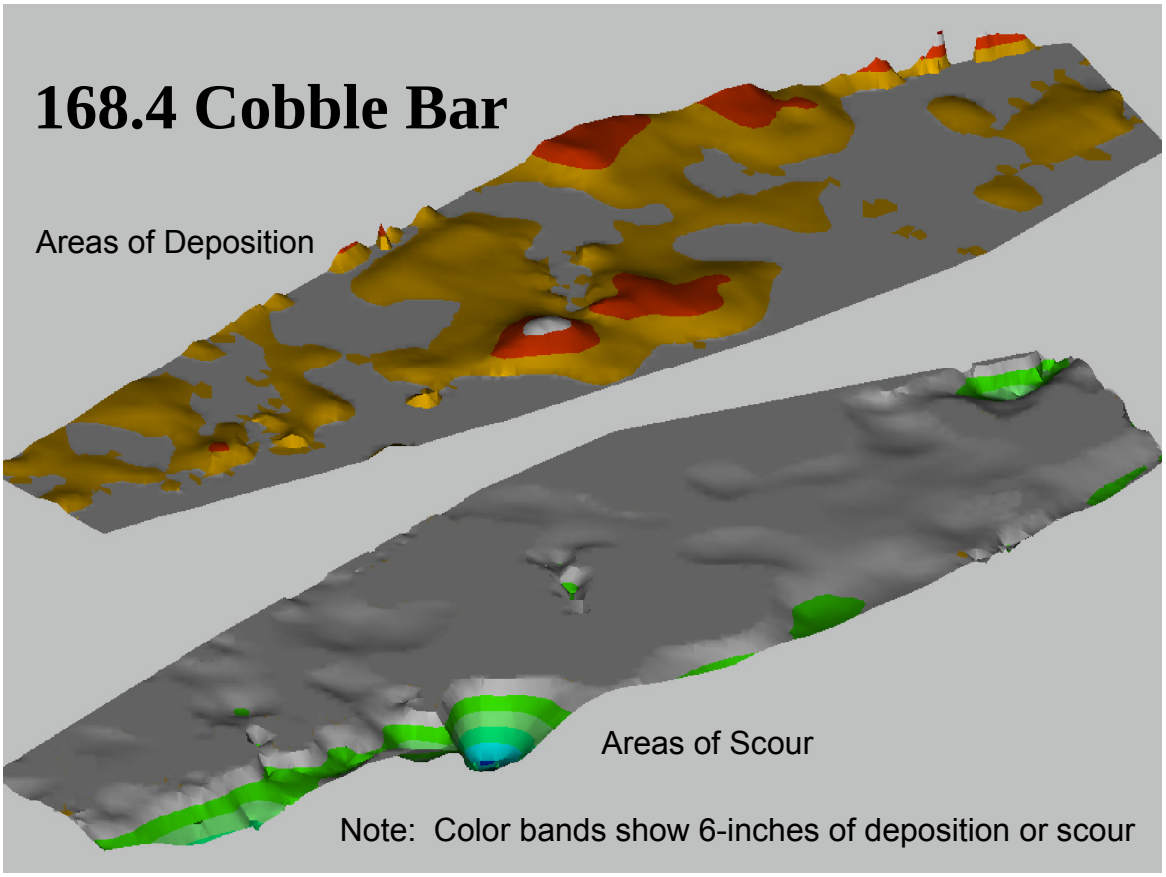

Figure A.15. Areas of Deposition and Scour between April 3, 1996 and July 9, 1996.

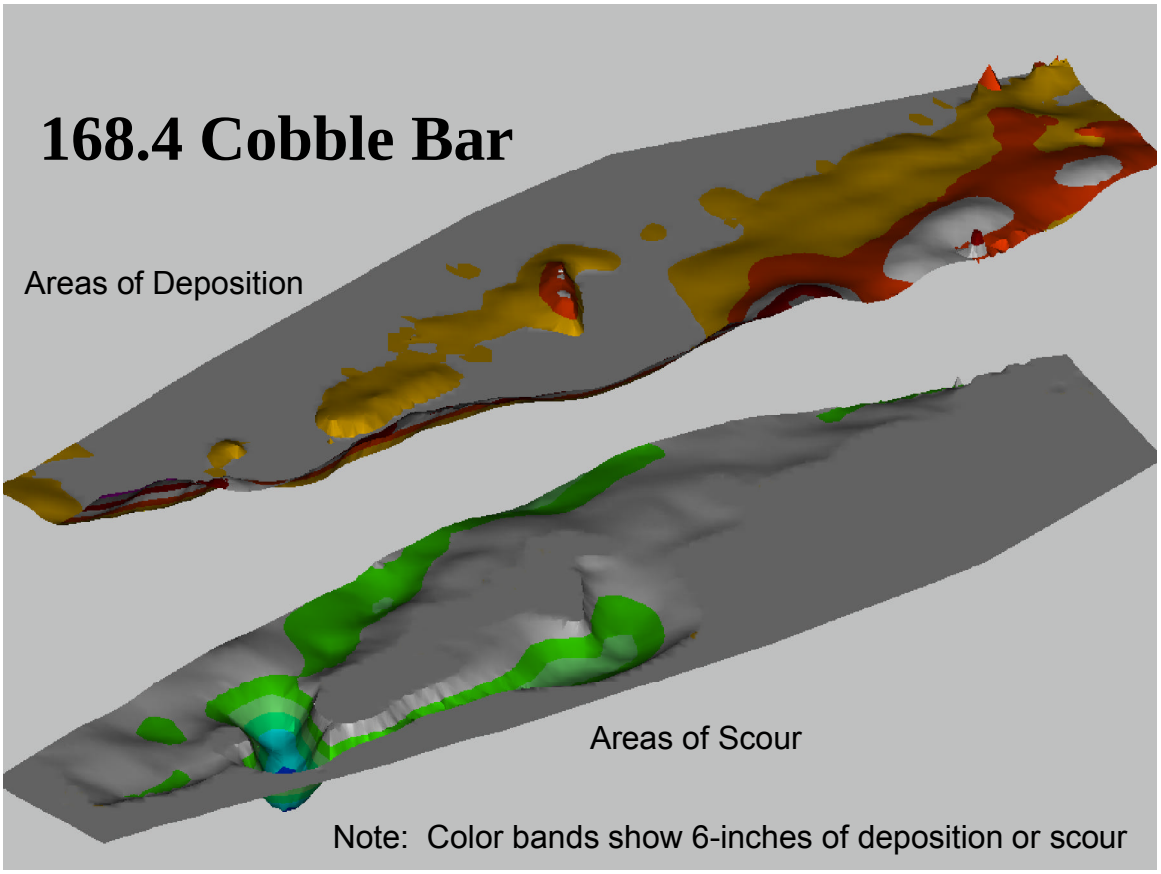

Figure A.16. Areas of Deposition and Scour between July 9, 1996 and August 22, 1997.

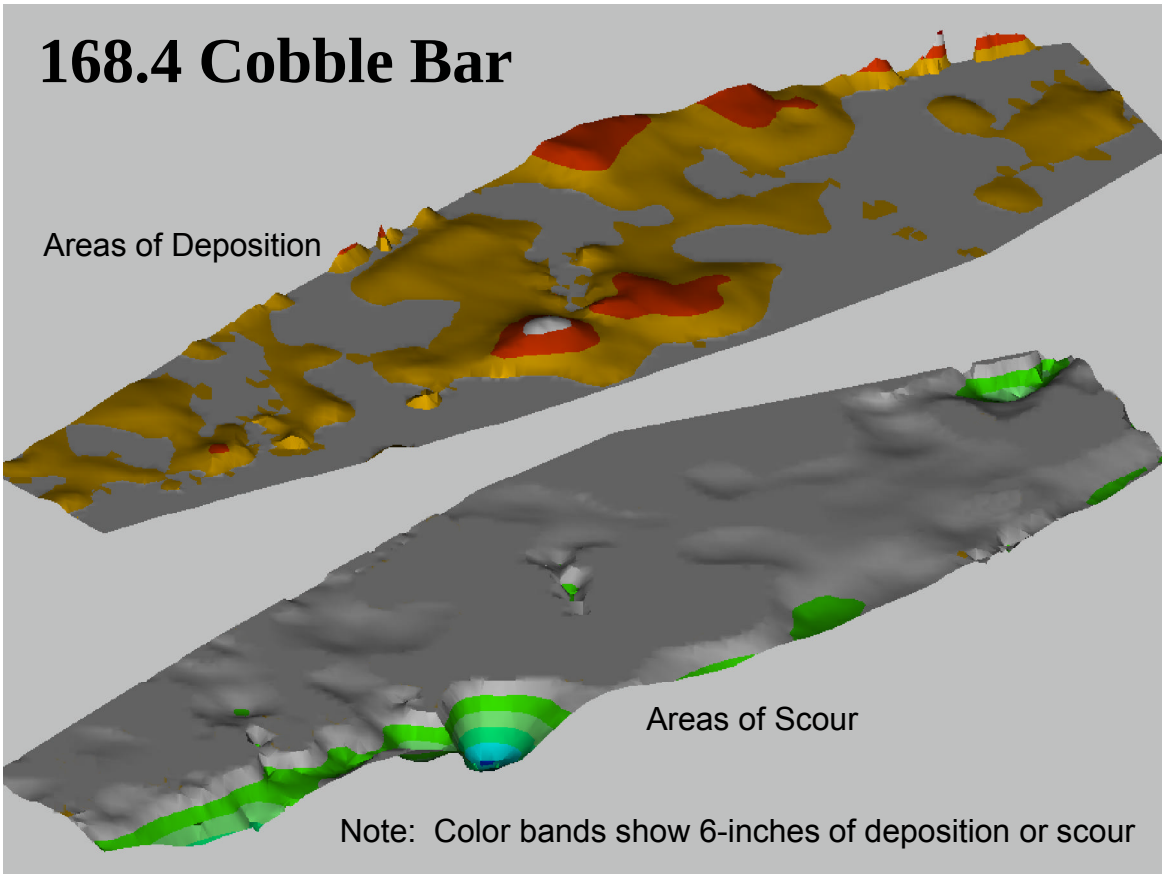

Figure A.17. Areas of Deposition and Scour between August 22, 1997 and July 29, 1998.

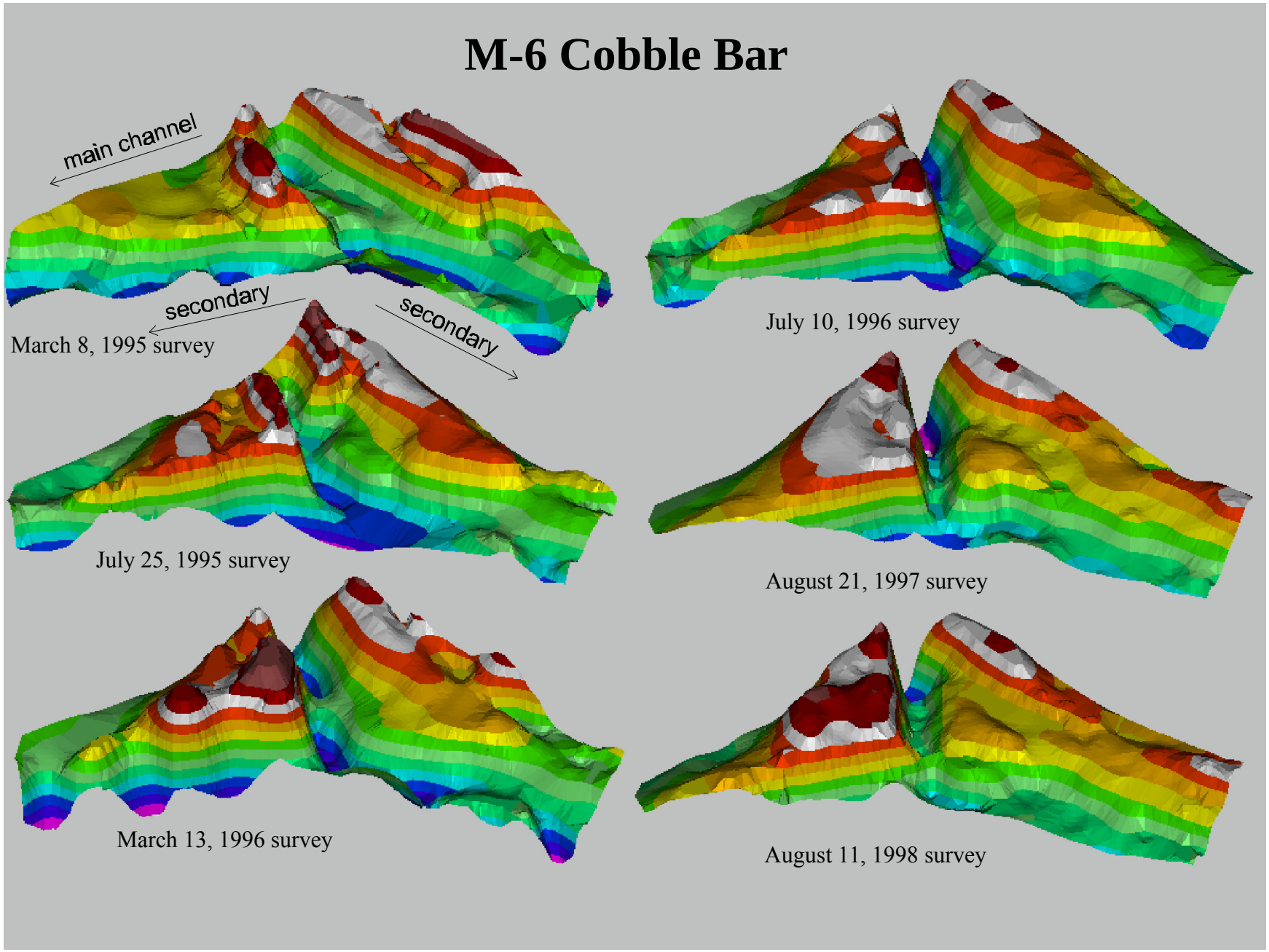

Figure A.18. Surface plots of cobble bar at RM 132 (1995-1998).

