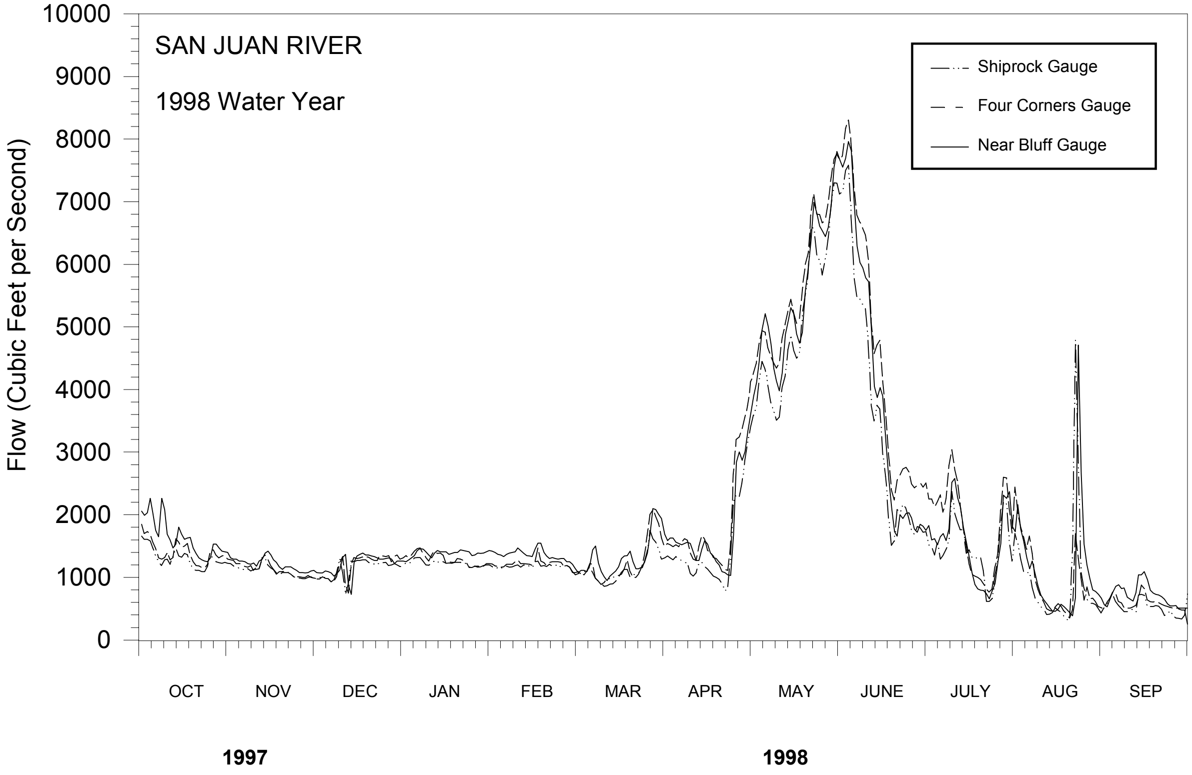
DOWNSTREAM TRANSPORT RATES OF PASSIVELY DRIFTING PARTICLES IN THE SAN JUAN RIVER IN 1998

Final Report



Robert K. Dudley and Steven P. Platania

Division of Fishes, Museum of Southwestern Biology
Department of Biology, University of New Mexico
Albuquerque, New Mexico 87131

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EXECUTIVE SUMMARY

Colorado pikeminnow is a federally endangered species that has declined throughout its historical range which includes the San Juan River Basin. A factor that has been hypothesized to have contributed to the loss of Colorado pikeminnow is the downstream transport of their drifting larvae into unsuitable habitats. Until recently, the lack of a suitable drift material has precluded quantitative testing of this hypothesis. Passively drifting particles (=beads) were used as surrogates for drifting larval Colorado pikeminnow. Their rate of downstream transport (drift) was measured in July 1998 through different reaches of the San Juan River at moderate flows (ca. 2,000 cfs). The transport rates of beads were measured over 130 river kilometers (from upstream of Four Corners, Colorado to Mexican Hat, Utah) in the San Juan River.

The similarity of transport rates between reaches indicated that habitat differences between sites selected probably were not great enough to cause notable changes in travel rates. The spatial dominance of high velocity mesohabitats (90-95%) throughout the study area may have negated subtle changes in channel width, sinuosity, channel slope, and the abundance of lower velocity habitats between sites. The consistent and rapid downstream displacement of passively drifting particles resulted in a total travel time of less than two days from the top of the study area to below Mexican Hat, Utah. Particle transport time in the Mexican Hat to Lake Powell reach (typified by a steeper gradient, confined river channel, low sinuosity, and an increased abundance of higher velocity mesohabitats) was hypothesized to be about one day. This study indicates that drifting larval Colorado pikeminnow will be transported from the spawning bar to Lake Powell in about three days.

Changes in river morphology and flow patterns in the San Juan River over the past century and especially since the operation of Navajo Dam in 1962 have led to narrowing of the river channel and floodplain, deepening of the main channel, reduction of the abundance of secondary channels, increased stabilization of channel banks, and loss of lower velocity habitats. The results of this study, fragmentation of the San Juan River, and the aforementioned changes, provide insight as to the causative mechanisms that have resulted in a severe reduction in the cohort size of early life stages of Colorado pikeminnow in the San Juan River.

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INTRODUCTION

Colorado pikeminnow (*Ptychocheilus lucius*) is a federally endangered species (U.S. Department of the Interior, 1974) endemic to the Colorado River basin where it was once abundant and widespread (Tyus, 1991). Populations in the lower basin appear to be extirpated as no individuals have been reported there since the 1960s (Minckley and Deacon, 1968; Minckley, 1973; Moyle, 1976). The Green River sub-basin apparently retains the majority of the remaining individuals (Holden and Wick, 1982; Bestgen et al., 1998). Colorado pikeminnow now occupies about 20% of its historical range (Tyus, 1990). A small but self-sustaining population of this species occurs in the San Juan River but is confined to about the lowermost 230 river kilometers (i.e., downstream of Cudei Diversion Dam to the inlet of Lake Powell Reservoir). The decline of this and other native fishes in the San Juan River has been attributed to flow modifications and the resultant changes to the thermal regime, instream barriers, and nonnative predation/competition for habitat and resources (Vanicek and Kramer, 1969; Holden and Wick, 1982; Tyus, 1991).

Studies in the Upper Colorado River Basin (Yampa and Green rivers) indicate that Colorado pikeminnow spawn as spring runoff is receding and at water temperatures between 18-20^{o}C (Haynes et al., 1984; Nesler et al., 1988). Females produce demersal adhesive eggs that attach to the substrata (Toney, 1974) and eggs take approximately 3.5-6 days to hatch at water temperatures of 20-22^{o}C (Hamman, 1981). Following incubation, larvae drift passively downstream from spawning beds. Inflation of swim bladder occurs in larvae about one to three days after hatching and exogenous feeding begins three to six days post-hatching (Bestgen and Williams, 1994). These two physiological states (swim bladder inflation and exogenous feeding) are generally considered indicative of the end of the drift stage in larval fishes as individuals have attained horizontal mobility and can seek foraging habitats.

Bestgen and Williams (1994) demonstrated that Colorado pikeminnow hatching, survival, and larval growth rates were correlated with water temperature. Times to start of hatch, swim bladder inflation, and exogenous feeding increased with decreasing water temperatures. Childs and Clarkson (1996) reported low water temperatures (< 20^{o}C) from hypolimnetic releases significantly reduced the prolonged swimming ability of larval Colorado pikeminnow. This probably results in lower survivorship of pikeminnow.

Drift studies of Colorado pikeminnow have yielded indirect evidence that larvae may be transported long distances (hundreds of km) from spawning areas (Haynes et al., 1984; Tyus and Haines, 1991). Researchers have also demonstrated the tenure that larvae remain a component of the drift is dependent on developmental rate which, in turn, is dependent on water temperature. The distance larval Colorado pikeminnow drift is dependent on water velocity and channel complexity in addition to the aforementioned factors. However, none of the previous studies were designed to the determine, quantitatively, the downstream travel rate of larvae or magnitude of displacement from potential spawning areas.

A means to quantify the rate and magnitude of downstream transport of larvae is to release a known number of particles whose physical properties are similar to those of passively drifting larvae in the river and capture those particles at downstream sites. Passively drifting particles which met this requirement were developed by researchers at the University of New Mexico and previously used to examine the downstream displacement of passively drifting eggs of several Rio Grande basin cyprinids (Dudley and Platania, 1999). Field trials indicated that these approximately neutrally buoyant particles also closely mimicked the downstream transport of drifting fish larvae.

