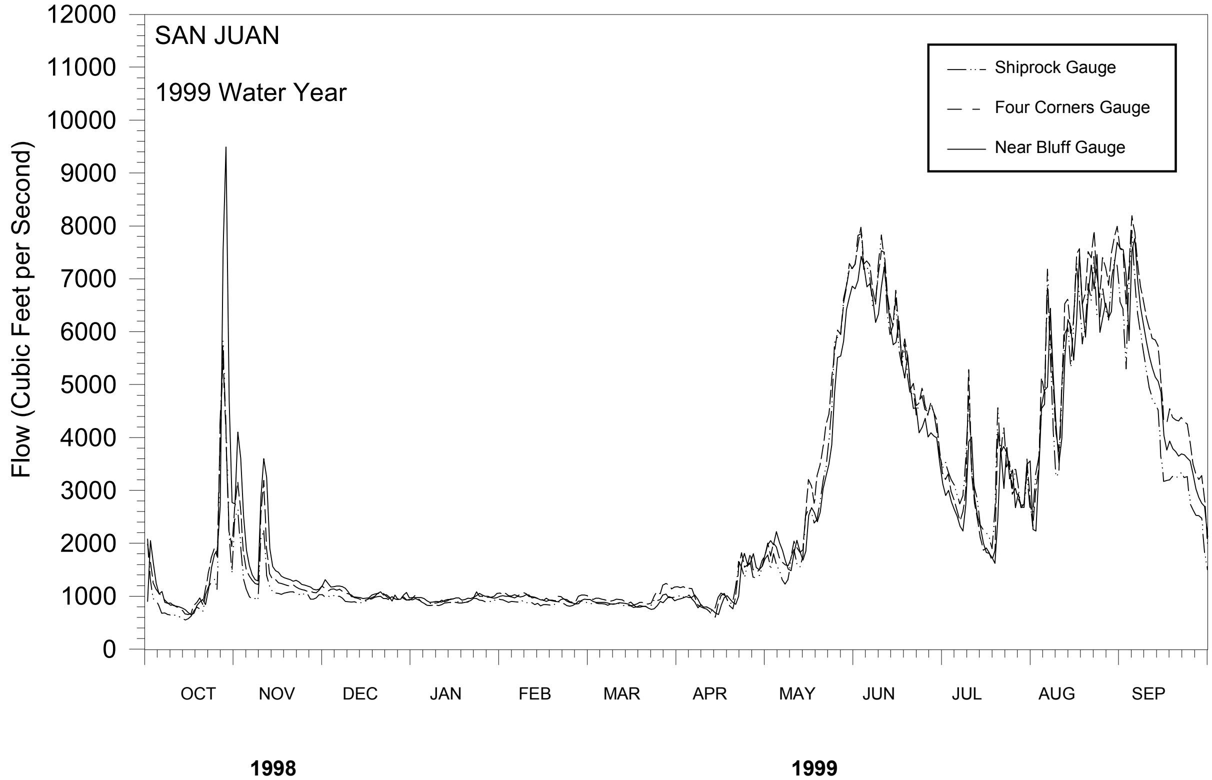
DOWNSTREAM TRANSPORT RATES OF PASSIVELY DRIFTING PARTICLES AND LARVAL COLORADO PIKEMINNOW IN THE SAN JUAN RIVER IN 1999

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. The objectives of this study were to test the rate of transport of beads during higher flows (ca. 3,000 versus 2,000 cfs) and over a longer distance (250 versus 130 river kilometers) than was measured in 1998. An additional objective was to ascertain how accurately beads emulated rate of downstream movement of drifting protolarval Colorado pikeminnow. Transport rates of beads and larval fish between Hogback Diversion Dam and Lake Powell were measured in July 1999.

The rate of travel of beads and larval Colorado pikeminnow between sites ranged from 3.1 km • h^{-1} to 4.2 km • h^{-1}. Larval Colorado pikeminnow and beads traveled at about the same speed even over long distances (e.g., 3.6 km • h^{-1} versus 3.5 km • h^{-1} respectively, for the 251 river km reach). Transport rates between study reaches were similar and indicated that habitat differences between sites probably were not great enough to cause notable changes in travel rate. The consistent and rapid downstream displacement of passively drifting particles and larval Colorado pikeminnow collaborated the results of the 1998 investigation which indicated 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. The recovery of this species in the San Juan River will be, in part, dependent on ameliorating the conditions which have led to the loss of this reproductive effort.

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INTRODUCTION

Colorado pikeminnow (*Ptychocheilus lucius*) is a federally endangered species (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 larval pikeminnow survival.

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 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. 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 (=beads) 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, however, a large-scale empirical test of this hypothesis had not been conducted.