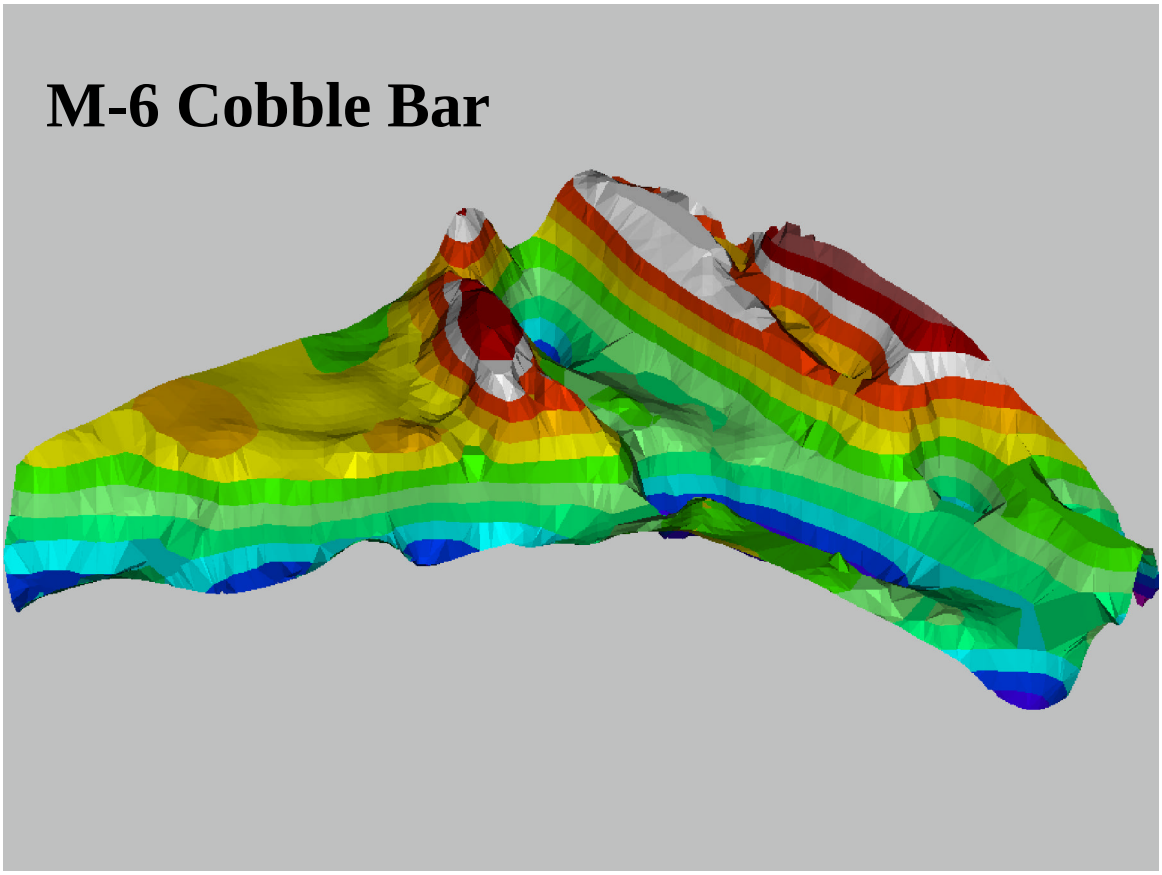

Figure A.19. March 8, 1995 survey (no embeddedness data taken).

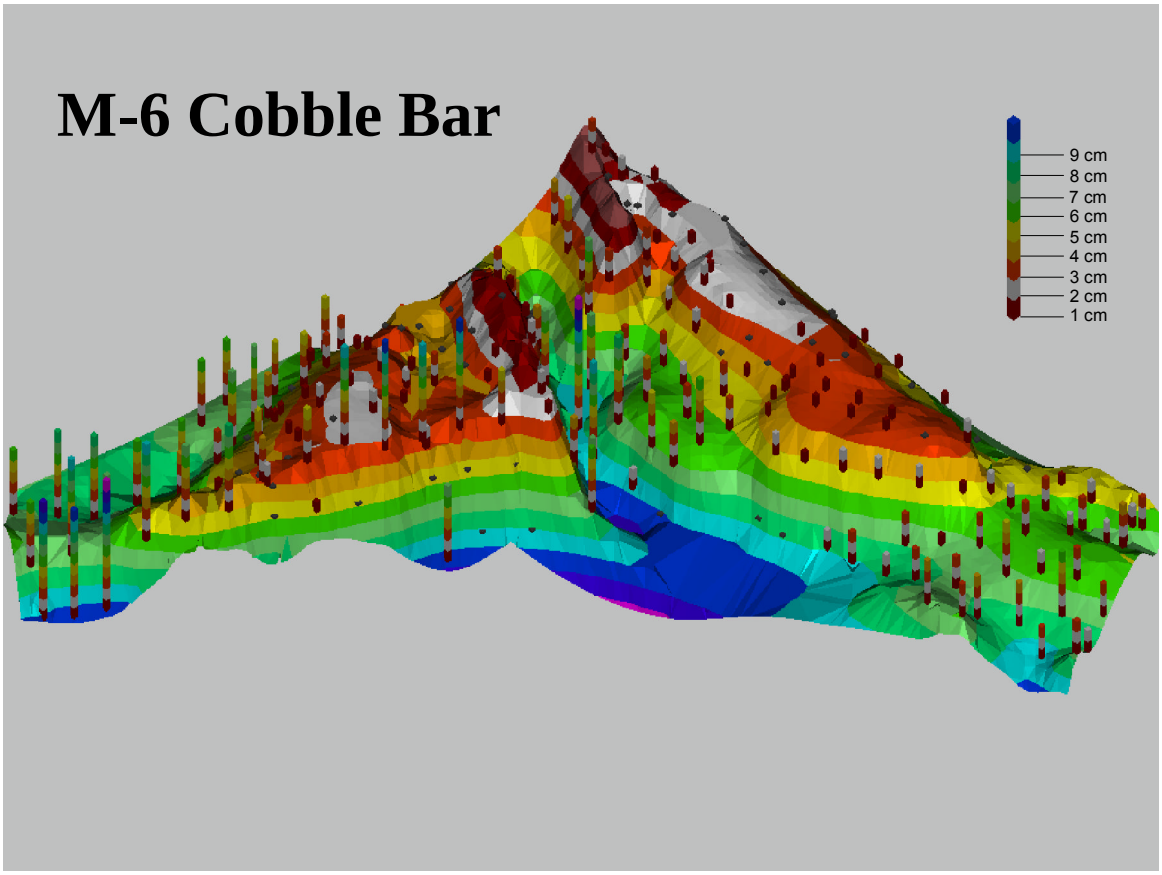

Figure A.20. July 25, 1995 survey with embeddedness markers.

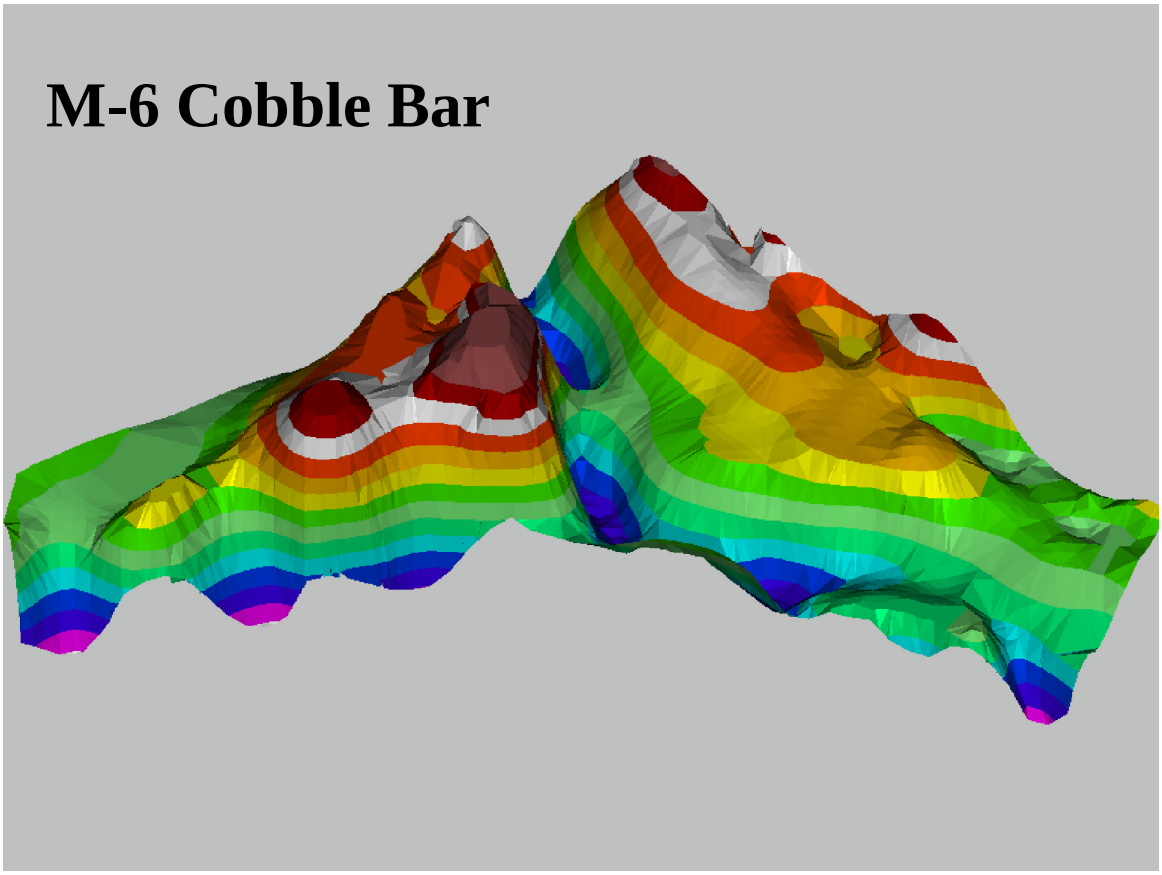

Figure A.21. March 13, 1996 survey (no embeddedness data taken).

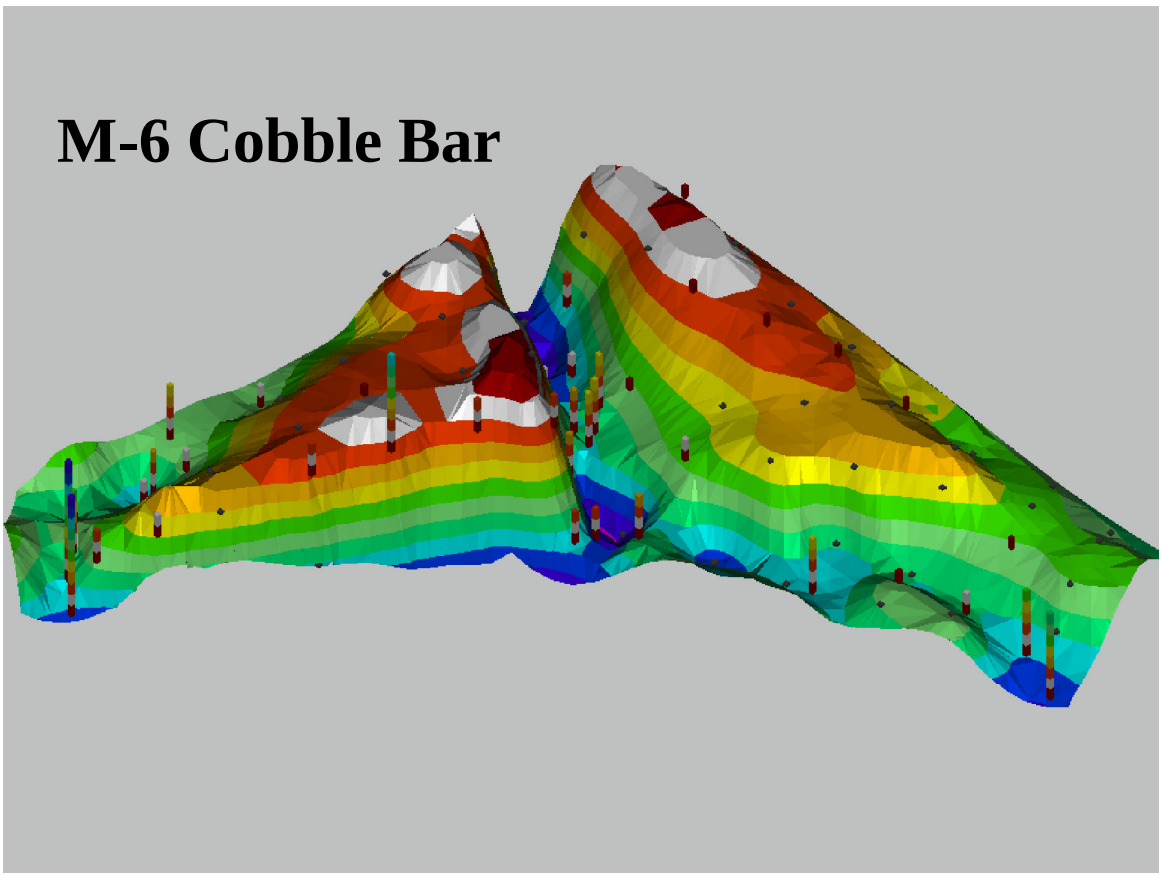

Figure A.22. July 10, 1996 survey with embeddedness markers.

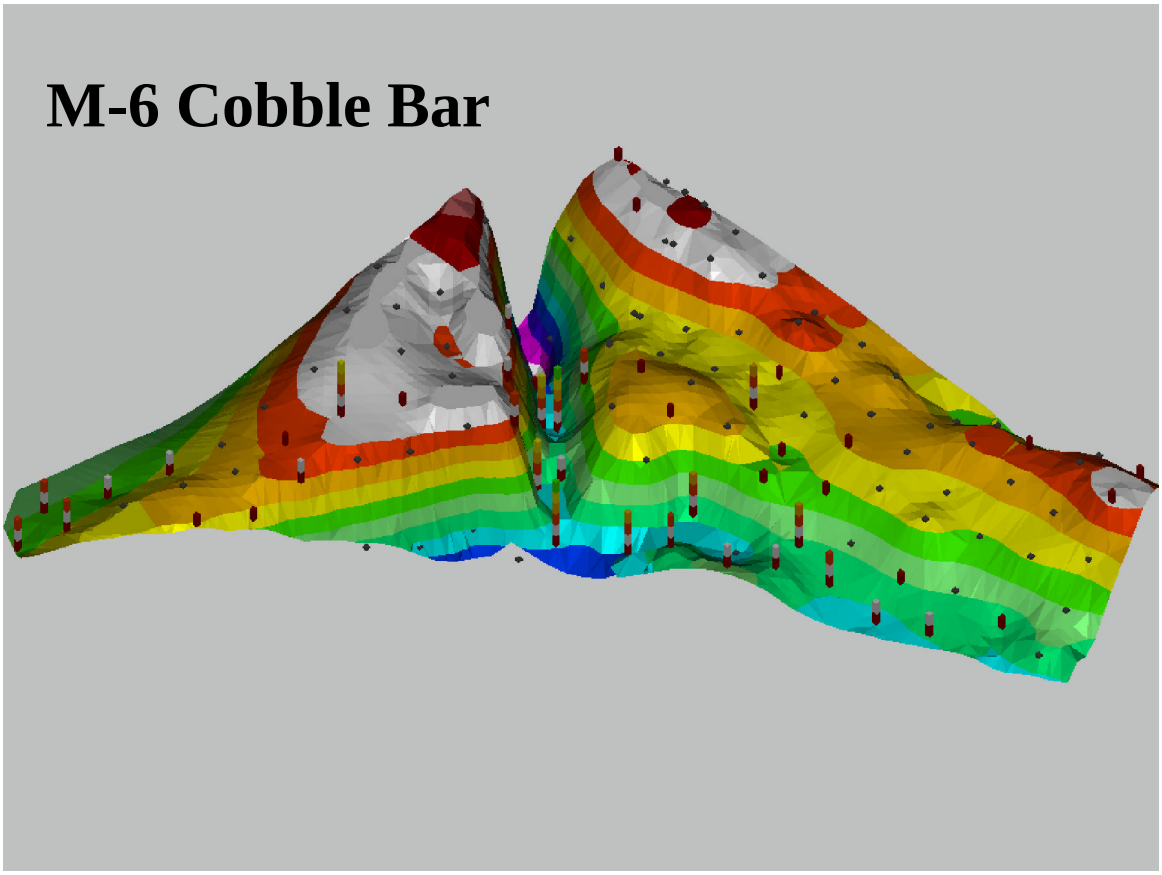

Figure A.23. August 21, 1997 survey with embeddedness markers.