A principal factor resulting in the low abundance of Colorado pikeminnow in the San Juan River appears to be the displacement of its larvae into downstream riverine habitats and Lake Powell. The ability to quantify the downstream displacement of drifting larval fishes at various discharges and between study reaches has been deemed critical to understanding the autecology of this species. The development of these passively drifting particles provides a mechanism to test these assumptions in discrete river reaches and under different hydrologic regimes. Tracking movement of these particles would provide preliminary empirical information on rates of downstream transport and the potential fate of drifting larval Colorado pikeminnow larvae.

Passively drifting particles were released simultaneously and subsequently collected at five locations in the San Juan River in July 1998. The objectives of this investigation were to acquire, through empirical field data, a preliminary assessment of the rate of downstream displacement of drifting particles (surrogates for larval Colorado pikeminnow) between study sites and correlate downstream transport rates with hydrology and river morphology. These objectives met goals 5.3.5 (Characterize fish community response to different annual flow regimes) and 5.3.6 (Identify limiting factors for the endangered and other native fishes) as defined in the San Juan River Basin Recovery Implementation Program document. This approach and data set will ultimately provide resource managers a tool necessary to make more informed decisions regarding water release patterns and habitat modifications in the San Juan River.

STUDY AREA

The San Juan River is a major tributary of the Colorado River and drains 99,200 km^2 in Colorado, New Mexico, Utah, and Arizona (Figure 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 before confluencing with the Colorado River. The major perennial tributaries to the San Juan River are (from upstream to downstream) Navajo, Piedra, Los Pinos, Animas, La Plata, and Mancos rivers, and McElmo Creek. In addition there are numerous ephemeral arroyos and washes that contribute relatively little flow annually but input large sediment loads.

Navajo Reservoir, completed in 1963, impounds and isolates the upper 124 km of the San Juan River and regulates downstream discharge. The completion of Glen Canyon Dam in 1966 and subsequent filling of Lake Powell ultimately inundated the lower 87 km of the San Juan River by the early 1980s. The San Juan River is now a 359 km lotic system bounded by two reservoirs (Navajo Reservoir near its head and Lake Powell at its mouth).

The San Juan River is canyon-bound and restricted to a single channel between its confluence with Chinle Creek (ca. 20 km downstream of Bluff, Utah) and Lake Powell. The river is predominately multi-channeled upstream of Chinle Creek with the highest density of secondary channels occurring between Bluff and the Hogback Diversion (ca. 13 km upstream of Shiprock, New Mexico). There is a general downstream decline in channel stability in the section of river between Bluff and Shiprock. Below the confluence with the Animas River near Farmington, New Mexico, the channel is less stable and more subject to floods from it largest and unregulated tributary, the Animas

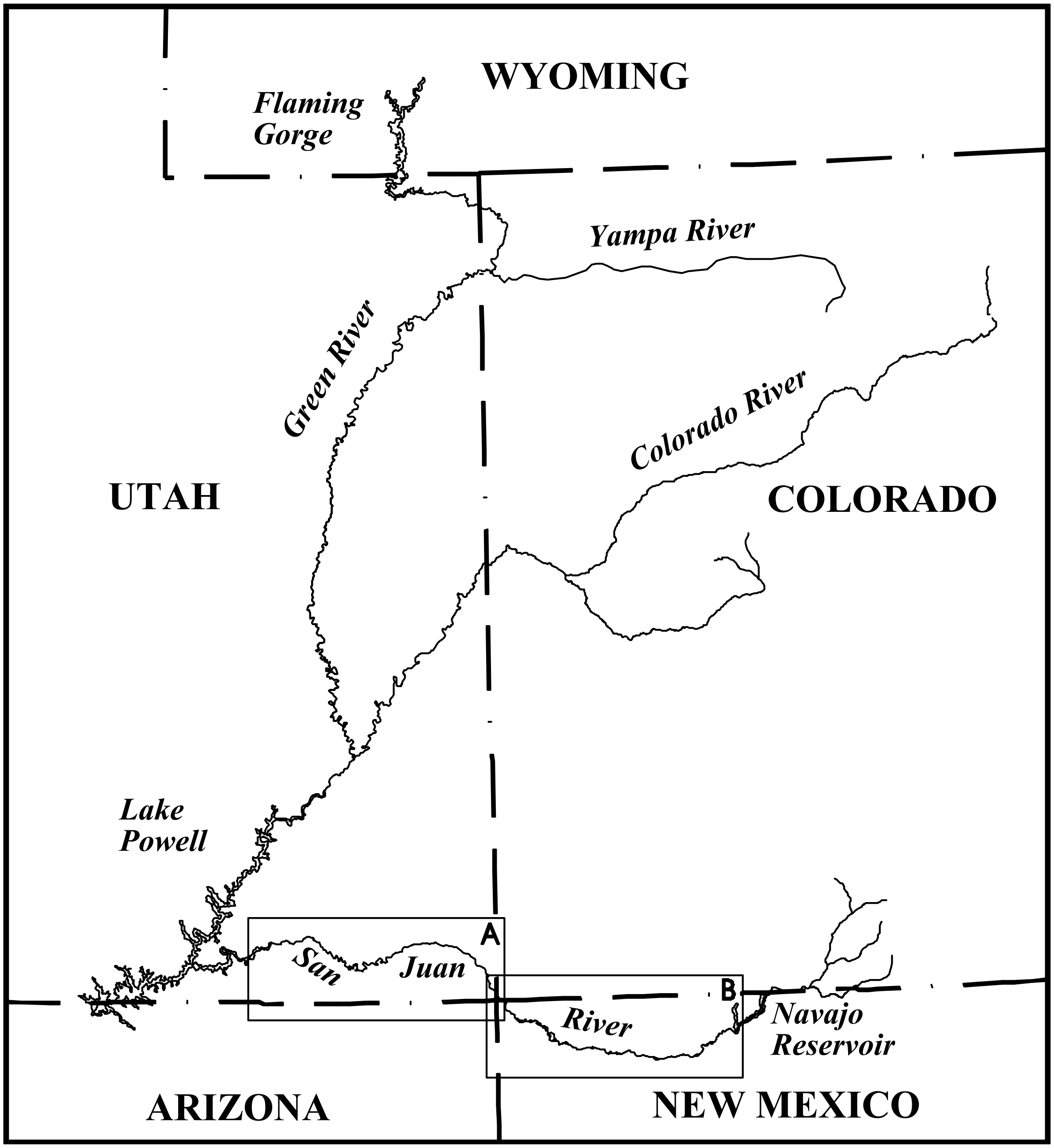

Figure 1. Location map of the San Juan River (A=lower reaches, B=upper reaches).

River. Conversely, the regulated reach of river between Farmington, New Mexico and Navajo Dam is relatively stable with few secondary channels.

From Lake Powell to Navajo Dam, the mean gradient of the San Juan River is 1.67 $m \bullet km^{-1}$. Examined in 30 km increments, river gradient ranges from 1.24 to 2.41 $m \bullet km^{-1}$ but locally (i.e., <30 km reaches) can be as high as 3.5 $m \bullet km^{-1}$. Between Shiprock and Bluff, San Juan River substrate is primarily sand mixed among some cobble. The proportion of sand is greatest in the downstream most reaches and declines along an upstream gradient. From Farmington to Navajo Dam, the San Juan River substrate is dominated by embedded cobble. Although less embedded, cobble is also the most common substrate between Shiprock and Farmington.

Except in canyon-bound reaches, the river is bordered by nonnative salt cedar (*Tamarix chinensis*) and Russian olive (*Elaeagnus angustifolia*) and native cottonwood (*Populus fremontii*) and willow (*Salix* sp.). Nonnative woody plants dominated nearly all sites and resulted in heavily stabilized banks. Cottonwood and willow accounted for less than 15% of the riparian vegetation.

The characteristic annual hydrographic pattern in the San Juan River is typical of rivers in the American Southwest with large flows during spring snowmelt, followed by low summer, autumn, and winter base flows. Summer and early autumn base flows are frequently punctuated by convective storm-induced flow spikes. Prior to closure of Navajo Dam, about 73% of the total annual San Juan River drainage discharge (based on USGS Gauge # 09379500; Near Bluff, Utah) occurred during spring runoff (1 March through 31 July). 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, 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 the magnitude and frequency of these storm induced flow spikes are greater than those recorded in the Green or Colorado rivers.

Closure of Navajo Dam altered the annual discharge pattern of the San Juan River. The natural flow of the Animas River ameliorated some aspects of regulated discharge by augmenting spring discharge. Regulation resulted in reduced magnitude and increased duration of spring runoff in wet years and substantially reduced magnitude and duration of spring flow 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. Conversely, post-dam base flow increased markedly over pre-dam base flows.

Since 1992, Navajo Dam has been operated to mimic a “natural” San Juan River hydrograph with the volume of release during spring linked to the amount of precipitation recorded 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 those between 1964-1991.