The development of these passively drifting particles provided a mechanism to test these assumptions in discrete river reaches and under different hydrologic regimes. A quantitative study to estimate rate and magnitude of downstream transport of larval Colorado pikeminnow was initiated in July 1998 (Dudley and Platania, 2000). In that study, drifting particles were simultaneously released in the San Juan River at sites between Four Corners and Bluff. Mean rate of travel between Four Corners and Mexican Hat, at discharge of about 2,000 cfs, was 2.9 km $\cdot$ h^{-1}. At this rate of transport, larval Colorado pikeminnow that emerge from the hypothesized spawning bar at RM 132 would arrive at Lake Powell in three days.

The 1999 objectives of this study were to determine downstream transport rates of passively drifting particles during higher flows than were tested in 1998, measure the rate of travel of passively drifting particles over a longer distance in the San Juan River than was measured in 1998 (i.e., Hogback Diversion Dam to Clay Hill), and determine how accurately passively drifting particles mirrored downstream displacement of hatchery reared larval Colorado pikeminnow. To accomplish these goals, beads and larval Colorado pikeminnow were simultaneously released and subsequently collected from multiple locations in the San Juan River in July 1999. This information will ultimately provide resource managers a tool necessary to make more informed decisions regarding water release patterns, habitat modifications, and the need for fish passage structures in the San Juan River. 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.

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).