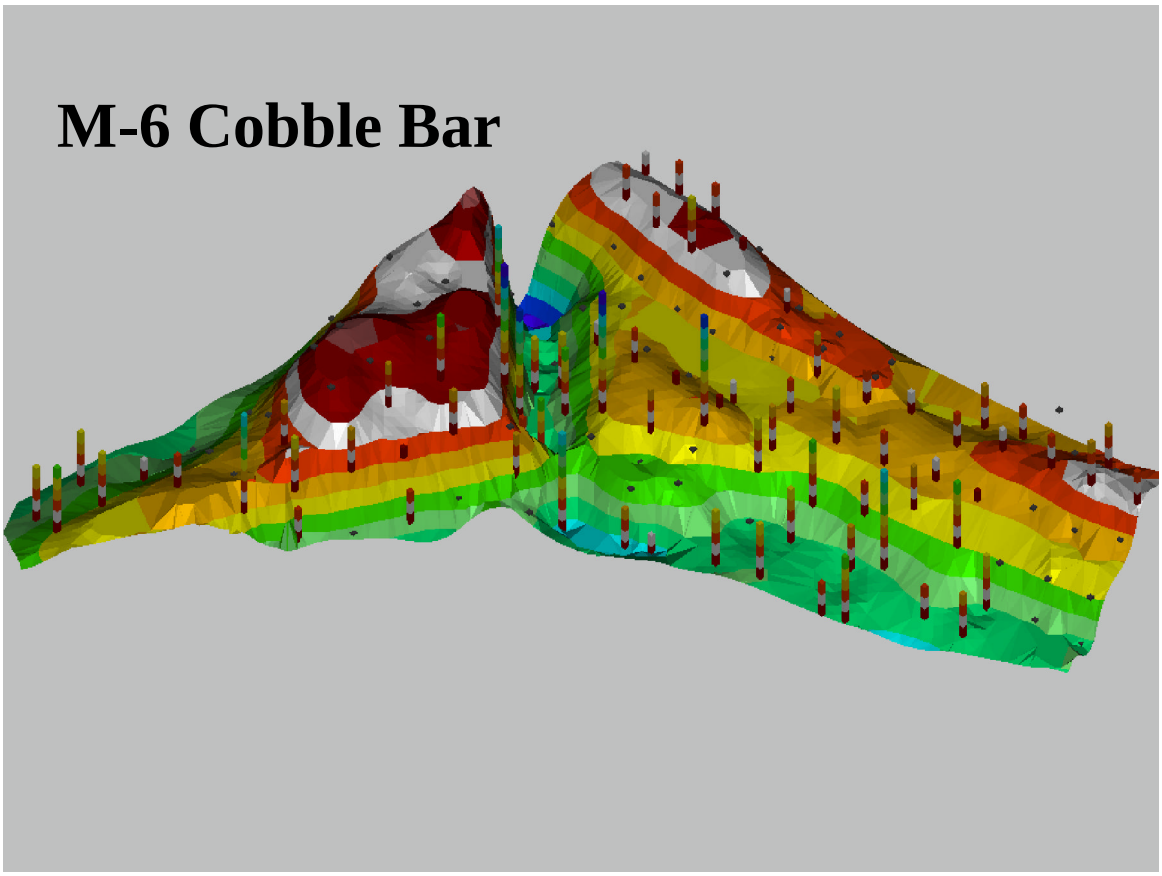

Figure A.24. August 11, 1998 survey with embeddedness markers.

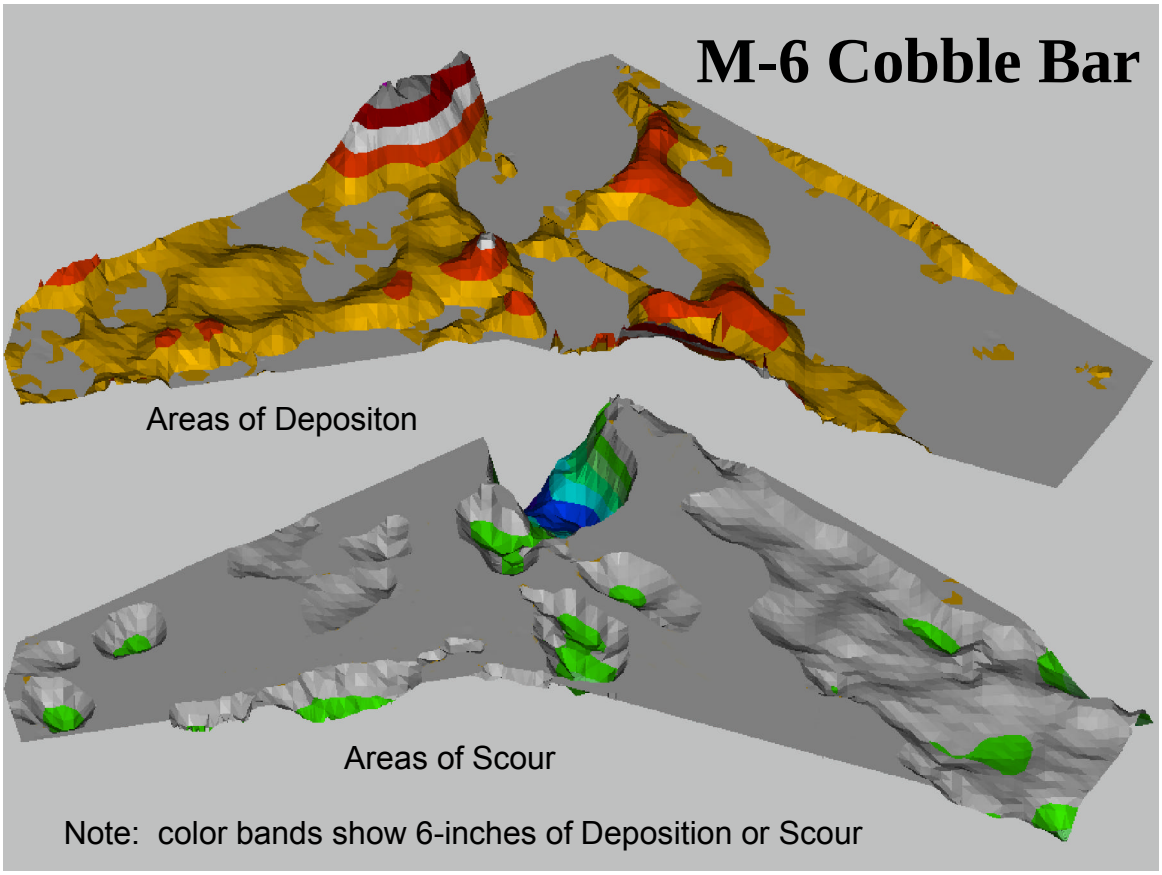

Figure A.25. Areas of Deposition and Scour between July 25, 1995 and July 10, 1996.

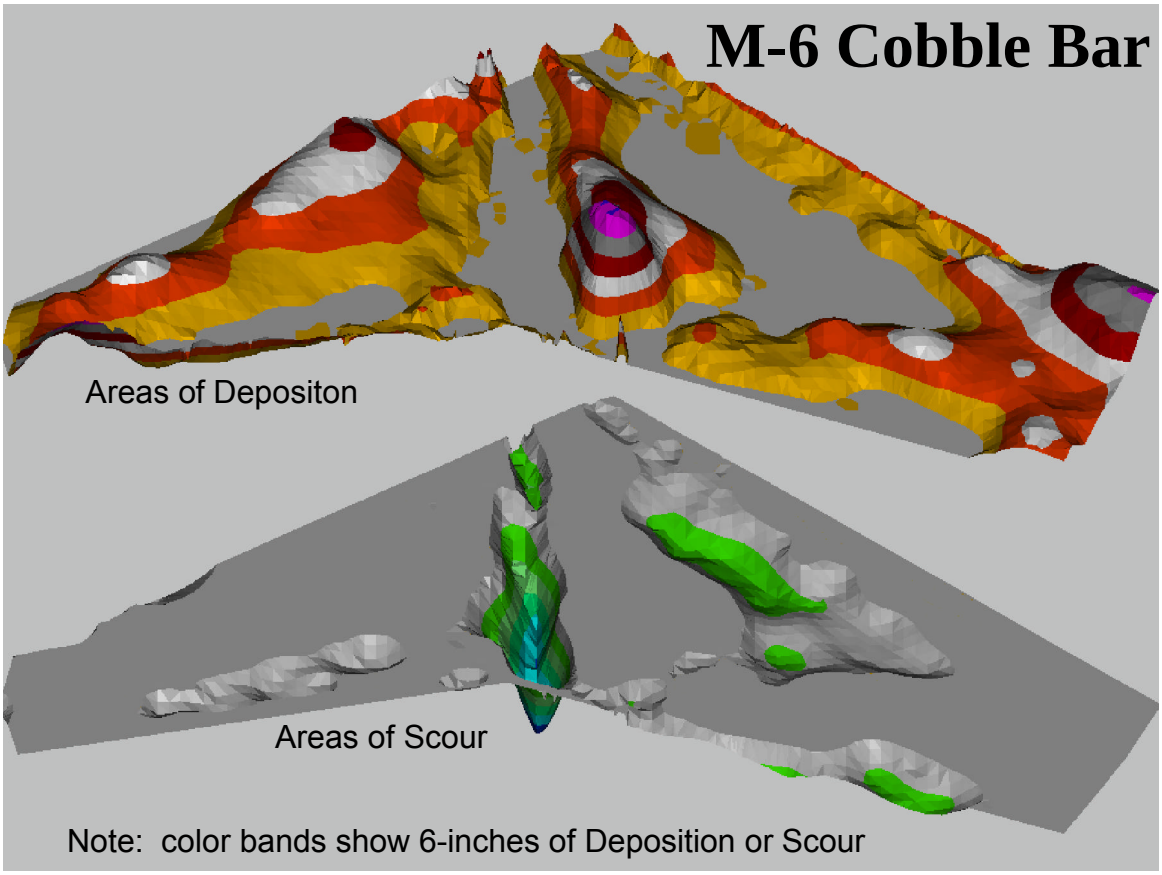

Figure A.26. Areas of Deposition and Scour between July 10, 1996 and August 21, 1997.

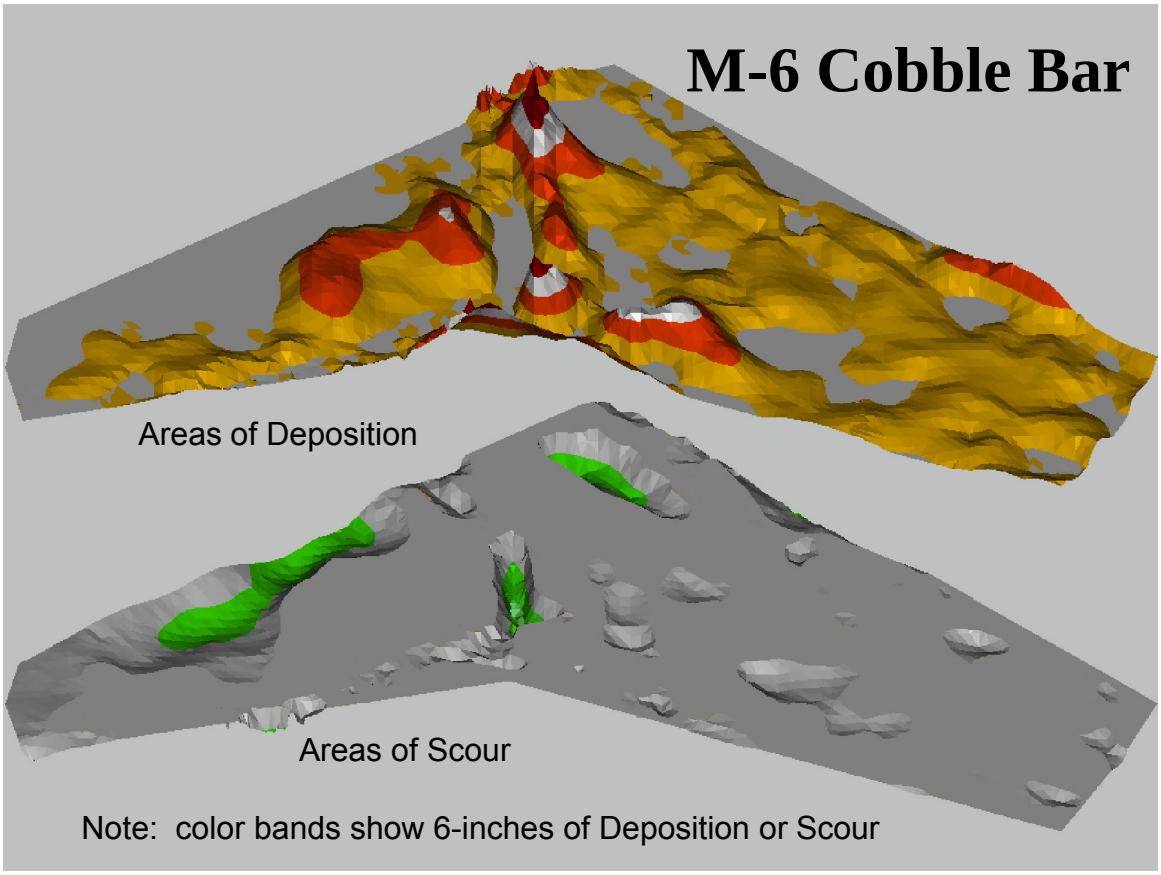

Figure A.27. Areas of Deposition and Scour between August 21, 1997 and August 11, 1998.