The primary study area for most investigations 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. There is considerable human activity within the floodplain of the San Juan River between Shiprock and Navajo Dam. Irrigated agriculture is practiced throughout this portion of the San Juan River Valley and adjacent 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 Animas River Valley is similarly developed. Small portions of the river valley and uplands from Shiprock to Bluff are farmed with dispersed livestock grazing as the primary land use. In the vicinity of Montezuma Creek and Aneth, petroleum extraction occurs in the floodplain and adjacent uplands. There are few human-caused modifications of the system from Bluff to Lake Powell.

A multivariate analysis of a suite of geomorphic features of the San Juan drainage was performed to segregate the river into distinct geomorphic reaches, enhance comparison between studies, and to provide a common reference for all research. This effort (Bliesner and Lamarra, 1999) resulted in the identification of eight reaches of the San Juan River between Lake Powell and Navajo Dam. A brief characterization of each reach (from downstream to upstream) follows.

Reach 1 (RM 0 to 16, Lake Powell confluence to near Slickhorn Canyon) has been greatly influenced by 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 this reach since the reservoir first filled in 1980. This deposition of suspended sediment into the delta-like environment of the river/reservoir transition makes it the lowest-gradient reach in the river. This portion of the river is canyon bound with an active sand bottom. Although an abundance of low-velocity habitat is present at certain flows, it is highly ephemeral, being influenced by both river flow and Lake Powell's elevation.

Reach 2 (RM 17 to 67, near Slickhorn Canyon to confluence with Chinle Creek) is also canyon bound but is upstream of the influence of Lake Powell. The gradient in this reach is greater than in either adjacent reach and the fourth highest in the system. The channel is primarily bedrock confined and influenced by debris fans at ephemeral tributary mouths. Riffle-type habitat dominates, and the only major rapids in the San Juan River occur in this reach. Backwater abundance is low in this reach, usually occurring in association with 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. While this reach has the second greatest density of backwater habitats after peak spring runoff, it is extremely vulnerable to change during summer and autumn storm events. After these storm events, this reach may have the second lowest density of backwaters of the eight reaches. The active channel distributes debris piles throughout the reach following spring runoff, leading to the nickname "Debris Field".

Reach 4 (RM 107 to 130, Aneth, Utah, to below "the Mixer") is a transitional zone between the upper cobble substrate-dominated reaches and the lower sand substrate-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 habitats are 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 and greatest secondary channel area of any of the reaches. Secondary channels in this section tend to be longer and more stable (but fewer) than in Reach 3. 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 are 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 are the dominant substrata with cobble bars containing clean interstitial spaces being most abundant in this reach. 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 containing fewer of these habitats. The channel has been altered by dike construction in several areas 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 that of 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 primarily 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 Gobernador 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 water temperatures. These cool, clear water conditions have allowed development of an intensively managed blue-ribbon trout fishery to the exclusion of native species in the uppermost portion of the reach.

The uppermost site (UFC) on the San Juan River (Figure 2) during this project was 9.4 km upstream [RM 133.4; *bottom of Reach 5*] of the Four Corners drift station. Drifting particles were released from this site but were not collected there. The next downstream locality (RM 127.5; *top of Reach 4*) was the Four Corners drift station (FCD); this sampling locality was only used to collect particles released from UFC. Passively drifting particles were collected at the Four Corners bridge sampling station (FCB). This site was located about 0.3 km downstream of Four Corners bridge (RM 119.0; *middle of Reach 4*) and was 13.8 km downstream of FCD. Particles were released from Four Corners Bridge, because of better access to the middle of the river channel, and subsequently collected at the next three downstream sampling localities. The next sampling station (ANE) was established 32.6 km downstream of FCB just west of Aneth, UT (RM 98.7; *top of Reach 3*). Particles were released from a footbridge just upstream (RM 100.9; *top of Reach 3*) of ANE. The Bluff, UT sampling station (BLF) was 36.6 km downstream (RM 75.9; *bottom of Reach 3*) of ANE. The BLF site was located about 100 m downstream of US Highway 191 bridge crossing; particles were released from the bridge. The final sampling station (MEX) was located near Mexican Hat, UT (RM 52.4; *top of Reach 2*) and was 37.9 km downstream of the previous site. The MEX site was only used for the collection of drifting particles.

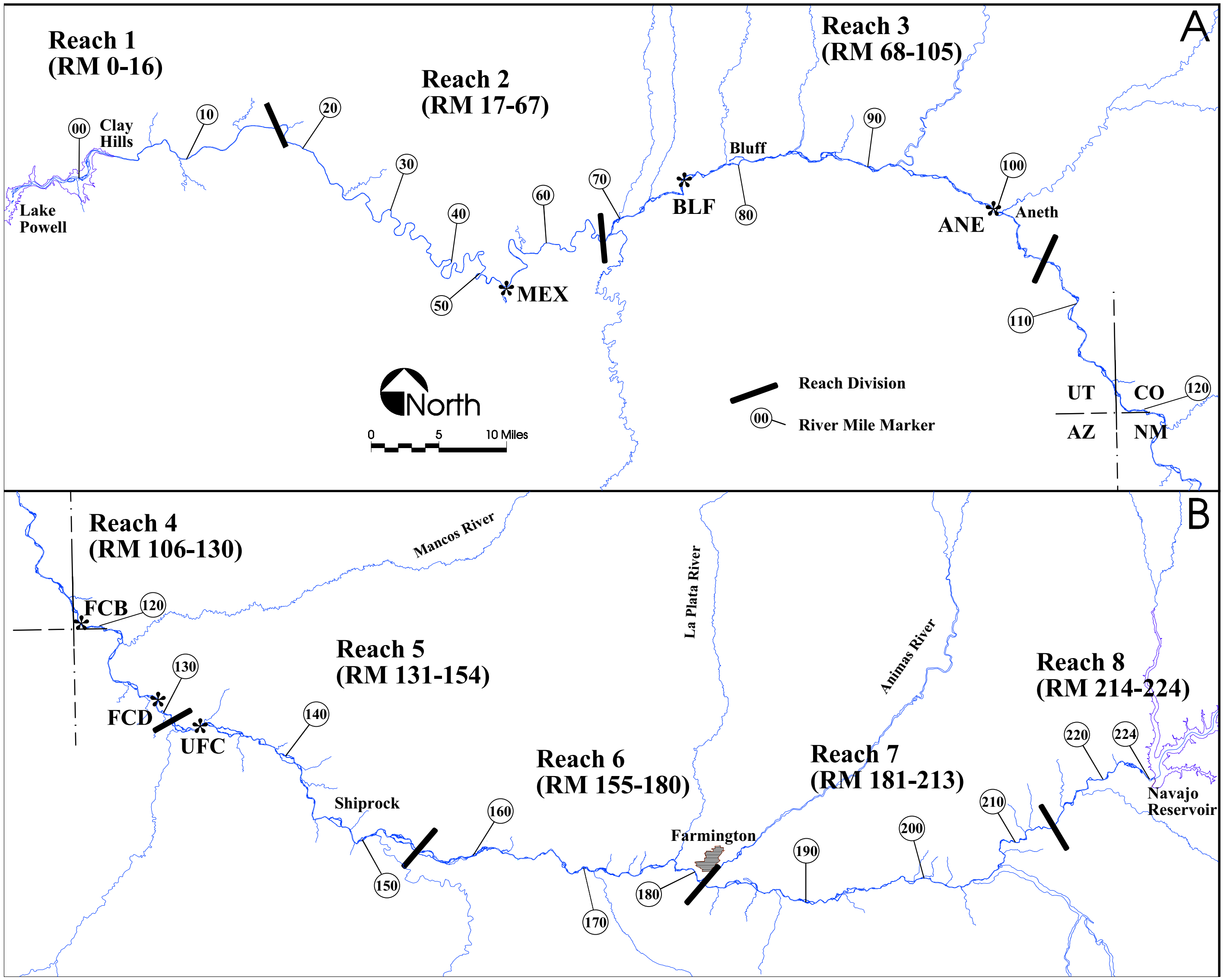

Figure 2. Study Area in the San Juan River (see Table 1 for site codes)..

METHODS

Information on the downstream transport of larval Colorado pikeminnow was obtained by releasing, and subsequently capturing, passively drifting particles (=beads) from six pre-selected localities. Releases of beads were made at multiple sites to provide greater resolution of reach-specific transport rates. Drifting particles used were nontoxic modified nylon 12 thermoplastic cylinders about 2.5 mm in diameter and length (Dudley and Platania, 1999). The specific gravity (SG =a dimensionless measure) of the beads (SG=1.005) was nearly that of water (SG=1.000) and as such, beads were almost neutrally buoyant.