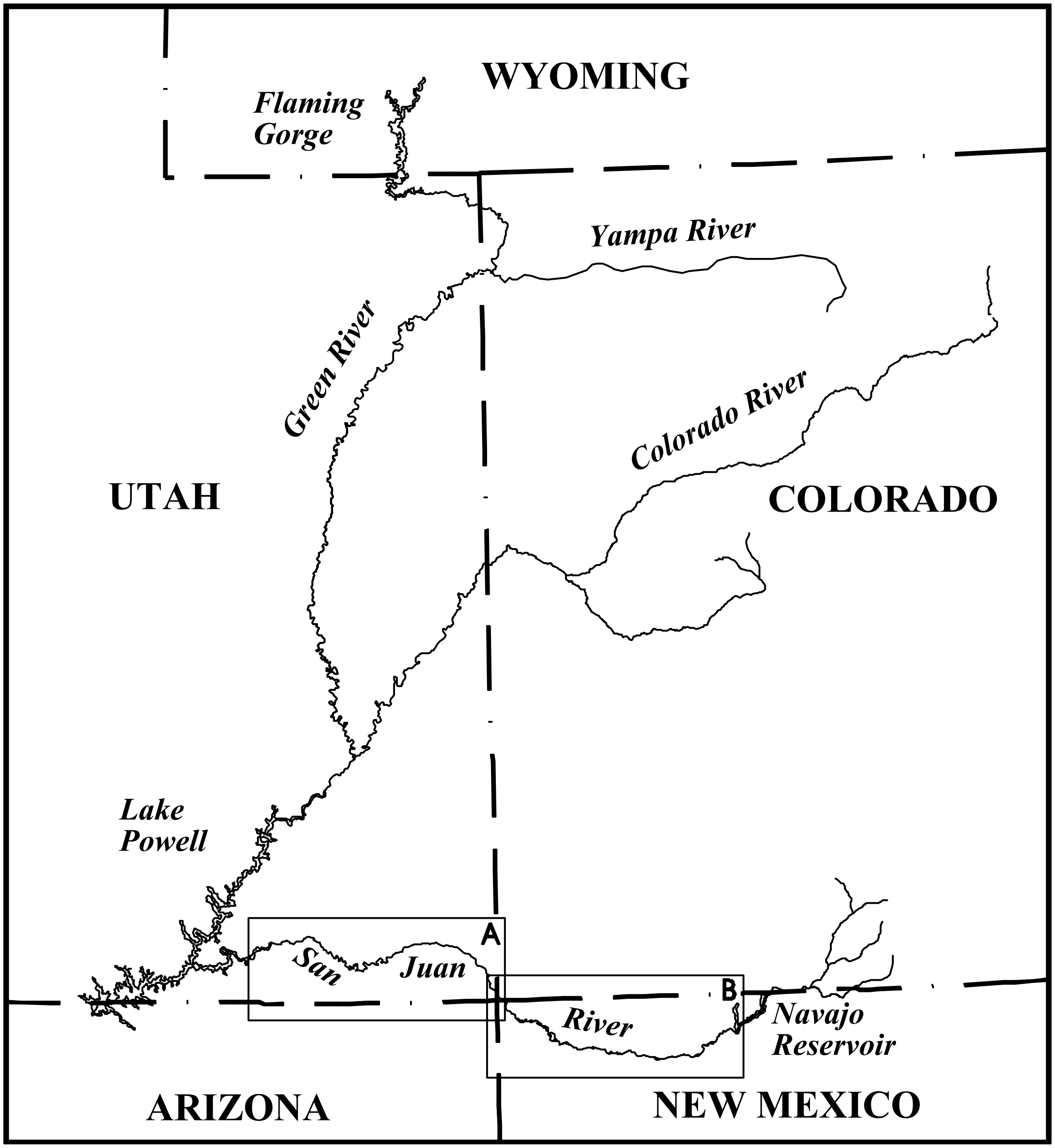

Figure 1. Location map of the San Juan River (A=lower reaches, B=upper reaches).

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 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 $m \cdot km^{-1}$. Examined in 30 km increments, river gradient ranges from 1.24 to 2.41 $m \cdot km^{-1}$ but locally (i.e., <30 km reaches) can be as high as 3.5 $m \cdot km^{-1}$. 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; 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 (HBD) on the San Juan River, New Mexico used during this project was located about 50 m downstream of Hogback Diversion Dam (RM 159, *Reach 6*; Figure 2). Drifting particles and larval fish were released from this site and then collected at downstream sampling localities. The first collecting station (SHP) was located near Shiprock, New Mexico (RM 148; *Reach 5*) and 16.7 km downstream of the Hogback Diversion Dam. The second sampling locality (CUD) was located within the Cudei Diversion Ditch (adjacent to RM 142, *Reach 5*). A downstream site (MEX) was established near Mexican Hat, Utah (RM 53, *Reach 2*). The final site (CLA) was located just upstream of Lake Powell Reservoir near Clay Hills, Utah (RM 3, *Reach 1*).

METHODS

Information on the downstream transport rate was obtained by releasing, and subsequently capturing, passively drifting particles (=beads) and larval Colorado pikeminnow from just downstream of Hogback Diversion Dam. Protolarval (one-two days post-hatching) Colorado pikeminnow (ca. 510,000) spawned at Dexter National Fish Hatchery and Technology Center were released simultaneously with beads. 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. Lighter (SG=0.97) and heavier beads (SG=1.01) were also tested to determine which type particle (SG) best mirrored the transport rate of hatchery protolarval Colorado pikeminnow.