APPENDIX B:
LOW VELOCITY HABITAT SAND/COBBLE BAR SURFACE PLOTS

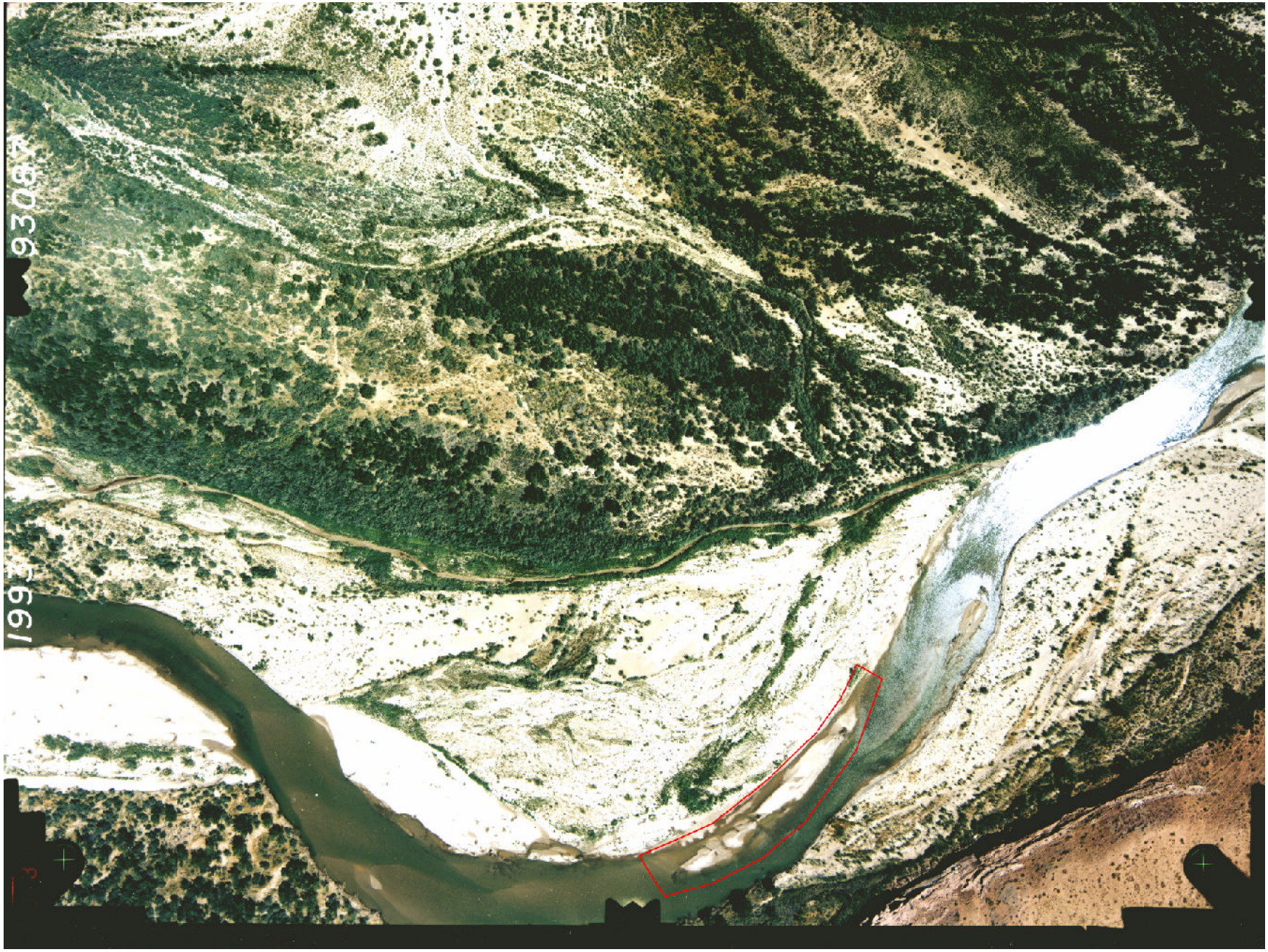

Figure B.1. Location photo of Bar D-4 at RM 86.4.

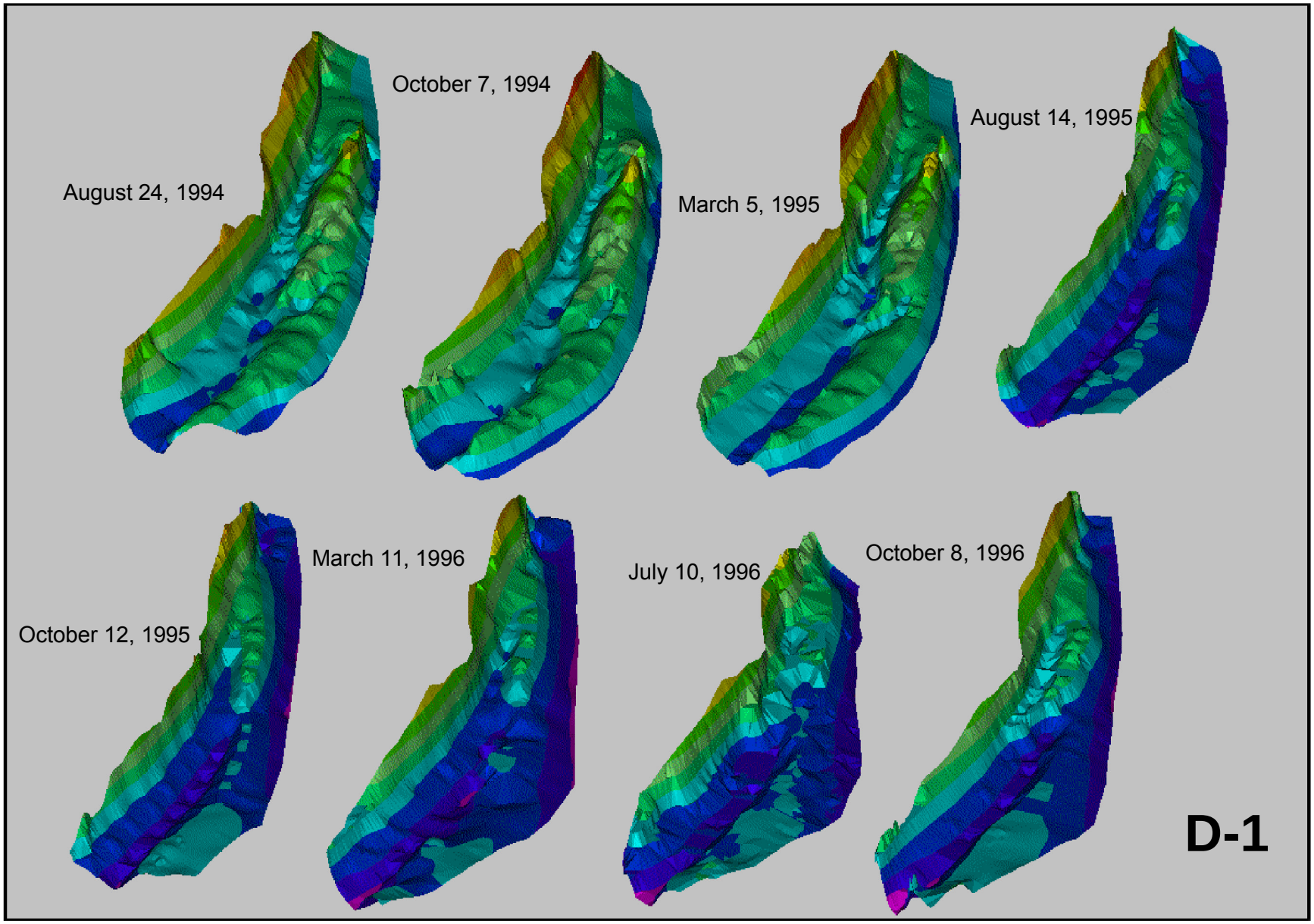

Figure B.2. Surface plots of D-1 Cobble Bar, August 24, 1994 - October 8, 1996.

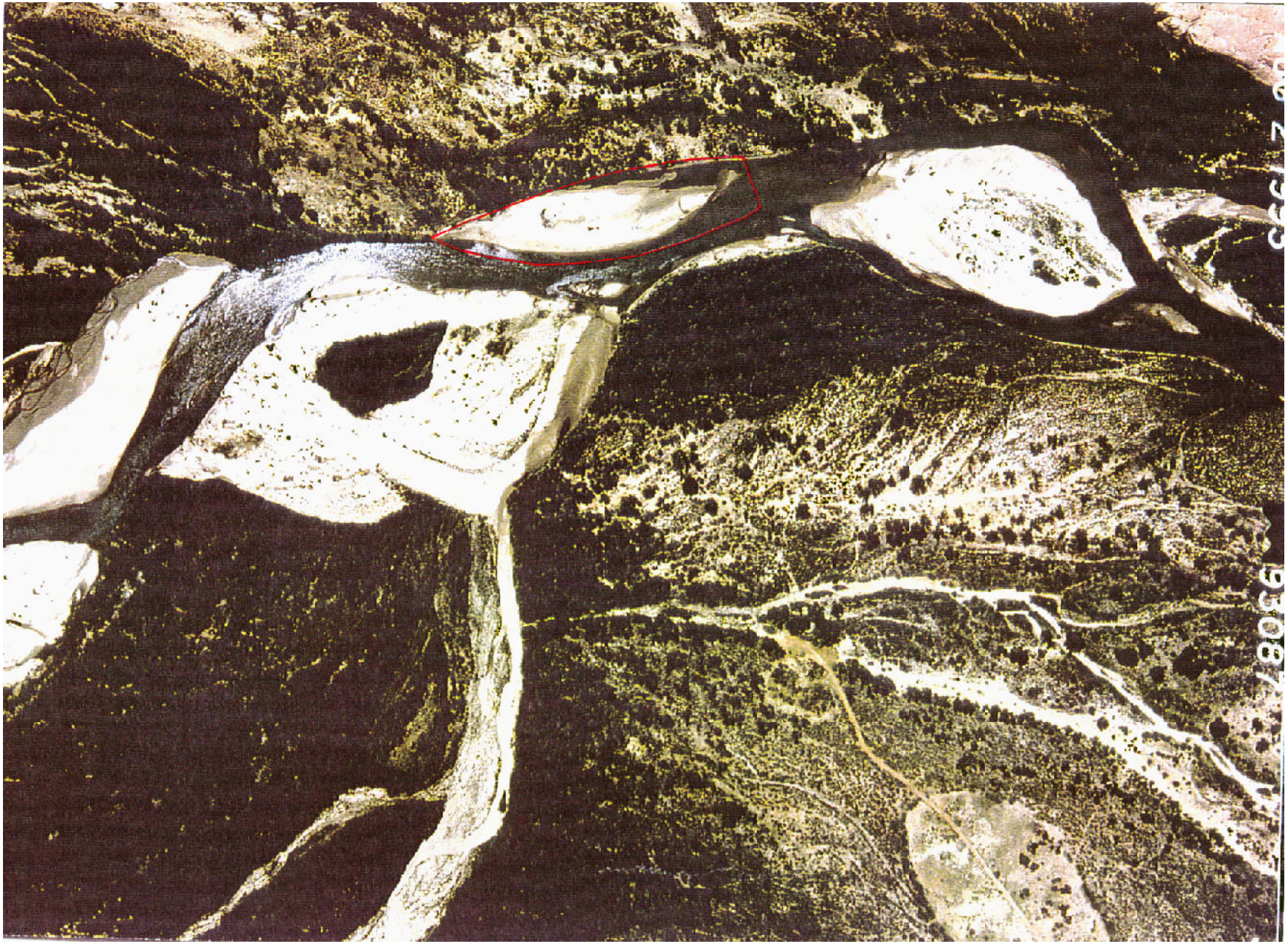

Figure B.3. Location photo of bar D-4 at RM 86.4.

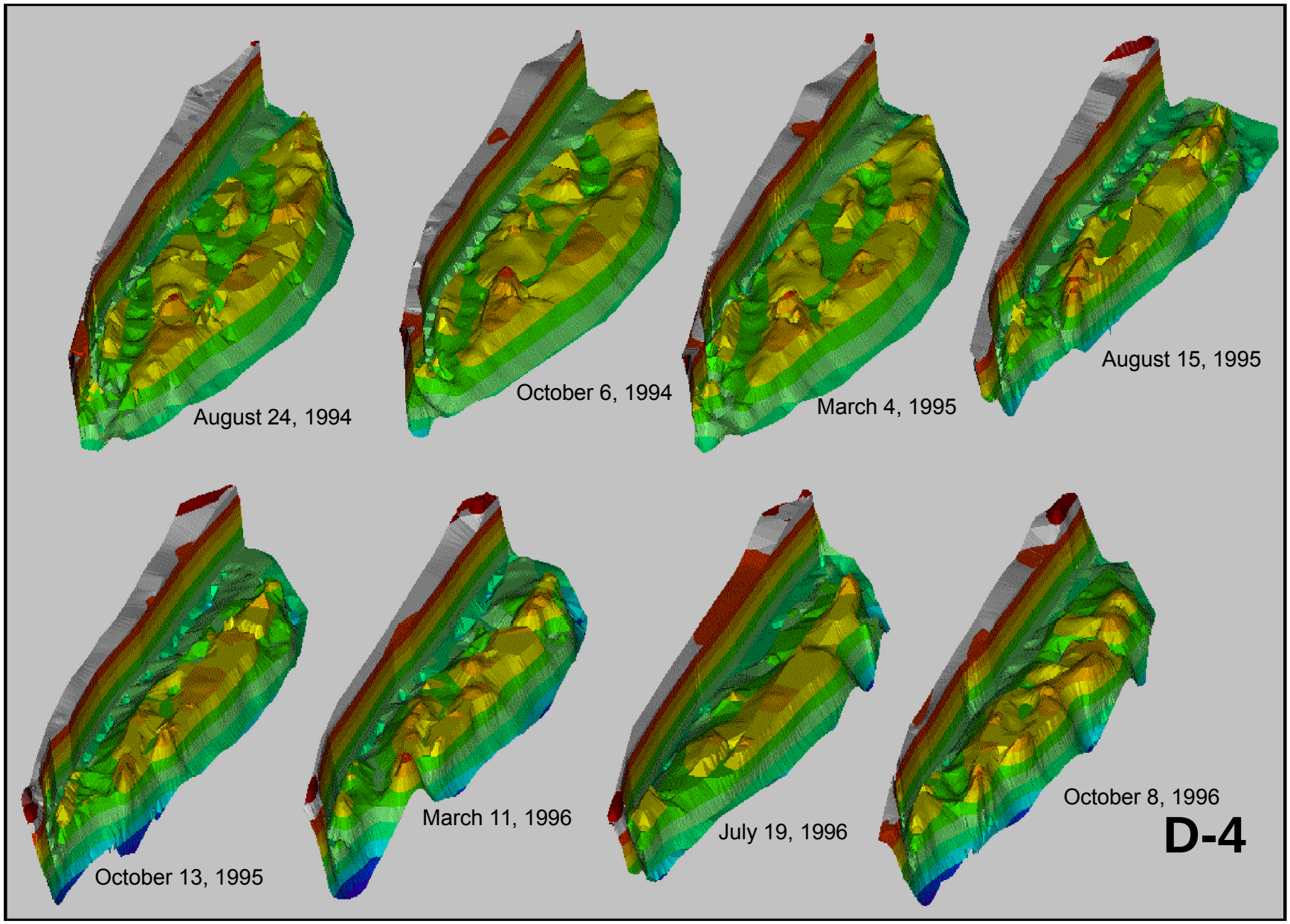

Figure B.4. Surface plots of D-4 cobble bar, August 24, 1994 - October 8, 1996.