Mean mass of an individual bead (0.01795 g ± 0.0001 g) was determined from 91 samples comprising 148,319 enumerated beads. The total mass of each bag (ca. 25 kg) of passively drifting particles was determined to the nearest 0.0001 g and divided by the mean individual mass to provide an estimate of the total number of particles per bag. These values were ultimately used to determine the total number of drifting particles released at each site.

Drifting particles were released simultaneously at 06:00 on 27 July 1998 at four sites (UFC, FCB, ANE, and BLF) on the San Juan River (Table 1). White beads were released from the site above the Four Corners drift station (UFC) and collected at FCD, FCB, ANE, BLF, and MEX. Neon-yellow particles were released at the Four Corners bridge site (FCB) and collected at ANE, BLF, and MEX. Black particles were released at the Aneth site (ANE) and collected at BLF and MEX. Two colors of beads, greenish-yellow and royal blue, were released at the Bluff site (BLF) and subsequently collected at MEX.

Passively drifting particles were collected with Moore Egg Collectors following the procedures described in Altenbach et al. (2000). Sampling began soon after the initial release of beads. However, once the first bead was collected, an intensive data collection regime, consisting of continuous 15-min interval samples, (i.e., 96 samples were collected during every 24 h sampling period) was initiated. Collection information recorded every 15 min included unique alphanumeric designation of the sample, start and stop times, start and stop flowmeter readings, and presence or absence of beads and fish. All beads collected during sampling were retained and stored in individual 20 ml scintillation vials containing a waterproof tag inscribed with the alphanumeric code that

Table 1. Schedule of releases and collections of passively drifting particles conducted in the San Juan River.

REACH	CODE and River Mile	DISTANCE [1] (km)	Color and # released [2]	Release [4] and Collection [5]	Sampling Duration (hours)
SITE					
UPSTREAM OF FOUR CORNERS DRIFT STATION	UFC 133.4	0	white 6.04	■	——
FOUR CORNERS DRIFT STATION	FCD 127.5	9.4	——	●	17.00
FOUR CORNERS BRIDGE	FCB 119.0	23.1	neon-yellow 3.35	■ ●	24.75
ANETH	ANE 98.7	55.7	black 3.37	■ ●	27.75
BLUFF	BLF 75.9	92.4	green-yellow 1.46 royal blue 1.39	■ ●	26.50
MEXICAN HAT	MEX 52.4	130.3	——	●	58.50
LAKE POWELL RESERVOIR [3]	—— 0	214.6	——	——	——
TOTAL	——	214.6	15.61	——	154.50

[1] indicates distance (in km) from UPSTREAM OF FOUR CORNERS DRIFT STATION (upstream-most release site)

[2] indicates the number (in millions) of drifting particles released at that site

[3] this site was not within the study area of this investigation but is included as a point of reference

[4] ■ indicates particle release site

[5] ● indicates particle collection station

corresponded with that sample. Volume of water sampled was determined with a mechanical flowmeter and recorded for each sampling interval.

The catch-per-unit-effort (CPUE) of passively drifting particles was calculated as the total number of beads collected • volume of water sampled^{-1}• sample interval^{-1} (i.e., N[beads]• m^{3} water^{-1} •15 min^{-1}). The "first arrival" rate of travel was the longitudinal river distance travelled by beads divided by the time required for the first particle to arrive at the collecting locality (km • h^{-1}). This value is considered indicative of the maximum rate of downstream transport. The "50% rate" of travel was also the longitudinal distance travelled by passively drifting particles but was divided by the time necessary for 50% of particles to arrive at the collecting locality (km • h^{-1}). This latter value was considered a surrogate (as opposed to statistical) mean transport rate. It could not be calculated until after all of the collection data had been processed.

This study was conducted during summer base flows that were occasionally elevated by rain events (Figure 3). Daily mean steam flow on 27 July 1998 was 1,750 cfs at the U.S. Geological Survey (USGS) Shiprock, New Mexico Gauge (# 09368000), 2,110 cfs at the USGS Four Corners, Colorado Gauge (# 09371010), and 1,680 cfs at the USGS Near Bluff, Utah Gauge (#09379500). Downstream travel rates between each of the study sites were largely based on data collected on 27 July 1998 as local rainstorms began to noticeably affect stream flows by 28 July 1998 (Figure 4).

RESULTS

The rate and magnitude of downstream displacement of drifting particles was rapid during the July 1998 test, conducted at moderate (ca. 2,000 cfs) flow, on the San Juan River (Figure 5). Sampling efforts revealed a relatively consistent temporal pattern of bead catch rate at each site. Soon (15-30 min) after the arrival of the first bead, there was a rapid and sustained (one-three h) increase in bead CPUE. The marked influx of drifting particles was followed by a slow and gradual decline, over the remainder of the study, in the numbers of beads collected. The magnitude of this increase and decrease in catch rates was more pronounced the closer the collection site was to the point of release.

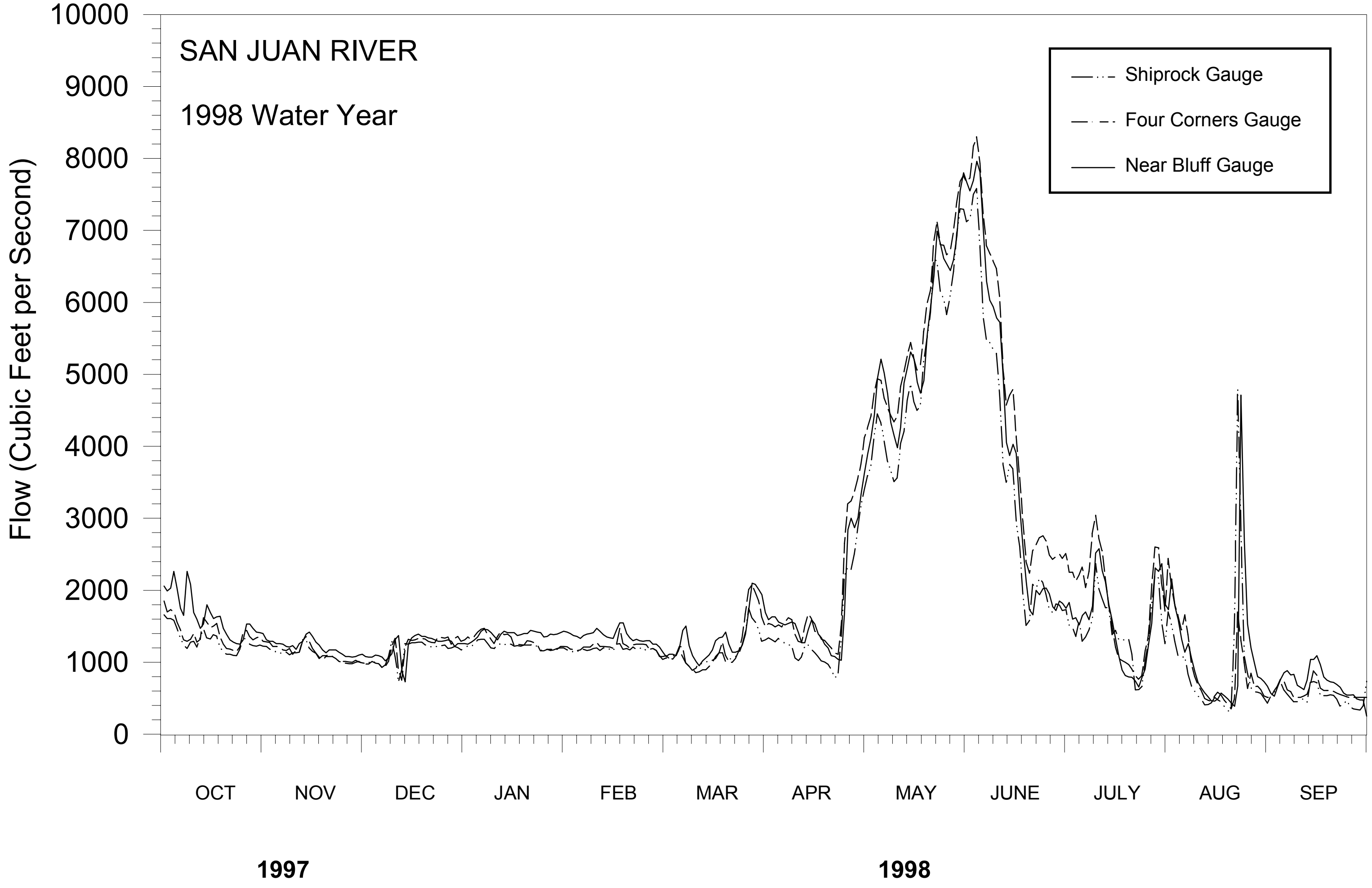

Figure 3. Hydrograph of the San Juan River at Shiprock, NM, Four Corners, CO, and Near Bluff, UT for the 1998 water year.