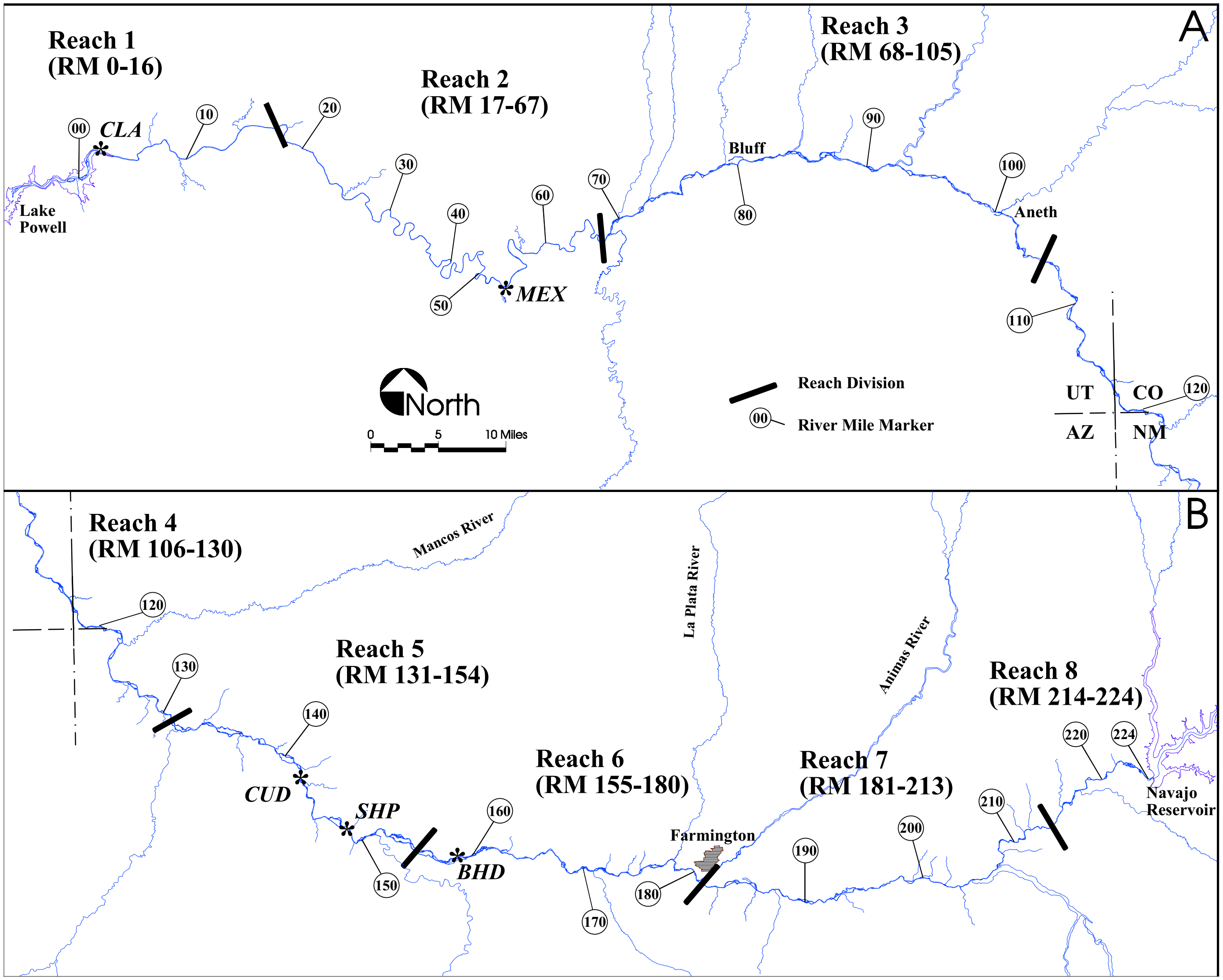

Figure 2. Study Area in the San Juan River (see Table 1 for site codes)..

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 and protolarval Colorado pikeminnow were released simultaneously from just below the Hogback Diversion Dam (HBD) on 7 July 1999 at 21:30 (Table 1). Beads and ~~larval fish~~ were subsequently collected at SHP, CUD, MEX, and CLA. This experiment was conducted during summer base flows that were occasionally elevated by rain events (Figure 3). White, yellow, and blue beads had SG=1.005, grey particles had a SG=1.01, and purple beads had SG= 0.97.

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

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 and could not be calculated until after all of the collection data had been processed. Percent magnitude of displacement (i.e., an

Table 1. Schedule of release and collections of passively drifting particles and larval Colorado pikeminnow conducted in the San Juan River.

REACH	CODE and River Mile	DISTANCE [1] (km)	Type [2] and # released [3]			Release [5] and Collection [6]	Sampling Duration (hours)
SITE							
BELOW HOGBACK DIVERSION	HBD 159	0	white 5.28	yellow 1.39	blue 4.18	■	———
			grey 2.79	purple 2.79	fish 0.51		
SHIPROCK	SHP 148	16.7			——	●	25.00
CUDEI DIVERSION DITCH	CDD 142	26.6			——	●	45.75
MEXICAN HAT	MEX 53	171.0			——	●	60.50
CLAY HILLS	CLA 3	250.6			——	●	63.75
LAKE POWELL RESERVOIR [4]	—— 0	255.2			——	——	——
TOTAL	——	255.2			——	——	195.00

[1] indicates distance (in km) from BELOW HOGBACK DIVERSION (upstream-most release site)

[2] white, yellow, and blue particles (SG=1.005), grey particles (SG=1.01), purple particles (SG=0.97), and fish (passively drifting larvae)

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

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

[5] ■ indicates particle and fish release site

[6] ● indicates particle and fish collection site

estimate of the percentage of particles transported between sites) was calculated as the sum of particle CPUE values from one collecting locality divided by the sum of particle CPUE values from another collecting locality multiplied by 100.

This study was conducted during summer base flow that was occasionally elevated by rain events (Figure 3). Daily mean steam flow on 7 July 1999 (Figure 4) was 2,750 cfs at the U.S. Geological Survey (USGS) Shiprock, New Mexico Gauge (# 09368000), 2,430 cfs at the USGS Four Corners, Colorado Gauge (# 09371010), and 2,320 cfs at the USGS Near Bluff, Utah Gauge (#09379500). Daily mean stream flow increased moderately by 8 July 1999 (2,900 cfs at Shiprock, 2,600 cfs at Four Corners, and 2,230 cfs at Bluff) and somewhat more following local rainstorms by 9 July 1999 (3,650 cfs at Shiprock, 3,040 cfs at Four Corners, and 2,740 cfs at Bluff). Downstream travel rates from HBD to SHP and CUD were based almost exclusively on data collected on 7-8 July 1999. Flow at the USGS Near Bluff, Utah Gauge began to rise noticeably by 10 July 1999 (3,920 cfs) and 11 July 1999 (4,010 cfs) but the majority of particles and larval Colorado pikeminnow had arrived at MEX and CLA prior to this large volume of water.