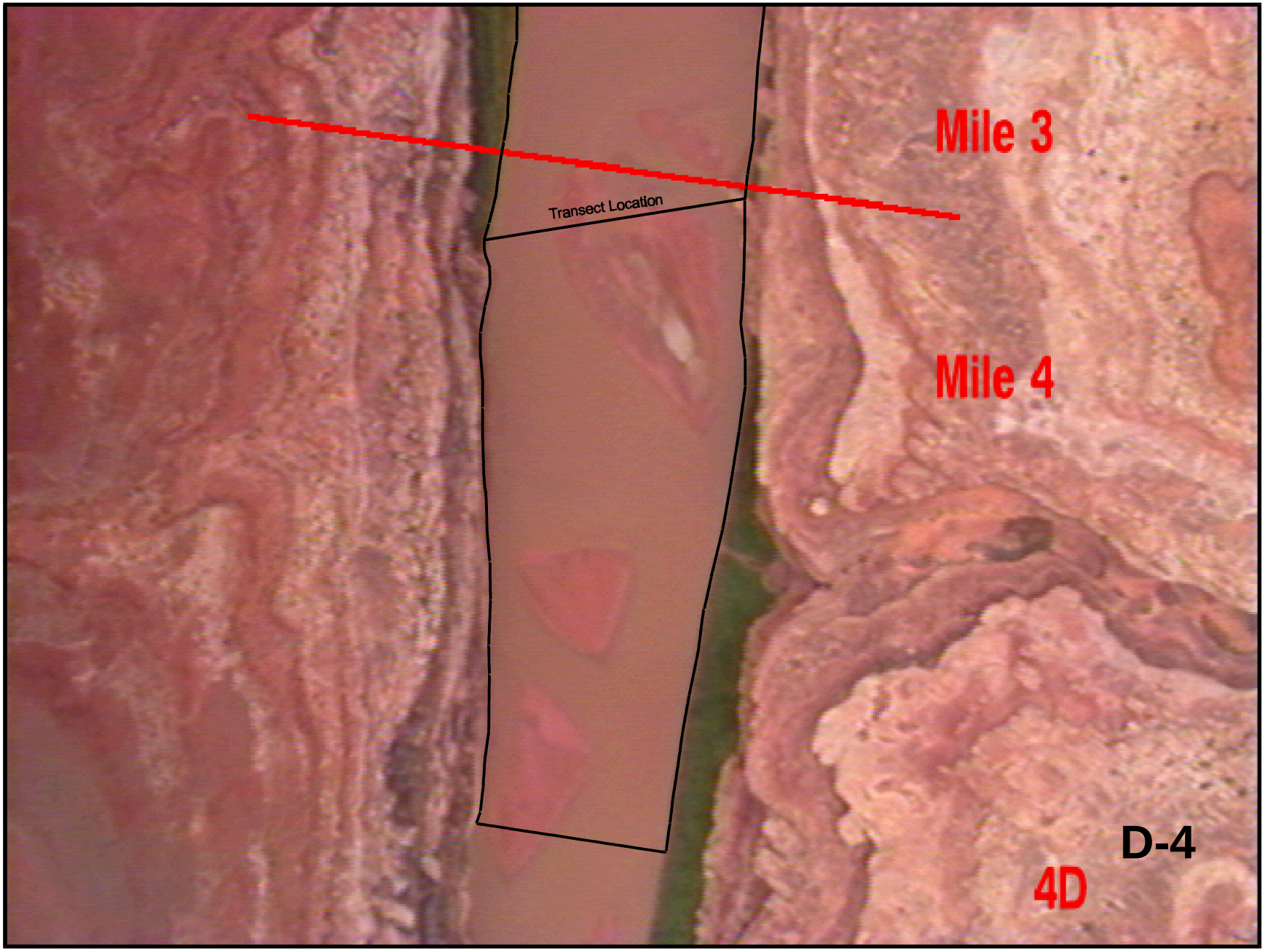

Figure B.5. Location photo of C-2 bar (RM 4).

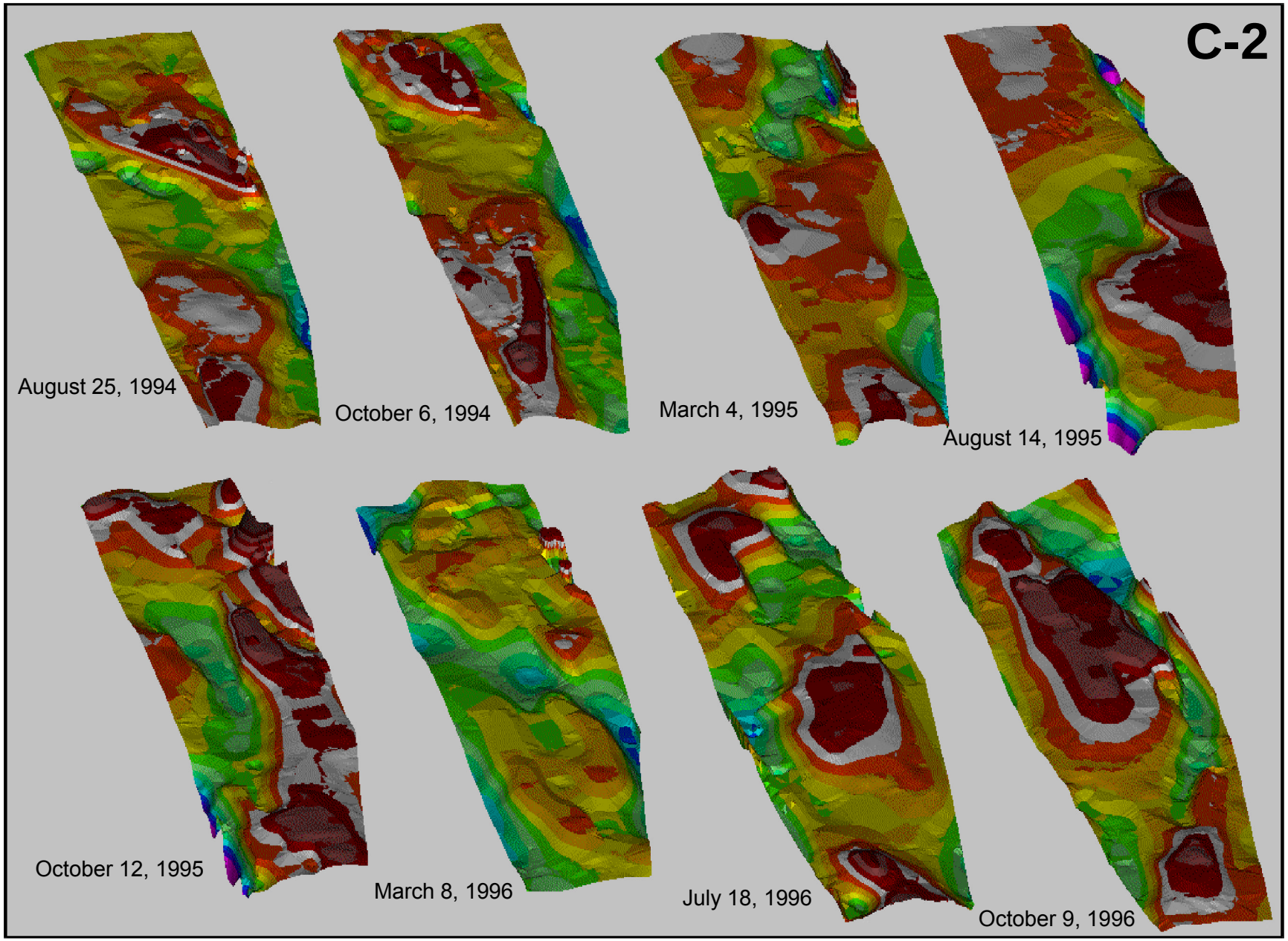

Figure B.6. Surface plots of C-2 cobble bar, August 25, 1994 - October 9, 1996.

APPENDIX C: STATISTICAL TABLES

Summary Statistics: All Habitats By Strata

		Sum of Squares	df	Mean Square	F	Sig.
<0.063 mm	Between Groups	0.04211	7	0.006016	3.19	0.003
	Within Groups	0.9	477	0.001886		
	Total	0.942	484			
.063-.25 mm	Between Groups	0.559	7	0.07991	3.164	0.003
	Within Groups	12.047	477	0.02526		
	Total	12.606	484			
.25-.50 mm	Between Groups	0.362	7	0.05177	3.717	0.001
	Within Groups	6.643	477	0.01393		
	Total	7.006	484			
.50-4.0 mm	Between Groups	0.922	7	0.132	5.153	0
	Within Groups	12.193	477	0.02556		
	Total	13.115	484			
4.0-12.5 mm	Between Groups	0.173	7	0.02477	2.883	0.006
	Within Groups	4.098	477	0.00859		
	Total	4.271	484			
>12.5 mm	Between Groups	1.997	7	0.285	3.653	0.001
	Within Groups	37.255	477	0.0781		
	Total	39.252	484			
D50	Between Groups	73695.764	7	10527.966	7.79	0
	Within Groups	631102.3	467	1351.397		
	Total	704798.064	474			
D16	Between Groups	18237.268	7	2605.324	3.55	0.001
	Within Groups	342763.933	467	733.97		
	Total	361001.201	474			
D84	Between Groups	642017.19	7	91716.741	17.715	0
	Within Groups	2417819.341	467	5177.343		
	Total	3059836.532	474			
CHLA	Between Groups	855.994	7	122.285	11.225	0
	Within Groups	6982.889	641	10.894		
	Total	7838.883	648			
DET	Between Groups	240505.287	7	34357.898	9.222	0
	Within Groups	2160827.32	580	3725.564		
	Total	2401332.608	587			
INVERT	Between Groups	6194.87	7	884.981	15.143	0
	Within Groups	35591.937	609	58.443		
	Total	41786.807	616			
EMB	Between Groups	3.531	7	0.504	5.655	0
	Within Groups	54.594	612	0.08921		
	Total	58.125	619			
DTE	Between Groups	40786.803	7	5826.686	1.499	0.165
	Within Groups	2363474.196	608	3887.293		
	Total	2404260.998	615			

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Summary Statistics: All Habitats By Strata

<0.063 mm	1	2	3	STRATA 4	5	6	7	8
1		0.68	1.00	0.90	1.00	1.00	1.00	1.00
2	0.68		0.01	0.99	0.15	0.03	0.01	0.17
3	1.00	0.01		0.21	0.98	1.00	1.00	1.00
STRATA 4	0.90	0.99	0.21		0.73	0.35	0.20	0.66
5	1.00	0.15	0.98	0.73		1.00	0.99	1.00
6	1.00	0.03	1.00	0.35	1.00		1.00	1.00
7	1.00	0.01	1.00	0.20	0.99	1.00		1.00
8	1.00	0.17	1.00	0.66	1.00	1.00	1.00	

0.063-0.25 mm	1	2	3	STRATA 4	5	6	7	8
1		0.63	1.00	0.97	1.00	0.95	1.00	1.00
2	0.63		0.02	0.75	0.01	0.80	0.13	0.01
3	1.00	0.02		0.77	1.00	0.54	0.99	1.00
STRATA 4	0.97	0.75	0.77		0.74	1.00	0.99	0.51
5	1.00	0.01	1.00	0.74		0.49	0.98	1.00
6	0.95	0.80	0.54	1.00	0.49		0.95	0.31
7	1.00	0.13	0.99	0.99	0.98	0.95		0.86
8	1.00	0.01	1.00	0.51	1.00	0.31	0.86	

0.25-0.5 mm	1	2	3	STRATA 4	5	6	7	8
1		0.61	0.94	0.99	1.00	0.75	0.82	1.00
2	0.61		0.85	0.42	0.01	1.00	0.99	0.02
3	0.94	0.85		1.00	0.39	0.98	1.00	0.41
STRATA 4	0.99	0.42	1.00		0.91	0.71	0.85	0.87
5	1.00	0.01	0.39	0.91		0.03	0.06	1.00
6	0.75	1.00	0.98	0.71	0.03		1.00	0.06
7	0.82	0.99	1.00	0.85	0.057	1.00		0.10
8	1.00	0.02	0.41	0.87	1.00	0.06	0.10	

0.5-4.0 mm	1	2	3	STRATA 4	5	6	7	8
1		0.79	0.12	1.00	0.94	0.98	0.91	0.99
2	0.79		0.16	0.03	0.99	0.91	1.00	0.94
3	0.12	0.16		0.00	0.02	0.00	0.02	0.02
STRATA 4	1.00	0.03	0.00		0.19	0.45	0.11	0.70
5	0.94	0.99	0.02	0.19		1.00	1.00	1.00
6	0.98	0.91	0.00	0.45	1.00		1.00	1.00
7	0.91	1.00	0.02	0.11	1.00	1.00		1.00
8	0.99	0.94	0.02	0.70	1.00	1.00	1.00	

4.0-12.5 mm	1	2	3	STRATA 4	5	6	7	8
1		0.55	0.93	0.59	1.00	0.83	0.85	1.00
2	0.55		0.79	1.00	0.05	0.97	0.95	0.04
3	0.93	0.79		0.87	0.83	1.00	1.00	0.66
STRATA 4	0.59	1.00	0.87		0.10	0.99	0.98	0.08
5	1.00	0.05	0.83	0.10		0.44	0.45	1.00
6	0.83	0.97	1.00	0.99	0.44		1.00	0.32
7	0.85	0.95	1.00	0.98	0.45	1.00		0.33
8	1.00	0.04	0.66	0.08	1.00	0.32	0.33	

>12.5 mm	1	2	3	STRATA 4	5	6	7	8
1		0.29	0.61	1.00	0.99	0.84	0.91	1.00
2	0.29		0.96	0.01	0.02	0.51	0.23	0.01
3	0.61	0.96		0.13	0.34	0.99	0.91	0.19
STRATA 4	1.00	0.01	0.13		1.00	0.52	0.73	1.00
5	0.99	0.02	0.34	1.00		0.85	0.96	1.00
6	0.84	0.51	0.99	0.52	0.85		1.00	0.60
7	0.91	0.23	0.91	0.73	0.96	1.00		0.78
8	1.00	0.01	0.19	1.00	1.00	0.60	0.78	

D50	1	2	3	STRATA 4	5	6	7	8
1		0.66	1.00	0.88	0.96	0.06	0.77	0.29
2	0.66		0.00	0.99	0.79	0.10	1.00	0.92
3	1.00	0.00		0.07	0.22	0.00	0.01	0.00
STRATA 4	0.88	0.99	0.07		1.00	0.01	1.00	0.58
5	0.96	0.79	0.22	1.00		0.00	0.94	0.18
6	0.06	0.10	0.00	0.01	0.00		0.03	0.96
7	0.77	1.00	0.01	1.00	0.94	0.03		0.77
8	0.29	0.92	0.00	0.58	0.18	0.96	0.77	