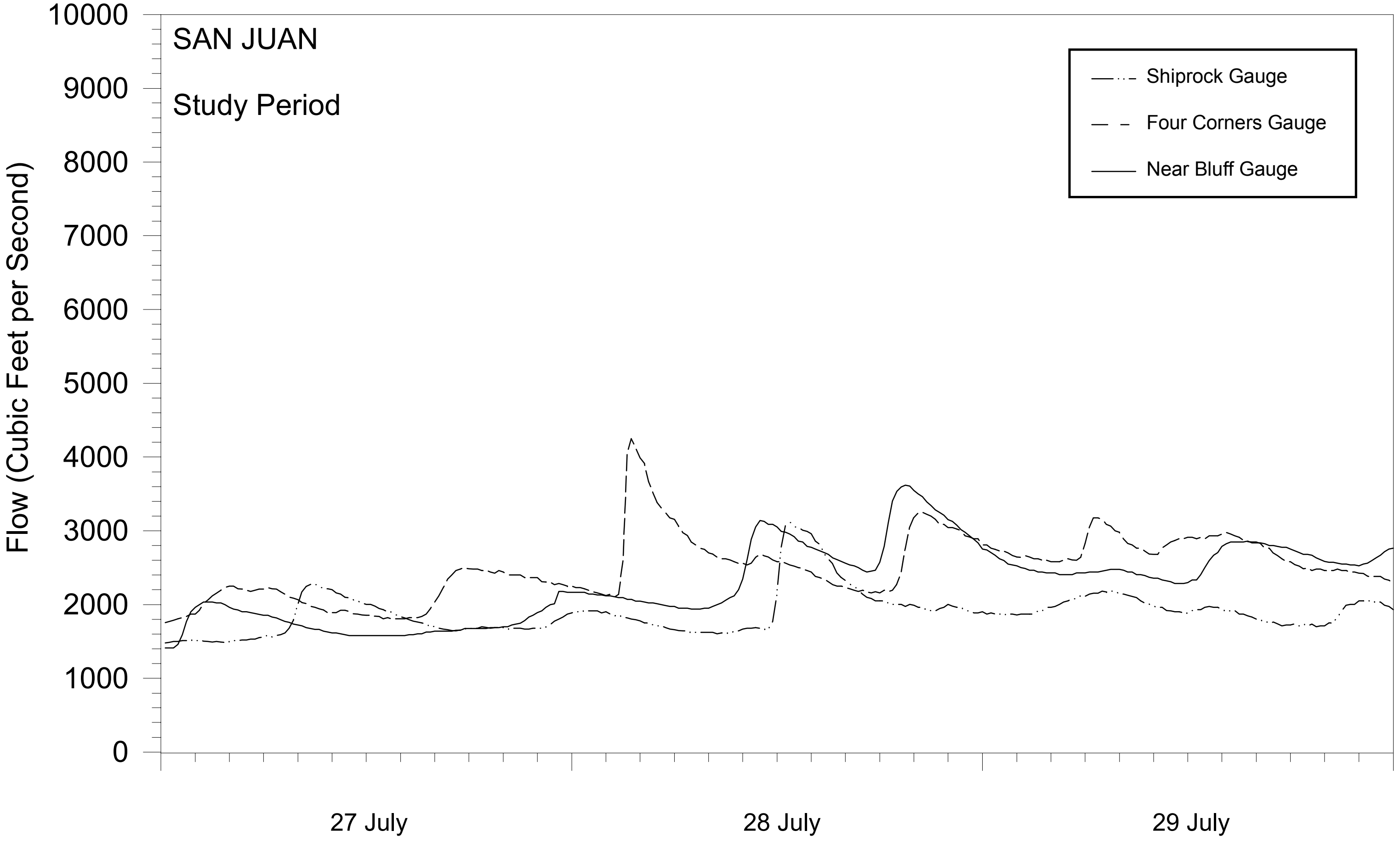

Figure 4. Hydrograph of the San Juan River at Shiprock, NM, Four Corners, CO, and Near Bluff, UT for the study period.

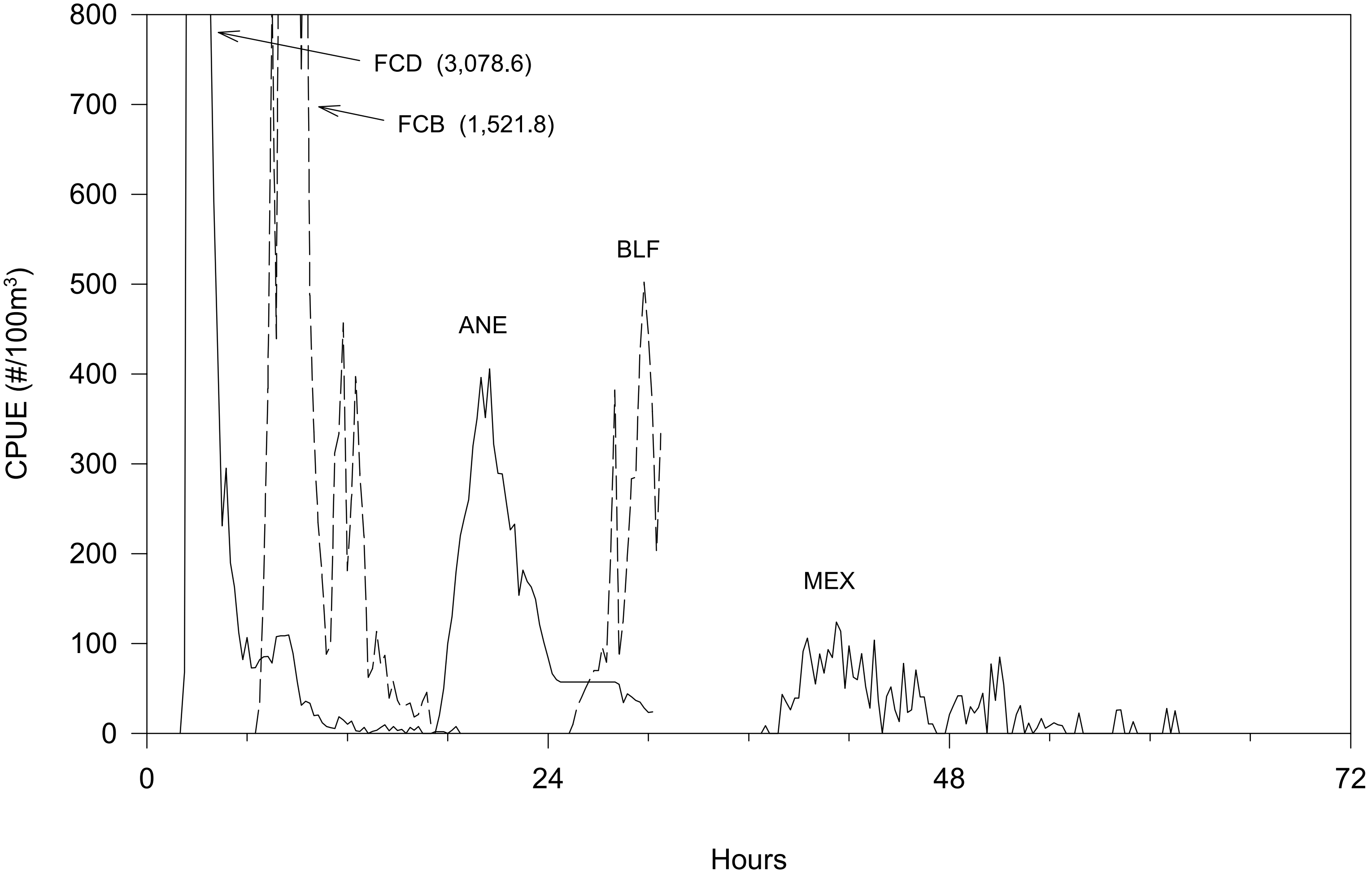

Figure 5. Travel time and dispersion of passively drifting particles released from above Four Corners drift station (RM 134) at five downstream localities.

Detecting the end of the white bead release was not possible at BLF or MEX due to a rainstorm event that resulted in dramatically higher stream flow (ca. 4,000 cfs) throughout the study area and premature termination of sampling (because of unsafe conditions). The increased flow also influenced catch rates and downstream transport times of white beads to BLF and MEX, and neon-yellow beads to MEX. The 50% rates of travel at other sites, and for other colors of beads, had been achieved prior to the arrival of the flow spike.

White beads released from UFC first arrived at FCD in 2.25 h, FCB in 6.75 h, ANE in 17.50 h, BLF in 25.50 h, and MEX in 37.00 h (Table 2). The 50% arrival of drifting particles was relatively soon after arrival of the first bead (UFC to: FCD- 3.25 h, FCB- 9.00 h, ANE- 21.00 h, BLF- 30.50 h, and MEX- 42.75 h). Drifting white particles continued to be collected at FCD 17.00 h after the arrival of the first white bead. Sampling for white beads at FCD was terminated when particle catch rate was <5 per 15 min sample.