RESULTS

The rate and magnitude of larval Colorado pikeminnow downstream displacement, as inferred from drifting particles, indicated that these small fishes were rapidly transported long distances in short periods during flows (ca. 2,500 cfs) tested on the San Juan River (Figure 5). As in 1998, sampling efforts revealed a relatively consistent temporal pattern of bead and larval Colorado pikeminnow catch rate at each site. Soon (15-30 min) after the arrival of the first bead and larval pikeminnow, there was a rapid and sustained (one-three h) increase in CPUE of both. This marked influx of drift was followed by a slow and gradual decline, over the remainder of the study, in the numbers of items collected. The magnitude of this increase and decrease in catch rates was more pronounced the closer the collection site was to the HBD point of release (i.e., SHP and CUD).

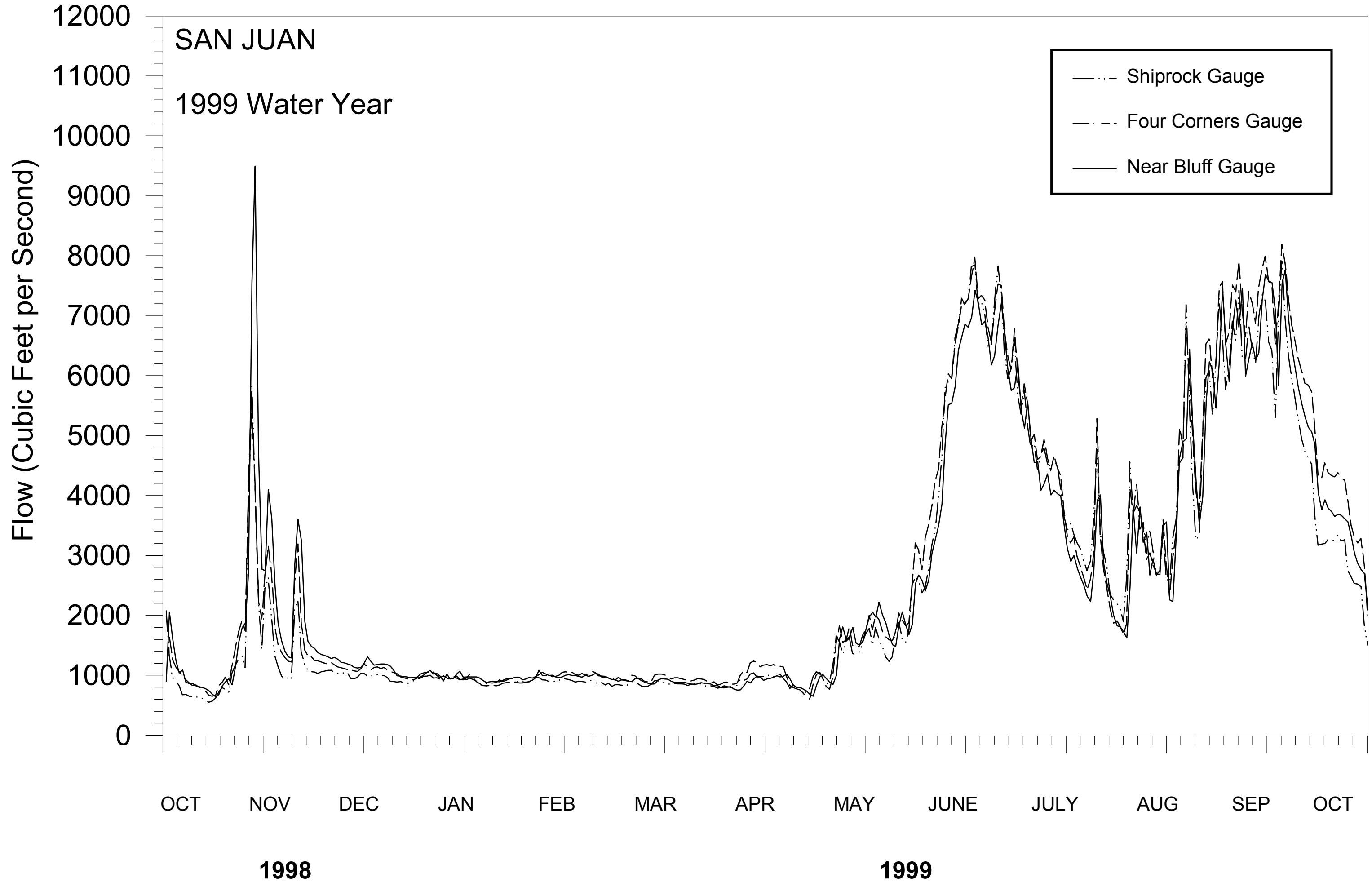

Figure 3. Hydrograph of the San Juan River at Shiprock, NM, Four Corners, CO, and Bluff, UT for the 1999 water year.