D16	1	2	3	STRATA 4	5	6	7	8
1		0.96	1.00	0.26	1.00	0.73	0.93	0.40
2	0.96		0.99	0.11	0.99	0.91	1.00	0.39
3	1.00	0.99		0.01	1.00	0.40	0.93	0.08
STRATA 4	0.26	0.11	0.01		0.01	0.75	0.20	1.00
5	1.00	0.99	1.00	0.01		0.41	0.95	0.09
6	0.73	0.91	0.40	0.75	0.41		0.98	0.96
7	0.93	1.00	0.93	0.20	0.95	0.98		0.56
8	0.40	0.39	0.08	1.00	0.09	0.96	0.56	

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Summary Statistics: All Habitats By Strata

D84	1	2	3	STRATA 4	5	6	7	8
1		0.40	0.99	1.00	1.00	0.08	1.00	0.94
2	0.40		0.00	0.00	0.00	0.74	0.01	0.70
3	0.99	0.00		1.00	1.00	0.00	0.06	0.01
STRATA 4	1.00	0.00	1.00		1.00	0.00	0.36	0.05
5	1.00	0.00	1.00	1.00		0.00	0.07	0.01
6	0.08	0.74	0.00	0.00	0.00		0.00	0.05
7	1.00	0.01	0.06	0.36	0.07	0.00		0.90
8	0.94	0.70	0.01	0.05	0.01	0.05	0.90	

CHLOROPHYL L A	1	2	3	STRATA 4	5	6	7	8
1		0.12	0.95	0.99	0.97	1.00	0.99	0.98
2	0.12		0.00	0.00	0.00	0.00	0.00	0.00
3	0.95	0.00		0.98	1.00	0.00	0.98	1.00
STRATA 4	0.99	0.00	0.98		1.00	0.01	1.00	1.00
5	0.97	0.00	1.00	1.00		0.00	1.00	1.00
6	1.00	0.00	0.00	0.01	0.00		0.00	0.01
7	0.99	0.00	0.98	1.00	1.00	0.00		1.00
8	0.98	0.00	1.00	1.00	1.00	0.01	1.00	

INVERTEBRAT ES	1	2	3	STRATA 4	5	6	7	8
1		0.97	0.99	1.00	1.00	1.00	1.00	0.03
2	0.97		1.00	0.77	0.99	0.11	0.01	0.00
3	0.99	1.00		0.94	1.00	0.28	0.05	0.00
STRATA 4	1.00	0.77	0.94		1.00	0.96	0.69	0.00
5	1.00	0.99	1.00	1.00		0.63	0.22	0.00
6	1.00	0.11	0.28	0.96	0.63		1.00	0.00
7	1.00	0.01	0.05	0.69	0.22	1.00		0.00
8	0.03	0.00	0.00	0.00	0.00	0.00	0.00	

EMBEDDEDN ESS	1	2	3	STRATA 4	5	6	7	8
1		0.93	1.00	1.00	0.74	1.00	1.00	0.44
2	0.93		0.43	0.84	0.97	0.22	0.02	0.50
3	1.00	0.43		1.00	0.05	1.00	0.94	0.01
STRATA 4	1.00	0.84	1.00		0.25	0.99	0.68	0.04
5	0.74	0.97	0.05	0.25		0.02	0.00	0.96
6	1.00	0.22	1.00	0.99	0.02		0.99	0.00
7	1.00	0.02	0.94	0.68	0.00	0.99		0.00
8	0.44	0.50	0.01	0.04	0.96	0.00	0.00	

DTE	1	2	3	STRATA 4	5	6	7	8
1		0.73	1.00	0.96	0.99	1.00	0.97	0.93
2	0.73		0.13	0.87	0.61	0.25	0.79	0.99
3	1.00	0.13		0.93	0.99	1.00	0.93	0.86
STRATA 4	0.96	0.87	0.93		1.00	0.98	1.00	1.00
5	0.99	0.61	0.99	1.00		1.00	1.00	1.00
6	1.00	0.25	1.00	0.98	1.00		0.99	0.94
7	0.97	0.79	0.93	1.00	1.00	0.99		1.00
8	0.93	0.99	0.86	1.00	1.00	0.94	1.00	

Summary Statistics: Riffle Habitats By Strata

		Sum of Squares	df	Mean Square	F	Sig.
<0.063 mm	Between Groups	0.007448	7	0.001064	2.168	0.038
	Within Groups	0.117	239	0.0004908		
	Total	0.125	246			
.063-.25 mm	Between Groups	0.139	7	0.01984	3.57	0.001
	Within Groups	1.328	239	0.005557		
	Total	1.467	246			
.25-.50 mm	Between Groups	0.132	7	0.01884	2.793	0.008
	Within Groups	1.612	239	0.006746		
	Total	1.744	246			
.50-4.0 mm	Between Groups	0.512	7	0.07311	3.895	0
	Within Groups	4.486	239	0.01877		
	Total	4.997	246			
4.0-12.5 mm	Between Groups	0.05113	7	0.007305	0.984	0.443
	Within Groups	1.773	239	0.00742		
	Total	1.825	246			
>12.5 mm	Between Groups	1.18	7	0.169	3.231	0.003
	Within Groups	12.471	239	0.05218		
	Total	13.651	246			
D50	Between Groups	81784.929	7	11683.561	16.105	0
	Within Groups	171937.308	237	725.474		
	Total	253722.237	244			
D16	Between Groups	26265.373	7	3752.196	6.565	0
	Within Groups	135446.12	237	571.503		
	Total	161711.493	244			
D84	Between Groups	407461.838	7	58208.834	14.126	0
	Within Groups	976630.593	237	4120.804		
	Total	1384092.431	244			
CHLA	Between Groups	624.355	7	89.194	5.623	0
	Within Groups	5059.927	319	15.862		
	Total	5684.282	326			
DET	Between Groups	269052.588	7	38436.084	6.964	0
	Within Groups	1639158.715	297	5519.053		
	Total	1908211.303	304			
INVERT	Between Groups	7623.799	7	1089.114	11.192	0
	Within Groups	30069.836	309	97.313		
	Total	37693.635	316			
EMB	Between Groups	1.735	7	0.248	6.021	0
	Within Groups	12.762	310	0.04117		
	Total	14.497	317			
DTE	Between Groups	16095.27	7	2299.324	0.941	0.475
	Within Groups	750094.73	307	2443.305		
	Total	766190	314			

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Summary Statistics: Riffle Habitats By Strata

<0.063 mm	1	2	3	STRATA 4	5	6	7	8
1		0.87	1.00	1.00	1.00	1.00	1.00	1.00
2	0.87		0.04	0.10	0.06	0.11	0.09	0.18
3	1.00	0.04		1.00	1.00	1.00	1.00	1.00
STRATA 4	1.00	0.10	1.00		1.00	1.00	1.00	1.00
5	1.00	0.06	1.00	1.00		1.00	1.00	1.00
6	1.00	0.11	1.00	1.00	1.00		1.00	1.00
7	1.00	0.09	1.00	1.00	1.00	1.00		1.00
8	1.00	0.18	1.00	1.00	1.00	1.00	1.00	

0.063-0.25 mm	1	2	3	STRATA 4	5	6	7	8
1		0.51	1.00	1.00	1.00	0.97	0.99	1.00
2	0.51		0.00	0.02	0.00	0.40	0.16	0.01
3	1.00	0.00		1.00	1.00	0.71	0.88	1.00
STRATA 4	1.00	0.02	1.00		1.00	0.85	0.95	1.00
5	1.00	0.00	1.00	1.00		0.70	0.88	1.00
6	0.97	0.40	0.71	0.85	0.70		1.00	0.66
7	0.99	0.16	0.88	0.95	0.88	1.00		0.83
8	1.00	0.01	1.00	1.00	1.00	0.66	0.83	

0.25-0.5 mm	1	2	3	STRATA 4	5	6	7	8
1		0.58	0.97	1.00	1.00	0.75	0.90	1.00
2	0.58		0.60	0.15	0.04	1.00	0.88	0.06
3	0.97	0.60		0.99	0.93	0.92	1.00	0.86
STRATA 4	1.00	0.15	0.99		1.00	0.44	0.84	1.00
5	1.00	0.04	0.93	1.00		0.19	0.59	1.00
6	0.75	1.00	0.92	0.44	0.19		1.00	0.21
7	0.90	0.88	1.00	0.84	0.59	1.00		0.55
8	1.00	0.06	0.86	1.00	1.00	0.21	0.55	

0.5-4.0 mm	1	2	3	STRATA 4	5	6	7	8
1		0.52	0.05	0.87	0.93	0.71	0.84	0.91
2	0.52		0.16	0.96	0.69	1.00	0.93	0.94
3	0.05	0.16		0.01	0.00	0.03	0.00	0.02
STRATA 4	0.87	0.96	0.01		1.00	1.00	1.00	1.00
5	0.93	0.69	0.00	1.00		0.97	1.00	1.00
6	0.71	1.00	0.03	1.00	0.97		1.00	1.00
7	0.84	0.93	0.00	1.00	1.00	1.00		1.00
8	0.91	0.94	0.02	1.00	1.00	1.00	1.00	

4.0-12.5 mm	1	2	3	STRATA 4	5	6	7	8
1		1.00	1.00	1.00	0.95	1.00	1.00	0.71
2	1.00		1.00	1.00	0.96	1.00	1.00	0.42
3	1.00	1.00		1.00	0.99	1.00	1.00	0.60
STRATA 4	1.00	1.00	1.00		0.99	1.00	1.00	0.64
5	0.95	0.96	0.99	0.99		0.98	0.98	0.94
6	1.00	1.00	1.00	1.00	0.98		1.00	0.52
7	1.00	1.00	1.00	1.00	0.98	1.00		0.51
8	0.71	0.42	0.60	0.64	0.94	0.52	0.51	

>12.5 mm	1	2	3	STRATA 4	5	6	7	8
1		0.08	0.16	0.84	0.84	0.35	0.54	0.78
2	0.08		1.00	0.07	0.03	0.82	0.33	0.26
3	0.16	1.00		0.27	0.14	0.98	0.73	0.56
STRATA 4	0.84	0.07	0.27		1.00	0.79	0.98	1.00
5	0.84	0.03	0.14	1.00		0.65	0.95	1.00
6	0.35	0.82	0.98	0.79	0.65		1.00	0.95
7	0.54	0.33	0.73	0.98	0.95	1.00		1.00
8	0.78	0.26	0.56	1.00	1.00	0.95	1.00	

D50	1	2	3	STRATA 4	5	6	7	8
1		0.21	1.00	0.39	1.00	0.01	0.62	0.00
2	0.21		0.00	1.00	0.00	0.11	0.79	0.06
3	1.00	0.00		0.00	1.00	0.00	0.01	0.00
STRATA 4	0.39	1.00	0.00		0.01	0.03	0.99	0.02
5	1.00	0.00	1.00	0.01		0.00	0.06	0.00
6	0.01	0.11	0.00	0.03	0.00		0.00	1.00
7	0.62	0.79	0.01	0.99	0.06	0.00		0.00
8	0.00	0.06	0.00	0.02	0.00	1.00	0.00	

D16	1	2	3	STRATA 4	5	6	7	8
1		1.00	1.00	0.59	1.00	0.64	0.98	0.35
2	1.00		0.75	0.10	0.95	0.11	0.99	0.02
3	1.00	0.75		0.00	1.00	0.00	0.25	0.00
STRATA 4	0.59	0.10	0.00		0.00	1.00	0.49	1.00
5	1.00	0.95	1.00	0.00		0.00	0.52	0.00
6	0.64	0.11	0.00	1.00	0.00		0.53	0.98
7	0.98	0.99	0.25	0.49	0.52	0.53		0.15
8	0.35	0.02	0.00	1.00	0.00	0.98	0.15	

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Summary Statistics: Riffle Habitats By Strata

D84	1	2	3	STRATA 4	5	6	7	8
1		0.75	0.99	1.00	0.93	0.57	1.00	0.69
2	0.75		0.00	0.00	0.00	1.00	0.00	1.00
3	0.99	0.00		0.98	0.99	0.00	0.64	0.00
STRATA 4	1.00	0.00	0.98		0.63	0.00	1.00	0.00
5	0.93	0.00	0.99	0.63		0.00	0.12	0.00
6	0.57	1.00	0.00	0.00	0.00		0.00	1.00
7	1.00	0.00	0.64	1.00	0.12	0.00		0.01
8	0.69	1.00	0.00	0.00	0.00	1.00	0.01	

CHLOROPHYLL A	1	2	3	STRATA 4	5	6	7	8
1		0.70	1.00	1.00	1.00	1.00	1.00	1.00
2	0.70		0.09	0.15	0.07	0.00	0.03	0.39
3	1.00	0.09		1.00	1.00	0.02	1.00	1.00
STRATA 4	1.00	0.15	1.00		1.00	0.01	1.00	1.00
5	1.00	0.07	1.00	1.00		0.02	1.00	1.00
6	1.00	0.00	0.02	0.01	0.02		0.02	0.05
7	1.00	0.03	1.00	1.00	1.00	0.02		1.00
8	1.00	0.39	1.00	1.00	1.00	0.05	1.00	

INVERTEBRATES	1	2	3	STRATA 4	5	6	7	8
1		0.96	0.98	1.00	0.99	1.00	1.00	0.17
2	0.96		1.00	0.76	1.00	0.20	0.08	0.00
3	0.98	1.00		0.91	1.00	0.38	0.19	0.00
STRATA 4	1.00	0.76	0.91		0.99	0.99	0.96	0.00
5	0.99	1.00	1.00	0.99		0.71	0.48	0.00
6	1.00	0.20	0.38	0.99	0.71		1.00	0.00
7	1.00	0.08	0.19	0.96	0.48	1.00		0.00
8	0.17	0.00	0.00	0.00	0.00	0.00	0.00	

EMBEDDEDNESS	1	2	3	STRATA 4	5	6	7	8
1		1.00	0.98	1.00	1.00	0.90	0.74	1.00
2	1.00		0.31	1.00	1.00	0.03	0.00	0.98
3	0.98	0.31		0.52	0.16	0.98	0.61	0.11
STRATA 4	1.00	1.00	0.52		1.00	0.09	0.01	0.97
5	1.00	1.00	0.16	1.00		0.01	0.00	1.00
6	0.90	0.03	0.98	0.09	0.01		0.99	0.01
7	0.74	0.00	0.61	0.01	0.00	0.99		0.00
8	1.00	0.98	0.11	0.97	1.00	0.01	0.00	

DTE	1	2	3	STRATA 4	5	6	7	8
1		1.00	1.00	1.00	1.00	1.00	1.00	0.98
2	1.00		0.96	1.00	0.97	1.00	0.74	1.00
3	1.00	0.96		0.96	1.00	1.00	1.00	0.81
STRATA 4	1.00	1.00	0.96		0.97	1.00	0.74	1.00
5	1.00	0.97	1.00	0.97		1.00	1.00	0.83
6	1.00	1.00	1.00	1.00	1.00		0.94	0.98
7	1.00	0.74	1.00	0.74	1.00	0.94		0.53
8	0.98	1.00	0.81	1.00	0.83	0.98	0.53	