The 50% rate of travel of white (UFC) particles (Table 3) varied between study sites (UFC to FCD- 2.9 km • h^{-1}, FCD to FCB- 2.4 km • h^{-1}, FCB to ANE- 2.7 km • h^{-1}, ANE to BLF- 3.9 km • h^{-1}, and BLF to MEX- 3.1 km • h^{-1}). The first arrival rate of travel yielded a reach specific travel rate similar to that calculated from the 50% catch rate information (UFC to FCD- 4.2 km • h^{-1}, FCD to FCB- 3.1 km • h^{-1}, FCB to ANE- 3.0 km • h^{-1}, ANE to BLF- 4.6 km • h^{-1}, and BLF to MEX- 3.3 km • h^{-1}). While the 50% travel rates of white beads in the UFC to FCD, FCD to FCB, and FCB to ANE reaches were similar, rate of transport in the two lowermost reaches (ANE to BLF and BLF to MEX) was notably faster. The increased travel rate (first arrival and 50%) of white particles between ANE to BLF and BLF to MEX appears due, in part, to increased flows from rains.

Neon-yellow drifting particles released from the FCB first arrived at ANE in 8.75 h (Figure 6) with 50% of the particles arriving at ANE in a total of 11.00 h. The distribution pattern of neon-yellow beads in the river, when they arrived at ANE, was still relatively clustered as the majority had reached ANE within 2.25 h of the first collected neon-yellow bead. These beads required 20.50 h to reach (first arrival) BLF and 30.25 h for first arrival at MEX. The difference in time between first and 50% arrival at downstream localities indicated that the distribution pattern of neon-yellow beads remained relatively clustered as they proceeded to MEX. The time from first arrival (20.50 h) until most neon-

Table 2. Times for the first arrival and 50% arrival of passively drifting particles to appear at downstream collecting localities in the San Juan River (see Study Area for locality codes).

REACH	CODE	DISTANCE [1] (km)	Egg Color First Arrival 50% Arrival	Egg Color First Arrival 50% Arrival	Egg Color First Arrival 50% Arrival	Egg Color First Arrival 50% Arrival
SITE						
ABOVE FOUR CORNERS DRIFT STATION	UFC	0	white	——	——	——
FOUR CORNERS DRIFT STATION	FCD	9.4	2.25 3.25	——	——	——
FOUR CORNERS BRIDGE	FCB	23.1	6.75 9.00	neon-yellow	——	——
ANETH	ANE	55.7	17.50 21.00	8.75 11.00	black	——
BLUFF	BLF	92.4	25.50 30.50	20.50 23.00	11.50 12.75	green-yellow and royal blue
MEXICAN HAT	MEX	130.3	37.00 42.75	30.25 32.50	23.25 24.75	11.50 13.00

[1] indicates distance (in km) from ABOVE FOUR CORNERS DRIFT STATION (upstream-most release site)

Table 3. Summary of downstream transport rates of passively drifting particles through different river reaches in the San Juan River (see Study Area for locality codes).

REACH	Length of Reach (km)	Transport Rate[a] (km/h) First (maximum)	Transport Rate[b] (km/h) 50% (mean)
RELEASE - CAPTURE			
UFC - FCD	9.4	4.2	2.9
UFC - FCB	23.1	3.4	2.6
FCB - ANE	32.9	3.8	3.0
ANE - BLF	40.2	3.5	3.2
BLF - MEX	38.0	3.3	2.9

[a] Transport rate based first arrival rate of travel for particles released immediately upstream of capture site to avoid problems of extrapolation and changing river conditions (e.g., ANE-BLF based on black particles released from ANE and captured at BLF).

[b] Transport rate based on 50% rate of travel for particles released immediately upstream of capture site to avoid problems of extrapolation and changing river conditions (e.g., ANE-BLF based on black particles released from ANE and captured at BLF).

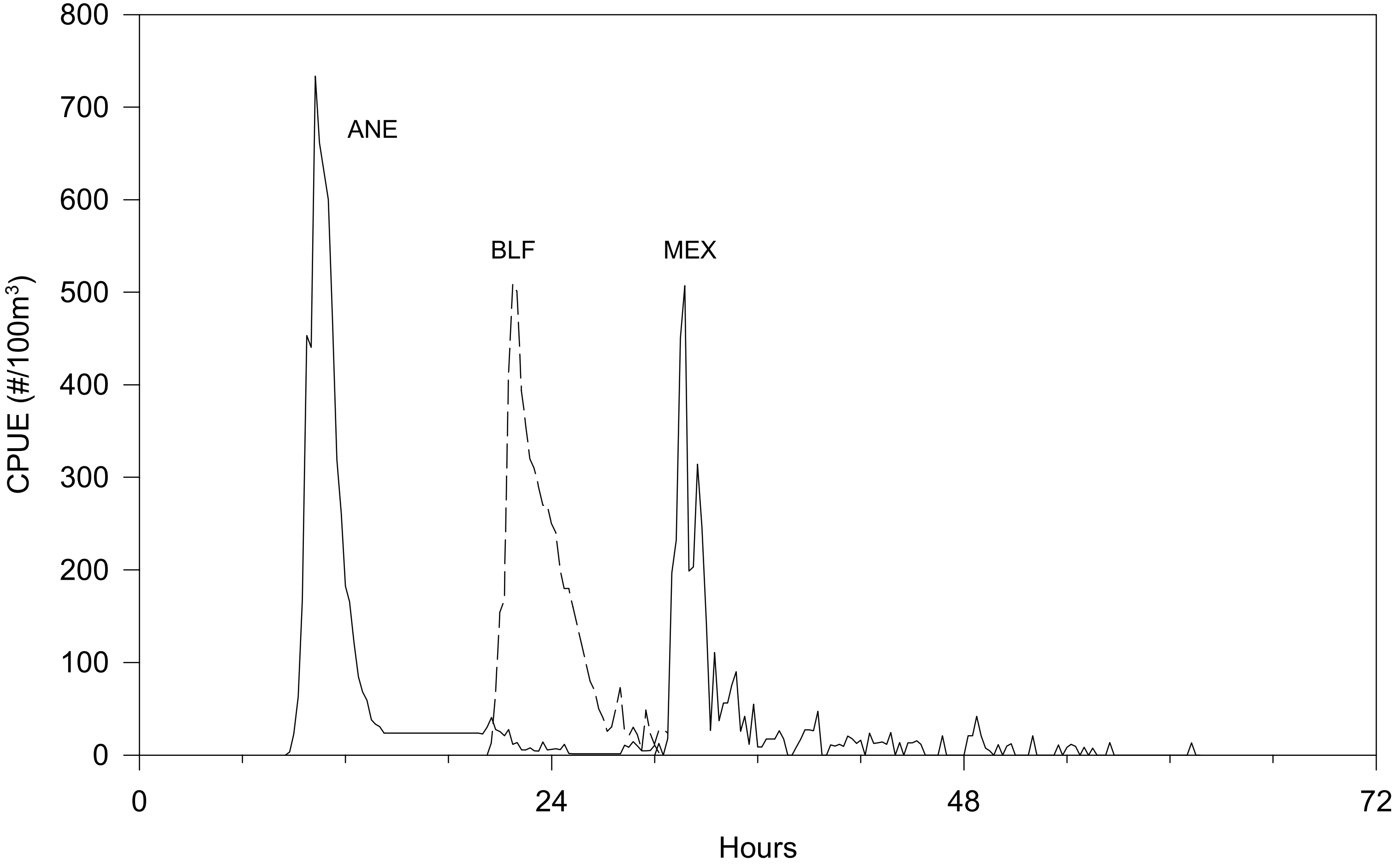

Figure 6. Travel time and dispersion of passively drifting particles released from Four Corners bridge (RM 119) at three downstream localities.

yellow drifting particles were distributed downstream of BLF was 2.50 h. Likewise, it was only 2.25 h between the first and 50% arrival of neon-yellow beads at MEX.

Travel time of neon-yellow particles between reaches varied moderately but trends were the same as noted for white particles. The rate of travel for first arrivals from FCB to ANE was 3.7 km • h^{-1}, 3.1 km • h^{-1} between ANE and BLF, and 3.9 km • h^{-1} between BLF and MEX. The 50% rate of travel of neon-yellow beads between FCB and ANE was 3.0 km • h^{-1}. The travel rate between ANE and BLF was about the same as FCB to ANE (travel rate=3.1 km • h^{-1}). Conversely, travel rate between BLF and MEX was slightly greater than the upper two reaches (4.0 km • h^{-1}) and was probably the result of increased flow from rain.