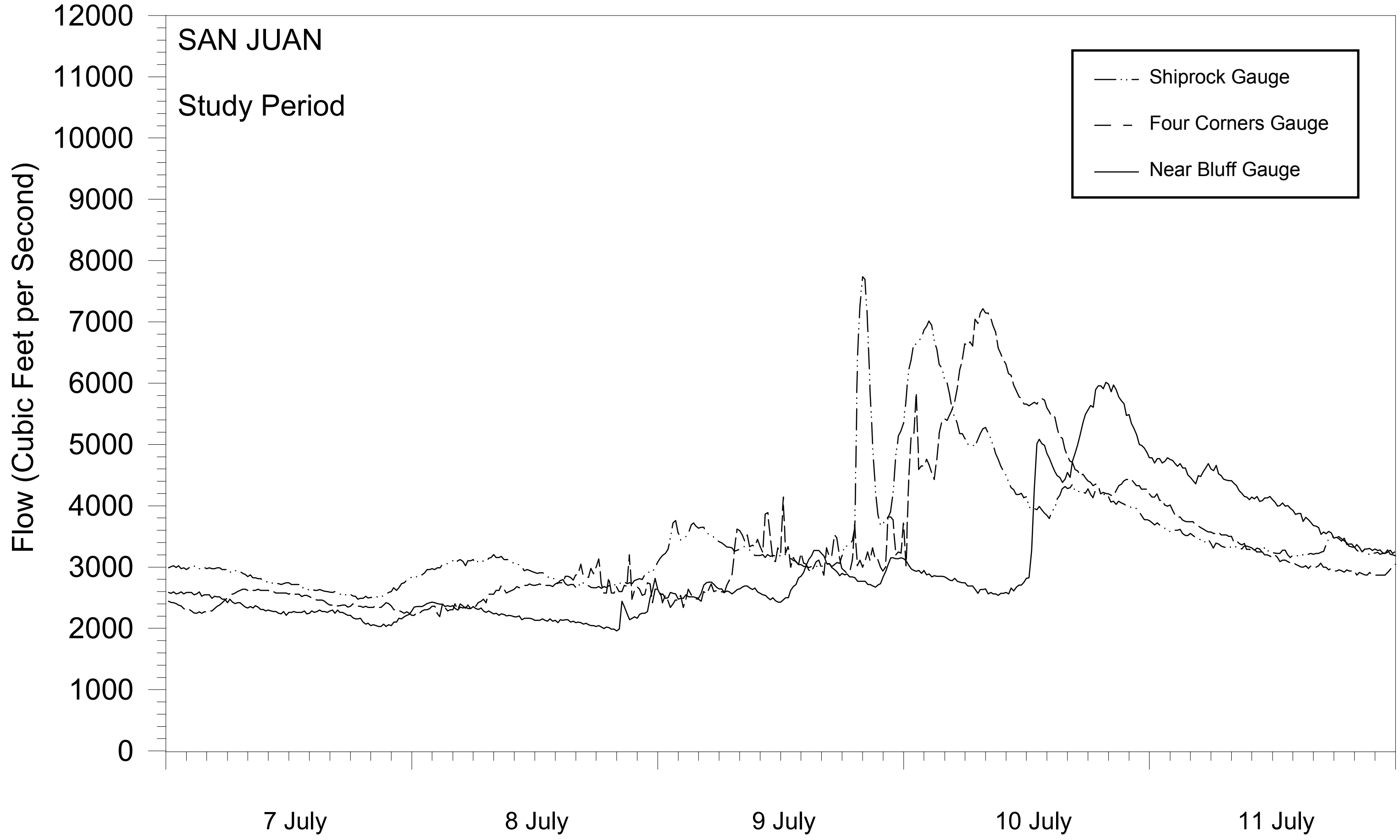

Figure 4. Hydrograph of the San Juan River at Shiprock, NM, Four Corners, CO, and Bluff, UT for the study period.

White, yellow, and blue drifting beads (SG=1.005) released from HBD first arrived at SHP in 3.00 h, at CUD in 4.75 h, at MEX in 41.75 h, and at CLA in 63.25 h (Table 2). The 50% arrival of drifting particles at collecting locality was relatively soon after their first arrival (HBD to: SHP- 5.00 h, CUD- 7.00 h, MEX- 55.00 h, and CLA- 72.25 h). Drifting beads continued to be collected at SHP 22.00 h after the arrival of the first particle. The collecting effort at SHP was terminated when particle catch rates had decreased <5 in each 15 min sample.