Summary Statistics: Run Habitats By Strata

		Sum of Squares	df	Mean Square	F	Sig.
<0.063 mm	Between Groups	0.05596	7	0.007994	2.548	0.015
	Within Groups	0.721	230	0.003137		
	Total	0.777	237			
.063-.25 mm	Between Groups	0.61	7	0.08714	2.193	0.036
	Within Groups	9.138	230	0.03973		
	Total	9.748	237			
.25-.50 mm	Between Groups	0.287	7	0.04099	2.106	0.044
	Within Groups	4.477	230	0.01947		
	Total	4.764	237			
.50-4.0 mm	Between Groups	0.739	7	0.106	3.349	0.002
	Within Groups	7.251	230	0.03153		
	Total	7.99	237			
4.0-12.5 mm	Between Groups	0.228	7	0.03261	3.621	0.001
	Within Groups	2.071	230	0.009006		
	Total	2.3	237			
>12.5 mm	Between Groups	1.32	7	0.189	2.164	0.038
	Within Groups	20.046	230	0.08716		
	Total	21.366	237			
D50	Between Groups	29247.545	7	4178.221	2.753	0.009
	Within Groups	336896.833	222	1517.553		
	Total	366144.378	229			
D16	Between Groups	4695.283	7	670.755	1.116	0.354
	Within Groups	133447.847	222	601.116		
	Total	138143.13	229			
D84	Between Groups	315066.942	7	45009.563	7.675	0
	Within Groups	1301863.581	222	5864.25		
	Total	1616930.523	229			
CHLA	Between Groups	301.948	7	43.135	7.582	0
	Within Groups	1786.322	314	5.689		
	Total	2088.27	321			
DET	Between Groups	38761.442	7	5537.349	5.614	0
	Within Groups	271262.342	275	986.409		
	Total	310023.785	282			
INVERT	Between Groups	629.572	7	89.939	13.018	0
	Within Groups	2017.296	292	6.909		
	Total	2646.867	299			
EMB	Between Groups	2.546	7	0.364	3.949	0
	Within Groups	27.081	294	0.09211		
	Total	29.628	301			
DTE	Between Groups	59353.738	7	8479.105	1.621	0.129
	Within Groups	1532903.073	293	5231.751		
	Total	1592256.811	300			

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Summary Statistics: Run Habitats By Strata

<0.063 mm	1	2	3	STRATA 4	5	6	7	8
1		0.84	1.00	0.87	1.00	1.00	1.00	1.00
2	0.84		0.12	1.00	0.53	0.14	0.05	0.46
3	1.00	0.12		0.19	0.99	1.00	1.00	1.00
STRATA 4	0.87	1.00	0.19		0.67	0.23	0.10	0.57
5	1.00	0.53	0.99	0.67		1.00	0.96	1.00
6	1.00	0.14	1.00	0.23	1.00		1.00	1.00
7	1.00	0.05	1.00	0.10	0.96	1.00		1.00
8	1.00	0.46	1.00	0.57	1.00	1.00	1.00	

0.063-0.25 mm	1	2	3	STRATA 4	5	6	7	8
1		0.84	1.00	0.98	1.00	0.99	1.00	1.00
2	0.84		0.17	0.97	0.09	0.91	0.25	0.06
3	1.00	0.17		0.81	1.00	0.85	1.00	1.00
STRATA 4	0.98	0.97	0.81		0.70	1.00	0.92	0.48
5	1.00	0.09	1.00	0.70		0.74	1.00	1.00
6	0.99	0.91	0.85	1.00	0.74		0.95	0.52
7	1.00	0.25	1.00	0.92	1.00	0.95		0.97
8	1.00	0.06	1.00	0.48	1.00	0.52	0.97	

0.25-0.5 mm	1	2	3	STRATA 4	5	6	7	8
1		0.94	0.99	1.00	1.00	0.98	0.97	1.00
2	0.94		1.00	0.91	0.12	1.00	1.00	0.20
3	0.99	1.00		1.00	0.51	1.00	1.00	0.59
STRATA 4	1.00	0.91	1.00		0.89	0.99	0.98	0.90
5	1.00	0.12	0.51	0.89		0.27	0.20	1.00
6	0.98	1.00	1.00	0.99	0.27		1.00	0.38
7	0.97	1.00	1.00	0.98	0.20	1.00		0.32
8	1.00	0.20	0.59	0.90	1.00	0.38	0.32	

0.5-4.0 mm	1	2	3	STRATA 4	5	6	7	8
1		1.00	0.96	0.97	1.00	1.00	1.00	1.00
2	1.00		0.93	0.03	1.00	0.93	1.00	1.00
3	0.96	0.93		0.00	0.96	0.20	0.88	0.64
STRATA 4	0.97	0.03	0.00		0.01	0.37	0.02	0.35
5	1.00	1.00	0.96	0.01		0.84	1.00	0.99
6	1.00	0.93	0.20	0.37	0.84		0.91	1.00
7	1.00	1.00	0.88	0.02	1.00	0.91		1.00
8	1.00	1.00	0.64	0.35	0.99	1.00	1.00	

4.0-12.5 mm	1	2	3	STRATA 4	5	6	7	8
1		0.02	0.26	0.03	0.63	0.14	0.14	0.57
2	0.02		0.44	1.00	0.01	0.77	0.69	0.13
3	0.26	0.44		0.70	0.89	1.00	1.00	0.99
STRATA 4	0.03	1.00	0.70		0.05	0.94	0.90	0.28
5	0.63	0.01	0.89	0.05		0.48	0.49	1.00
6	0.14	0.77	1.00	0.94	0.48		1.00	0.87
7	0.14	0.69	1.00	0.90	0.49	1.00		0.88
8	0.57	0.13	0.99	0.28	1.00	0.87	0.88	

>12.5 mm	1	2	3	STRATA 4	5	6	7	8
1		0.97	1.00	1.00	1.00	1.00	1.00	1.00
2	0.97		0.93	0.04	0.28	0.61	0.57	0.04
3	1.00	0.93		0.50	0.96	1.00	1.00	0.45
STRATA 4	1.00	0.04	0.50		0.98	0.81	0.78	1.00
5	1.00	0.28	0.96	0.98		1.00	1.00	0.94
6	1.00	0.61	1.00	0.81	1.00		1.00	0.74
7	1.00	0.57	1.00	0.78	1.00	1.00		0.71
8	1.00	0.04	0.45	1.00	0.94	0.74	0.71	

D50	1	2	3	STRATA 4	5	6	7	8
1		1.00	1.00	1.00	0.96	0.83	0.99	1.00
2	1.00		0.84	1.00	0.84	0.30	0.98	1.00
3	1.00	0.84		0.93	0.07	0.00	0.22	0.99
STRATA 4	1.00	1.00	0.93		0.77	0.24	0.95	1.00
5	0.96	0.84	0.07	0.77		0.99	1.00	0.77
6	0.83	0.30	0.00	0.24	0.99		0.87	0.30
7	0.99	0.98	0.22	0.95	1.00	0.87		0.94
8	1.00	1.00	0.99	1.00	0.77	0.30	0.94	

D16	1	2	3	STRATA 4	5	6	7	8
1		0.98	0.95	0.56	0.97	0.99	0.97	0.98
2	0.98		1.00	0.49	1.00	1.00	1.00	1.00
3	0.95	1.00		0.76	1.00	1.00	1.00	1.00
STRATA 4	0.56	0.49	0.76		0.58	0.29	0.52	0.76
5	0.97	1.00	1.00	0.58		1.00	1.00	1.00
6	0.99	1.00	1.00	0.29	1.00		1.00	1.00
7	0.97	1.00	1.00	0.52	1.00	1.00		1.00
8	0.98	1.00	1.00	0.76	1.00	1.00	1.00	

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Summary Statistics: Run Habitats By Strata

D84	1	2	3	STRATA 4	5	6	7	8
1		0.86	1.00	1.00	1.00	0.35	1.00	1.00
2	0.86		0.00	0.01	0.07	0.65	0.85	0.18
3	1.00	0.00		1.00	0.97	0.00	0.19	1.00
STRATA 4	1.00	0.01	1.00		0.99	0.00	0.30	1.00
5	1.00	0.07	0.97	0.99		0.00	0.76	1.00
6	0.35	0.65	0.00	0.00	0.00		0.02	0.00
7	1.00	0.85	0.19	0.30	0.76	0.02		0.84
8	1.00	0.18	1.00	1.00	1.00	0.00	0.84	

CHLOROPHYLL A	1	2	3	STRATA 4	5	6	7	8
1		0.22	0.91	1.00	0.96	1.00	1.00	1.00
2	0.22		0.05	0.00	0.01	0.00	0.00	0.00
3	0.91	0.05		0.44	1.00	0.01	0.81	0.94
STRATA 4	1.00	0.00	0.44		0.76	0.84	1.00	1.00
5	0.96	0.01	1.00	0.76		0.04	0.98	1.00
6	1.00	0.00	0.01	0.84	0.04		0.29	0.54
7	1.00	0.00	0.81	1.00	0.98	0.29		1.00
8	1.00	0.00	0.94	1.00	1.00	0.54	1.00	

INVERTEBRATES	1	2	3	STRATA 4	5	6	7	8
1		1.00	1.00	1.00	1.00	1.00	0.91	0.01
2	1.00		1.00	1.00	0.99	0.41	0.01	0.00
3	1.00	1.00		1.00	1.00	0.74	0.03	0.00
STRATA 4	1.00	1.00	1.00		1.00	0.86	0.07	0.00
5	1.00	0.99	1.00	1.00		0.91	0.10	0.00
6	1.00	0.41	0.74	0.86	0.91		0.83	0.00
7	0.91	0.01	0.03	0.07	0.10	0.83		0.00
8	0.01	0.00	0.00	0.00	0.00	0.00	0.00	

EMBEDDEDNESS	1	2	3	STRATA 4	5	6	7	8
1		0.77	0.96	0.98	0.37	0.92	0.98	0.15
2	0.77		0.94	0.82	0.80	0.99	0.76	0.23
3	0.96	0.94		1.00	0.14	1.00	1.00	0.02
STRATA 4	0.98	0.82	1.00		0.07	1.00	1.00	0.01
5	0.37	0.80	0.14	0.07		0.29	0.04	0.95
6	0.92	0.99	1.00	1.00	0.29		1.00	0.04
7	0.98	0.76	1.00	1.00	0.04	1.00		0.00
8	0.15	0.23	0.02	0.01	0.95	0.04	0.00	

DTE	1	2	3	STRATA 4	5	6	7	8
1		0.81	1.00	0.99	0.99	1.00	0.93	0.99
2	0.81		0.19	0.67	0.80	0.16	1.00	0.86
3	1.00	0.19		1.00	0.97	1.00	0.60	1.00
STRATA 4	0.99	0.67	1.00		1.00	0.99	0.97	1.00
5	0.99	0.80	0.97	1.00		0.96	0.99	1.00
6	1.00	0.16	1.00	0.99	0.96		0.55	0.99
7	0.93	1.00	0.60	0.97	0.99	0.55		0.99
8	0.99	0.86	1.00	1.00	1.00	0.99	0.99	

Summary Statistics: All Habitats By Trip

		Sum of Squares	df	Mean Square	F	Sig.
<0.063 mm	Between Groups	0.06411	4	0.016	8.765	0.00
	Within Groups	0.878	480	0.002		
	Total	0.942	484			
.063-.25 mm	Between Groups	1.343	4	0.336	14.304	0.00
	Within Groups	11.264	480	0.023		
	Total	12.606	484			
.25-.50 mm	Between Groups	0.378	4	0.094	6.843	0.00
	Within Groups	6.628	480	0.014		
	Total	7.006	484			
.50-4.0 mm	Between Groups	2.376	4	0.594	26.552	0.00
	Within Groups	10.739	480	0.022		
	Total	13.115	484			
4.0-12.5 mm	Between Groups	0.09089	4	0.023	2.609	0.04
	Within Groups	4.18	480	0.009		
	Total	4.271	484			
>12.5 mm	Between Groups	4.014	4	1.003	13.668	0.00
	Within Groups	35.239	480	0.073		
	Total	39.252	484			
D50	Between Groups	24402.834	4	6100.709	4.214	0.00
	Within Groups	680395.23	470	1447.649		
	Total	704798.064	474			
D16	Between Groups	9077.45	4	2269.363	3.031	0.02
	Within Groups	351923.751	470	748.774		
	Total	361001.201	474			
D84	Between Groups	140292.358	4	35073.090	5.646	0.00
	Within Groups	2919544.174	470	6211.796		
	Total	3059836.532	474			
CHLA	Between Groups	1531.306	4	382.826	39.086	0.00
	Within Groups	6307.577	644	9.794		
	Total	7838.883	648			
DET	Between Groups	122467.557	4	30616.889	7.833	0.00
	Within Groups	2278865.051	583	3908.859		
	Total	2401332.608	587			
INVERT	Between Groups	2856.164	4	714.041	11.225	0.00
	Within Groups	38930.643	612	63.612		
	Total	41786.807	616			
EMB	Between Groups	1.606	4	0.401	4.368	0.00
	Within Groups	56.519	615	0.092		
	Total	58.125	619			
DTE	Between Groups	124568.529	4	31142.132	8.347	0.00
	Within Groups	2279692.469	611	3731.084		
	Total	2404260.998	615			

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Summary Statistics: All Habitats By Trip

<0.063 mm	1	2	TRIP 3	4	5
1		1.00	0.64	0.00	0.00
2	1.00		0.59	0.00	0.00
TRIP 3	0.64	0.59		0.78	0.14
4	0.00	0.00	0.78		0.46
5	0.00	0.00	0.14	0.46	

0.063-0.25 mm	1	2	TRIP 3	4	5
1		0.99	0.00	0.09	0.00
2	0.99		0.00	0.04	0.00
TRIP 3	0.00	0.00		0.00	0.69
4	0.09	0.04	0.00		0.03
5	0.00	0.00	0.69	0.03	

0.25-0.50mm	1	2	TRIP 3	4	5
1		0.33	0.00	1.00	0.98
2	0.33		0.03	0.48	0.14
TRIP 3	0.00	0.03		0.00	0.00
4	1.00	0.48	0.00		0.89
5	0.98	0.14	0.00	0.89	

0.5-4.0mm	1	2	TRIP 3	4	5
1		0.00	0.92	1.00	1.00
2	0.00		0.00	0.00	0.00
TRIP 3	0.92	0.00		0.86	0.99
4	1.00	0.00	0.86		0.98
5	1.00	0.00	0.99	0.98	

4.0-12.5mm	1	2	TRIP 3	4	5
1		0.14	0.88	1.00	0.99
2	0.14		0.06	0.06	0.44
TRIP 3	0.88	0.06		0.93	0.70
4	1.00	0.06	0.93		0.95
5	0.99	0.44	0.70	0.95	

> 12.5 mm	1	2	TRIP 3	4	5
1		0.00	0.00	0.30	0.00
2	0.00		0.97	0.00	0.23
TRIP 3	0.00	0.97		0.00	0.17
4	0.30	0.00	0.00		0.22
5	0.00	0.23	0.17	0.22	