Black beads released from the footbridge at ANE required 11.50 h to first arrive at BLF (Figure 7) and 23.25 h before being collected at MEX. The temporal pattern of bead catch rate recorded for white and neon-yellow particles was also observed at the two black bead sampling stations (BLF and MEX). The number of beads increased markedly soon after the first particle was collected. This initial surge in number of drifting particles was followed by a protracted period of low catch rates. The tenure of elevated catch was about equal in duration at BLF and MEX. The 50% catch level was achieved 1.25 h and 1.50 h after first catch at BLF and MEX, respectively. The relatively similar first-to-50% periods indicate little change in the in-river distribution pattern (clustered) of black beads over the 74.6 km reach they traversed.

The maximum rate of travel between ANE and BLF, BLF and MEX, and ANE and MEX were all 3.2 km • h^{-1}. The 50% rate of travel from ANE to BLF was 2.9 km • h^{-1} and from BLF to MEX was 3.2 km • h^{-1}. The rate of travel of the majority of drifting particles between ANE and MEX was 3.0 km • h^{-1}. Sampling for black beads was sufficiently completed so as not be affected by the rain-induced increase in discharge in the river.

Both greenish-yellow and royal blue beads were simultaneously released from the U.S. Highway 191 bridge crossing at BLF. These particles first arrived at MEX 11.50 h after the release (Figure 8) and 50% had been captured 2.50 h later. Sampling at the MEX site continued longer than at any of the other sites (for 58.50 h following the initial release) but neither green-yellow nor royal blue particles were collected after the 32nd h of sampling. The maximum rate of travel between BLF and MEX was 3.3 km • h^{-1} and 50% travel rate was 2.9 km • h^{-1}. Both BLF travel rates compared

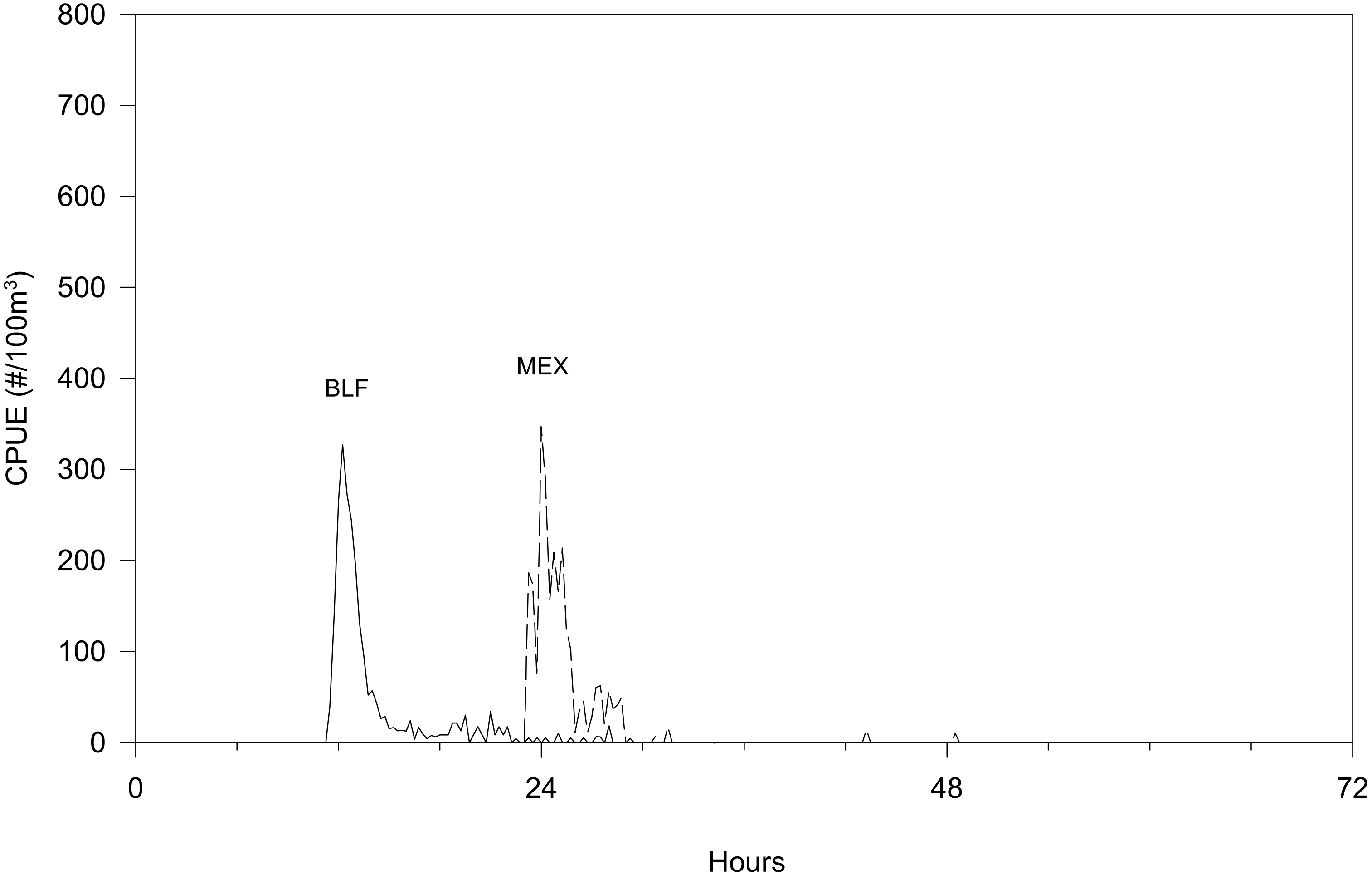

Figure 7. Travel time and dispersion of passively drifting particles released from Aneth, UT (RM 100) at two downstream localities.

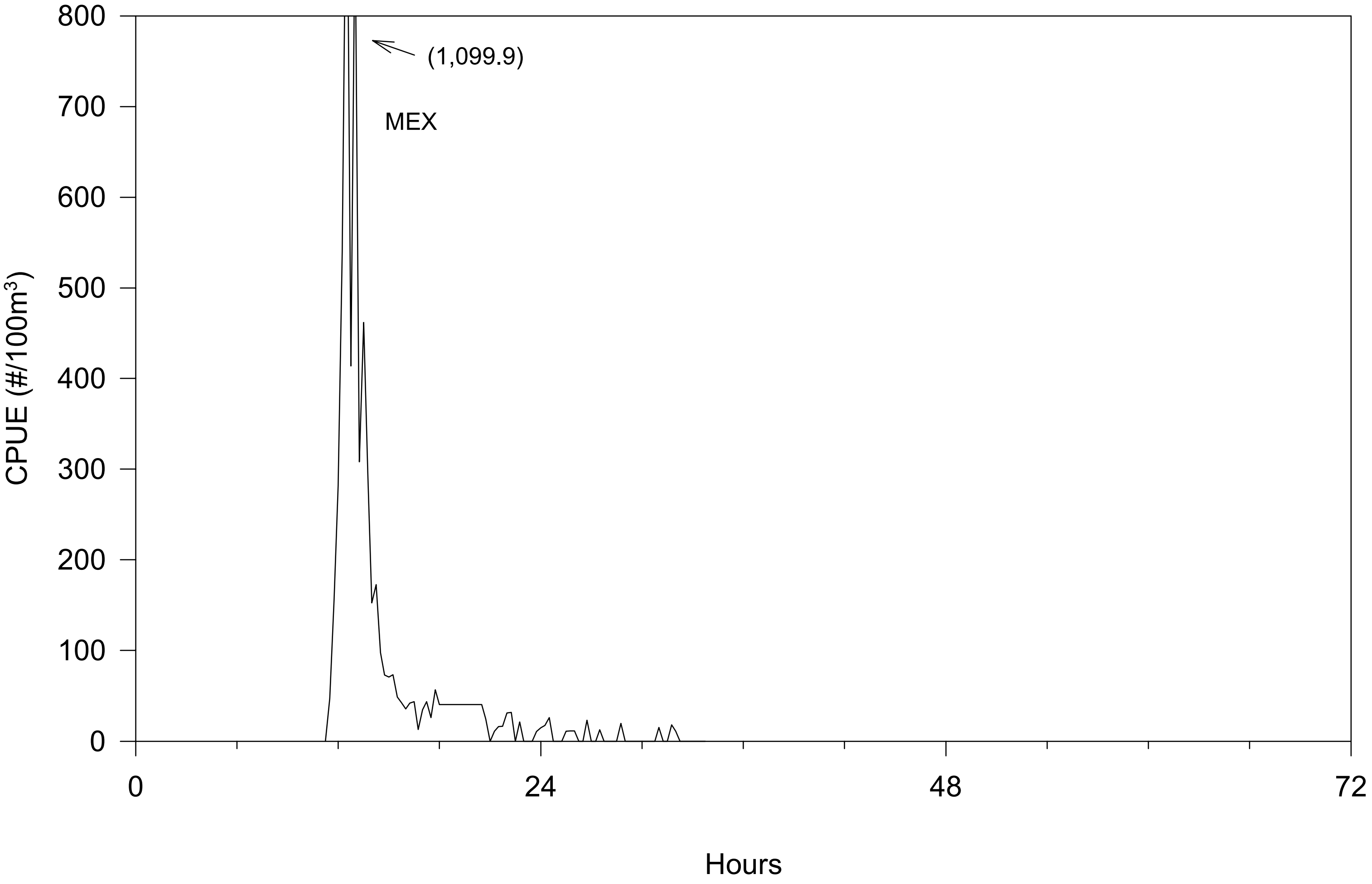

Figure 8. Travel time and dispersion of passively drifting particles released from Bluff, UT (RM 76) at one downstream locality.

favorably with BLF to MEX travel rates calculated from the black bead (ANE) release (maximum: BLF-3.3 km • h^{-1} versus ANE-3.2 km • h^{-1}; 50%: BLF-2.9 km • h^{-1} versus ANE-3.2 km • h^{-1}).