The maximum travel rate for beads was greater at sites closer to the point of release than downstream (HBD to SHP- 5.6 km $\cdot$ h^{-1}, HBD to CUD- 5.6 km $\cdot$ h^{-1}, HBD to MEX- 4.1 km $\cdot$ h^{-1}, HBD to CLA- 4.0 km $\cdot$ h^{-1}). The mean travel rate of particles released from the HBD site (Table 3) varied slightly between study reaches (HBD to SHP- 3.3 km $\cdot$ h^{-1}, HBD to CUD- 3.8 km $\cdot$ h^{-1}, HBD to MEX- 3.1 km $\cdot$ h^{-1}, HBD to CLA- 3.5 km $\cdot$ h^{-1}). Travel rate between SHP and CUD and MEX and CLA appeared slightly higher than rate of travel between other reaches. The magnitude of displacement between SHP and MEX was 42.0% and between SHP and CLA was 26.6%.

Grey (SG=1.01) and purple particles (SG=0.97) drifted at about the same rate and exhibited a similar temporal distribution as did the SG 1.005 beads (white, yellow, and blue). Likewise, the mean travel rate of grey (HBD to SHP- 3.3 km $\cdot$ h^{-1}, HBD to CUD- 3.7 km $\cdot$ h^{-1}, and HBD to MEX- 3.1 km $\cdot$ h^{-1}) and purple (HBD to SHP- 3.5 km $\cdot$ h^{-1} and HBD to CUD- 3.8 km $\cdot$ h^{-1}) particles was nearly identical to that of SG 1.005 beads. Between reach variation in SG 0.97 and 1.01 bead travel rates were similar to those estimated for white, yellow, and blue particles (SG 1.005). The low number of grey and purple beads collected at CLA and MEX and CLA, respectively, precluded accurate estimation of the 50% travel rates.

Protolarval Colorado pikeminnow drifted, even over long distances (i.e., HBD to CLA), at about the same rate as SG 1.005 particles (Figure 6). There was a broad overlap in temporal distribution of catch rates for drifting larval Colorado pikeminnow and beads at all sites. The maximum travel rate for larval Colorado pikeminnow was identical to that recorded for passively drifting particles at the upper two sites (HBD and SHP) and was very close (within 2.25 h) at CLA. The 50% travel rate for protolarval pikeminnow varied slightly between sites (HBD to SHP- 4.2 km $\cdot$ h^{-1}, HBD to CUD-