D50	1	2	TRIP 3	4	5
1		0.93	0.02	0.79	0.97
2	0.93		0.11	0.30	1.00
TRIP 3	0.02	0.11		0.00	0.13
4	0.79	0.30	0.00		0.47
5	0.97	1.00	0.13	0.47	

D50	1	2	TRIP 3	4	5
1		0.93	0.02	0.79	0.97
2	0.93		0.11	0.30	1.00
TRIP 3	0.02	0.11		0.00	0.13
4	0.79	0.30	0.00		0.47
5	0.97	1.00	0.13	0.47	

D84	1	2	TRIP 3	4	5
1		1.00	0.00	0.81	1.00
2	1.00		0.00	0.90	1.00
TRIP 3	0.00	0.00		0.00	0.00
4	0.81	0.90	0.00		0.88
5	1.00	1.00	0.00	0.88	

DETRITUS	1	2	TRIP 3	4	5
1		0.96	0.03	0.57	0.41
2	0.96		0.13	0.93	0.07
TRIP 3	0.03	0.13		0.46	0.00
4	0.57	0.93	0.46		0.00
5	0.41	0.07	0.00	0.00	

CHLOROPHYLL A	1	2	TRIP 3	4	5
1		0.00	0.00	0.00	0.00
2	0.00		0.00	0.04	0.00
TRIP 3	0.00	0.00		0.69	0.95
4	0.00	0.04	0.69		0.34
5	0.00	0.00	0.95	0.34	

% EMBEDDED	1	2	TRIP 3	4	5
1		0.27	0.65	0.97	0.52
2	0.27		0.01	0.59	0.00
TRIP 3	0.65	0.01		0.21	1.00
4	0.97	0.59	0.21		0.14
5	0.52	0.00	1.00	0.14	

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Summary Statistics: All Habitats By Trip

INVERTEBRATES	1	2	TRIP 3	4	5
1		0.00	0.00	0.98	0.00
2	0.00		0.99	0.01	0.87
TRIP 3	0.00	0.99		0.00	0.98
4	0.98	0.01	0.00		0.00
5	0.00	0.87	0.98	0.00	

DTE	1	2	TRIP 3	4	5
1		0.00	0.00	0.00	0.53
2	0.00		0.42	0.32	0.00
TRIP 3	0.00	0.42		1.00	0.14
4	0.00	0.32	1.00		0.20
5	0.53	0.00	0.14	0.20	

Summary Statistics: Riffle Habitats By Trip

		Sum of Squares	df	Mean Square	F	Sig.
<0.063 mm	Between Groups	0.007547	4	0.001887	3.896	0.004
	Within Groups	0.117	242	0.0004843		
	Total	0.125	246			
.063-.25 mm	Between Groups	0.07864	4	0.01966	3.427	0.01
	Within Groups	1.388	242	0.005736		
	Total	1.467	246			
.25-.50 mm	Between Groups	0.07377	4	0.01844	2.672	0.033
	Within Groups	1.67	242	0.006902		
	Total	1.744	246			
.50-4.0 mm	Between Groups	0.54	4	0.135	7.324	0
	Within Groups	4.458	242	0.01842		
	Total	4.997	246			
4.0-12.5 mm	Between Groups	0.189	4	0.04716	6.975	0
	Within Groups	1.636	242	0.00676		
	Total	1.825	246			
>12.5 mm	Between Groups	1.865	4	0.466	9.574	0
	Within Groups	11.786	242	0.0487		
	Total	13.651	246			
D50	Between Groups	17101.87	4	4275.467	4.337	0.002
	Within Groups	236620.368	240	985.918		
	Total	253722.237	244			
D16	Between Groups	4808.796	4	1202.199	1.839	0.122
	Within Groups	156902.697	240	653.761		
	Total	161711.493	244			
D84	Between Groups	52663.412	4	13165.853	2.373	0.053
	Within Groups	1331429.019	240	5547.621		
	Total	1384092.431	244			
CHLA	Between Groups	1110.923	4	277.731	19.554	0
	Within Groups	4573.359	322	14.203		
	Total	5684.282	326			
DET	Between Groups	152509.898	4	38127.475	6.515	0
	Within Groups	1755701.404	300	5852.338		
	Total	1908211.303	304			
INVERT	Between Groups	3396.691	4	849.173	7.725	0
	Within Groups	34296.944	312	109.926		
	Total	37693.635	316			
EMB	Between Groups	0.556	4	0.139	3.12	0.015
	Within Groups	13.942	313	0.04454		
	Total	14.497	317			
DTE	Between Groups	261734.313	4	65433.578	40.21	0
	Within Groups	504455.687	310	1627.276		
	Total	766190	314			

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Summary Statistics: Riffle Habitats By Trip

<0.06 mm	1	2	TRIP 3	4	5
1		1.00	0.99	1.00	0.01
2	1.00		0.99	1.00	0.01
TRIP 3	0.99	0.99		1.00	0.20
4	1.00	1.00	1.00		0.01
5	0.01	0.01	0.20	0.01	

0.063-0.25 mm	1	2	TRIP 3	4	5
1		0.98	0.31	1.00	0.02
2	0.98		0.59	0.99	0.11
TRIP 3	0.31	0.59		0.37	0.99
4	1.00	0.99	0.37		0.02
5	0.02	0.11	0.99	0.02	

0.25-0.50 mm	1	2	TRIP 3	4	5
1		0.21	0.76	0.94	1.00
2	0.21		1.00	0.03	0.15
TRIP 3	0.76	1.00		0.40	0.64
4	0.94	0.03	0.40		1.00
5	1.00	0.15	0.64	1.00	

0.5-4.0 mm	1	2	TRIP 3	4	5
1		0.00	0.82	0.91	1.00
2	0.00		0.27	0.00	0.00
TRIP 3	0.82	0.27		0.44	0.84
4	0.91	0.00	0.44		0.94
5	1.00	0.00	0.84	0.94	

4.0-12.5 mm	1	2	TRIP 3	4	5
1		0.00	0.03	0.01	0.01
2	0.00		0.93	0.36	0.70
TRIP 3	0.03	0.93		0.99	1.00
4	0.01	0.36	0.99		1.00
5	0.01	0.70	1.00	1.00	

>12.5 mm	1	2	TRIP 3	4	5
1		0.00	0.03	0.98	0.09
2	0.00		0.79	0.00	0.08
TRIP 3	0.03	0.79		0.08	0.91
4	0.98	0.00	0.08		0.22
5	0.09	0.08	0.91	0.22	

D50	1	2	TRIP 3	4	5
1		0.29	0.97	0.00	0.49
2	0.29		0.24	0.67	1.00
TRIP 3	0.97	0.24		0.01	0.37
4	0.00	0.67	0.01		0.63
5	0.49	1.00	0.37	0.63	

D16	1	2	TRIP 3	4	5
1		0.82	0.60	0.82	0.98
2	0.82		0.98	0.22	0.99
TRIP 3	0.60	0.98		0.17	0.90
4	0.82	0.22	0.17		0.57
5	0.98	0.99	0.90	0.57	

D84	1	2	TRIP 3	4	5
1		0.52	0.40	0.82	0.99
2	0.52		0.03	0.98	0.90
TRIP 3	0.40	0.03		0.08	0.26
4	0.82	0.98	0.08		0.99
5	0.99	0.90	0.26	0.99	

DETRITUS	1	2	TRIP 3	4	5
1		1.00	0.40	1.00	0.03
2	1.00		0.52	1.00	0.02
TRIP 3	0.40	0.52		0.38	0.00
4	1.00	1.00	0.38		0.01
5	0.03	0.02	0.00	0.01	

CHLOROPHYLL A	1	2	TRIP 3	4	5
1		0.00	0.00	0.00	0.00
2	0.00		0.01	0.10	0.06
TRIP 3	0.00	0.01		0.94	0.99
4	0.00	0.10	0.94		1.00
5	0.00	0.06	0.99	1.00	

EMBEDDEDNESS	1	2	TRIP 3	4	5
1		0.05	0.05	0.02	0.41
2	0.05		1.00	1.00	0.78
TRIP 3	0.05	1.00		1.00	0.86
4	0.02	1.00	1.00		0.73
5	0.41	0.78	0.86	0.73	

Summary Statistics: Riffle Habitats By Trip

INVERTEBRATES	1	2	TRIP 3	4	5
1		0.02	0.01	1.00	0.00
2	0.02		1.00	0.01	1.00
TRIP 3	0.01	1.00		0.00	1.00
4	1.00	0.01	0.00		0.00
5	0.00	1.00	1.00	0.00	

DTE	1	2	TRIP 3	4	5
1		0.00	0.00	0.00	0.33
2	0.00		0.48	0.29	0.00
TRIP 3	0.00	0.48		1.00	0.00
4	0.00	0.29	1.00		0.00
5	0.33	0.00	0.00	0.00	

Summary Statistics: Run Habitats By Trip

		Sum of Squares	df	Mean Square	F	Sig.
<0.063 mm	Between Groups	0.08529	4	0.02132	7.177	0.000
	Within Groups	0.692	233	0.002971		
	Total	0.777	237			
.063-.25 mm	Between Groups	1.876	4	0.469	13.879	0.000
	Within Groups	7.873	233	0.03379		
	Total	9.748	237			
.25-.50 mm	Between Groups	0.458	4	0.115	6.199	0.000
	Within Groups	4.306	233	0.01848		
	Total	4.764	237			
.50-4.0 mm	Between Groups	2.169	4	0.542	21.701	0.000
	Within Groups	5.821	233	0.02498		
	Total	7.99	237			
4.0-12.5 mm	Between Groups	0.188	4	0.04696	5.181	0.001
	Within Groups	2.112	233	0.009064		
	Total	2.3	237			
>12.5 mm	Between Groups	2.208	4	0.552	6.713	0.000
	Within Groups	19.159	233	0.08223		
	Total	21.366	237			
D50	Between Groups	25538.923	4	6384.731	4.218	0.003
	Within Groups	340605.455	225	1513.802		
	Total	366144.378	229			
D16	Between Groups	8336.05	4	2084.013	3.612	0.007
	Within Groups	129807.08	225	576.92		
	Total	138143.13	229			
D84	Between Groups	119287.054	4	29821.763	4.48	0.002
	Within Groups	1497643.469	225	6656.193		
	Total	1616930.523	229			
CHLA	Between Groups	486.008	4	121.502	24.039	0.000
	Within Groups	1602.262	317	5.054		
	Total	2088.27	321			
DET	Between Groups	19664.561	4	4916.14	4.707	0.001
	Within Groups	290359.223	278	1044.458		
	Total	310023.785	282			
INVERT	Between Groups	261.159	4	65.29	8.073	0.000
	Within Groups	2385.708	295	8.087		
	Total	2646.867	299			
EMB	Between Groups	3.029	4	0.757	8.456	0.000
	Within Groups	26.598	297	0.08956		
	Total	29.628	301			
DTE	Between Groups	54802.121	4	13700.53	2.638	0.034
	Within Groups	1537454.69	296	5194.104		
	Total	1592256.811	300			

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Summary Statistics: Run Habitats By Trip

<0.06 mm	1	2	TRIP 3	4	5
1		1.00	0.69	0.00	0.00
2	1.00		0.62	0.00	0.00
TRIP 3	0.69	0.62		0.60	0.40
4	0.00	0.00	0.60		0.98
5	0.00	0.00	0.40	0.98	

0.063-0.25 mm	1	2	TRIP 3	4	5
1		0.93	0.00	0.06	0.00
2	0.93		0.00	0.00	0.00
TRIP 3	0.00	0.00		0.01	0.55
4	0.06	0.00	0.01		0.17
5	0.00	0.00	0.55	0.17	

0.25-0.50 mm	1	2	TRIP 3	4	5
1		0.92	0.00	0.96	0.97
2	0.92		0.00	1.00	0.60
TRIP 3	0.00	0.00		0.00	0.00
4	0.96	1.00	0.00		0.66
5	0.97	0.60	0.00	0.66	

0.5-4.0 mm	1	2	TRIP 3	4	5
1		0.00	1.00	0.99	0.98
2	0.00		0.00	0.00	0.00
TRIP 3	1.00	0.00		1.00	1.00
4	0.99	0.00	1.00		1.00
5	0.98	0.00	1.00	1.00	

4.0-12.5 mm	1	2	TRIP 3	4	5
1		0.75	0.00	0.01	0.11
2	0.75		0.04	0.22	0.73
TRIP 3	0.00	0.04		0.65	0.37
4	0.01	0.22	0.65		0.96
5	0.11	0.73	0.37	0.96	

>12.5 mm	1	2	TRIP 3	4	5
1		0.00	0.00	0.33	0.04
2	0.00		0.54	0.20	0.92
TRIP 3	0.00	0.54		0.01	0.19
4	0.33	0.20	0.01		0.76
5	0.04	0.92	0.19	0.76	

D50	1	2	TRIP 3	4	5
1		0.09	0.00	0.81	0.19
2	0.09		0.45	0.50	1.00
TRIP 3	0.00	0.45		0.03	0.46
4	0.81	0.50	0.03		0.69
5	0.19	1.00	0.46	0.69	

D16	1	2	TRIP 3	4	5
1		0.78	0.03	0.22	0.02
2	0.78		0.26	0.92	0.24
TRIP 3	0.03	0.26		0.59	1.00
4	0.22	0.92	0.59		0.61
5	0.02	0.24	1.00	0.61	

D84	1	2	TRIP 3	4	5
1		0.80	0.00	0.98	0.99
2	0.80		0.07	0.40	0.98
TRIP 3	0.00	0.07		0.00	0.03
4	0.98	0.40	0.00		0.87
5	0.99	0.98	0.03	0.87	

DETRITUS	1	2	TRIP 3	4	5
1		0.96	0.02	0.04	0.95
2	0.96		0.06	0.11	1.00
TRIP 3	0.02	0.06		1.00	0.03
4	0.04	0.11	1.00		0.07
5	0.95	1.00	0.03	0.07	

CHLOROPHYLL A	1	2	TRIP 3	4	5
1		0.00	0.00	0.00	0.00
2	0.00		0.05	0.58	0.00
TRIP 3	0.00	0.05		0.70	0.21
4	0.00	0.58	0.70		0.01
5	0.00	0.00	0.21	0.01	

EMBEDDEDNESS	1	2	TRIP 3	4	5
1		0.75	0.00	0.94	0.02
2	0.75		0.00	0.23	0.00
TRIP 3	0.00	0.00		0.02	0.98
4	0.94	0.23	0.02		0.11
5	0.02	0.00	0.98	0.11	

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Summary Statistics: Run Habitats By Trip

INVERTEBRATES	1	2	TRIP 3	4	5
1		0.21	0.00	0.66	0.00
2	0.21		0.36	0.88	0.10
TRIP 3	0.00	0.36		0.02	0.95
4	0.66	0.88	0.02		0.00
5	0.00	0.10	0.95	0.00	

DTE	1	2	TRIP 3	4	5
1		0.32	0.93	0.91	0.04
2	0.32		0.74	0.76	0.92
TRIP 3	0.93	0.74		1.00	0.17
4	0.91	0.76	1.00		0.18
5	0.04	0.92	0.17	0.18	