DISCUSSION

Numerous changes to the flow patterns of the San Juan River have occurred over the past century. Historical accounts and aerial photographs from the early 1900s reveal a river that was highly braided, relatively shallow, sand bottomed, and possessing a broad floodplain during high flows. Although surveys of instream habitats were not made during this time, the general morphology of the river suggests that a wide variety of dynamic depth and velocity combinations were present. Anthropogenic alterations to the San Juan River became noticeable by the mid 1900s with evidence of heavy overgrazing and erosion of the surrounding landscape. The operation of Navajo Dam, beginning in 1962, directly or indirectly led to narrowing of the average river channel width and floodplain, deepening of the main channel, reduction of the abundance of active secondary channels, increased stabilization of channel banks, dampening of peak flows, reduction of periods of lower flow, alteration of the timing of high spring flows, reduction of instream suspended sediments, reduced water temperatures, and loss of lower velocity habitats (Bliesner and Lamarra, 1999). Additionally, alterations to the natural hydrologic conditions in other parts of the Colorado River basin appear to be favoring the recent successful establishment and abundance of nonnative fishes that compete with or consume larval Colorado pikeminnow (Haines and Tyus, 1990). This combination of factors have likely resulted in many of the subsequent declines in native San Juan River fish populations.

The inherent drifting behavior of larval Colorado pikeminnow results in an unknown, but potentially large, portion of drifting larvae being transported downstream into unsuitable riverine habitats or Lake Powell. The presence of numerous postlarval Colorado pikeminnow several hundred kilometers downstream of hypothesized spawning areas in the Green and Yampa rivers suggests that larvae may be displaced over long distances (Tyus, 1986; Tyus et al., 1987; Tyus and Haines, 1991). This has also been suggested for San Juan River larval Colorado pikeminnow based on the distribution of adults (190 to 230 km upstream of Lake Powell), presumed spawning bed location (212 km upstream of Lake Powell), and collection of larval pikeminnow near the inflow to Lake Powell (Platania et al., 1991; Ryden and Ahlm, 1996).

The rapid downstream displacement rates of drifting particles between San Juan River study reaches were similar (range = 2.6 km • h^{-1} to 3.2 km • h^{-1}) despite reach-dependent differences in mesohabitat conditions, sinuosity, substrate composition, and channel slope. Most of the collection sites (4 of 5) were in reaches 3 and 4. Differences in geomorphological variables between these reaches (3 & 4) were not as great as they were between other reaches (Bliesner and Lamarra, 1999). The Mexican Hat collection site was in reach 2 (lower sinuosity, narrower channel width, and higher channel slope than in reaches 3 or 4) but travel rates did vary noticeably from those recorded between sites in reaches 3 or 4. It appears that physical differences between reaches were not large enough to have resulted in any substantial differences in drifting particle travel times.

It is possible that, despite differences in geomorphology between reaches, the prevalence of high velocity mesohabitats throughout the study area resulted in similar travel times of passively drifting particles between reaches. Although there were differences in the relative abundance in lower velocity mesohabitats (e.g., backwaters, backwater pools, debris pools, eddies, eddy pools, embayments, inundated vegetation areas, pocket waters, pools, riffle eddies, rootwad pools, sand shoal, cobble shoal, and slackwaters) between reaches, the absolute abundance of these areas was low throughout the San Juan River study area. High velocity areas (e.g., chutes, rapids, riffles, riffle/chutes, runs, run/riffles, scour runs, shoal/riffles, shore runs, and undercut runs) generally accounted for 90-95% of the total available habitats. The absolute abundance of high velocity areas might have negated differences in travel rates that would have resulted because of other variations in geomorphology (i.e., abundance of islands, channel width, sinuosity, and channel slope).

A large rainstorm event that occurred after drifting particles had travelled from their release site to their initial site of capture precluded accurate estimates of the percent displacement of beads to subsequent downstream localities. While the catch rates of drifting particles between most sites were similar and would indicate that a substantial number probably were displaced downstream in the dominant high velocity habitat types (i.e., runs and riffles), it is uncertain how much of this similarity was due to the increased and potentially flushing flows created by the rainstorm. Even with the effects of a rainstorm or higher base flows, some proportion of these particles would be slowed down as they travelled through low velocity habitats, others would be caught for a period of time in eddies or along the shoreline, and some would end their journey in backwaters or pools. While the magnitude of this effect between different reaches is unknown, it appeared that over longer distances (e.g., UFC to MEX, Figure 4; FCB to MEX, Figure 5) the overall catch of drifting particles declined regardless of temporarily increased flows from the rainstorm. The transport of particles immediately following the higher flows from the rainstorm, however, seemed to be quite efficient (e.g., ANE to BLF, Figure 5; BLF to MEX, Figure 6).

Conditions during this study, including rain events, were similar to those observed in the San Juan River when larval Colorado pikeminnow have been collected in the past. Flows during the study were moderate (about 2,000 cfs with an increase following the rainstorm) and fairly typical for the San Juan River during the late summer months of the 1992-1997. The 1996 water year was an exception to this trend; flows during late July were generally less than 500 cfs and few substantial rain events occurred. Back-calculated dates of Colorado pikeminnow spawning (Platania et al., 2000) during the 1992-1997 research period demonstrated that height of spawning for this species occurred in early to mid-July. It would be expected, based on hatching time (Hamman, 1981), that larval Colorado pikeminnow would initially become a component of the drift about five days after hatching. Field collections (Platania et al., 2000) demonstrated that Colorado pikeminnow were still a component of the drift at least 13 days after hatching at which time individuals were < 10 mm total length (TL). Collections of drifting Colorado pikeminnow were made on 26 July and 27 July 1993, 2 August and 3 August 1995, and 2 August 1996.

Passively drifting particles released from near the upper portion of the distribution for Colorado pikeminnow in the San Juan River were displaced into Reach 2 (typified by a steeper gradient, confined river channel, low sinuosity, and dominated by riffle-type habitat) and downstream of the Mexican Hat study site within two days. The additional travel time, though not measured during this study, to Lake Powell was probably about one day. This calculation (one day) is based on the distance between Mexican Hat and Lake Powell and the travel rate information from other reaches obtained during this study. Even if drifting particles moved at the slowest rates observed during the study ($2.6 \text{ km} \bullet \text{h}^{-1}$), they would reach Lake Powell within 32 h of the time that they arrived at Mexican Hat.

Prior to the construction of Glenn Canyon Dam, some proportion of drifting Colorado pikeminnow likely dispersed into the mainstem Colorado River. Some of these individuals would presumably have returned to the tributaries from which they were spawned. Adult Colorado pikeminnow have been shown to make spawning migrations up to several hundred km, often passing apparently suitable spawning sites. This apparent homing behavior has been attributed to olfactory cues (Tyus, 1985, 1990). The upstream movement of subadults (30-50 cm TL) may be another mechanism for repopulating upper river reaches (Tyus, 1991). However, instream barriers and reservoirs now block upstream movement of fishes and may prevent adults from reaching optimal spawning areas (Tyus, 1985).

The only natural source of larval Colorado pikeminnow recruitment in the San Juan River is from the population that currently inhabits the fragmented river reach between Lake Powell and Navajo Reservoir. The results of this study suggest that, under normal hydrologic conditions, larval Colorado pikeminnow are transported into Lake Powell. Even those larval pikeminnow not drifting into the lake, are likely transported into the lowermost portion of the San Juan River (Reach 1). This section of the San Juan River contains few habitats suitable for larval Colorado pikeminnow and individuals transported to Reach 1 are likely to perish prior to recruitment. The recovery of Colorado pikeminnow in the San Juan River will be, in part, dependent on ameliorating conditions that have led to the severe reduction of this life history stage.

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