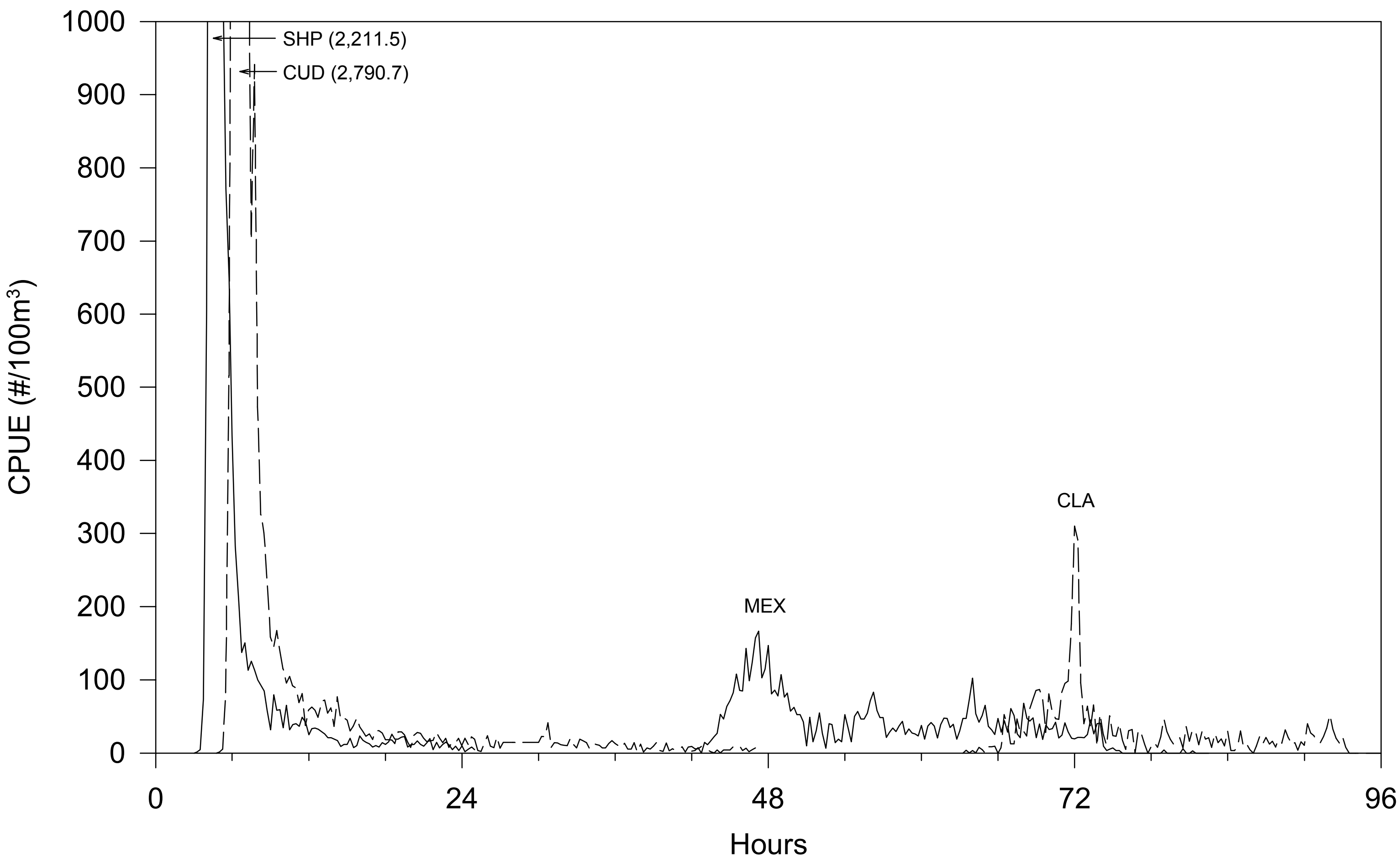

Figure 5. Travel time and dispersion of white, yellow, and blue particles released from below Hogback Diversion Dam (RM 159) at four downstream localities.

Table 2. Times for the first arrival and 50% arrival of passively drifting particles and larval Colorado pikeminnow to appear at downstream collecting localities in the San Juan River.

REACH (km)	CODE	DISTANCE [1]	Egg Color [2] First Arrival 50% Arrival	Egg Color [2] First Arrival 50% Arrival	Egg Color [2] First Arrival 50% Arrival	Larval fish First Arrival 50% Arrival
SITE						
BELOW HOGBACK DIVERSION	HBD	0	white, yellow, and blue	grey	purple	fish
SHIPROCK	SHP	16.7	3.00 5.00	3.50 5.00	3.25 4.75	3.00 4.00
CUDEI DIVERSION DITCH	CUD	26.6	4.75 7.00	5.25 7.25	5.00 7.00	4.75 6.50
MEXICAN HAT	MEX	171.0	41.75 55.00	43.25 55.25	NA NA	NA NA
CLAY HILLS	CLA	250.6	63.25 72.25	NA NA	NA NA	61.00 69.50

[1] indicates distance (in km) from BELOW HOGBACK DIVERSION (upstream-most release site)

[2] white, yellow, and blue particles (SG=1.005), grey particles (SG=1.01), and purple particles (SG=0.97)

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

REACH	Length of Reach (km)	Transport Rate (km/h)			
		white, yellow, and blue	grey	purple	fish
RELEASE - CAPTURE					
HBD - SHP[a]	16.7	5.6	4.8	5.1	5.6
HBD - SHP[b]	16.7	3.3	3.3	3.5	4.2
HBD - CUD[a]	26.6	5.6	5.1	5.3	5.6
HBD - CUD[b]	26.6	3.8	3.7	3.8	4.1
HBD - MEX[a]	171.0	4.1	4.0	NA	NA
HBD - MEX[b]	171.0	3.1	3.1	NA	NA
HBD - CLA[a]	250.6	4.0	NA	NA	4.1
HBD - CLA[b]	250.6	3.5	NA	NA	3.6

[a] Transport rate based on first arrival rate of travel for white, yellow, and blue particles (SG=1.005), grey particles (SG=1.01), purple particles (SG=0.97), and fish (passively drifting protolarvae).

[b] Transport rate based on 50% rate of travel for white, yellow, and blue particles (SG=1.005), grey particles (SG=1.01), purple particles (SG=0.97), and fish (passively drifting protolarvae).

4.1 km · h^{-1}, and HBD to CLA- 3.6 km · h^{-1}). These values (mean travel rate of larval pikeminnow) were most similar to those calculated for passively drifting particles at the CUD and CLA site. The magnitude of displacement of protolarval Colorado pikeminnow between SHP and CLA was 40.6%.

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).

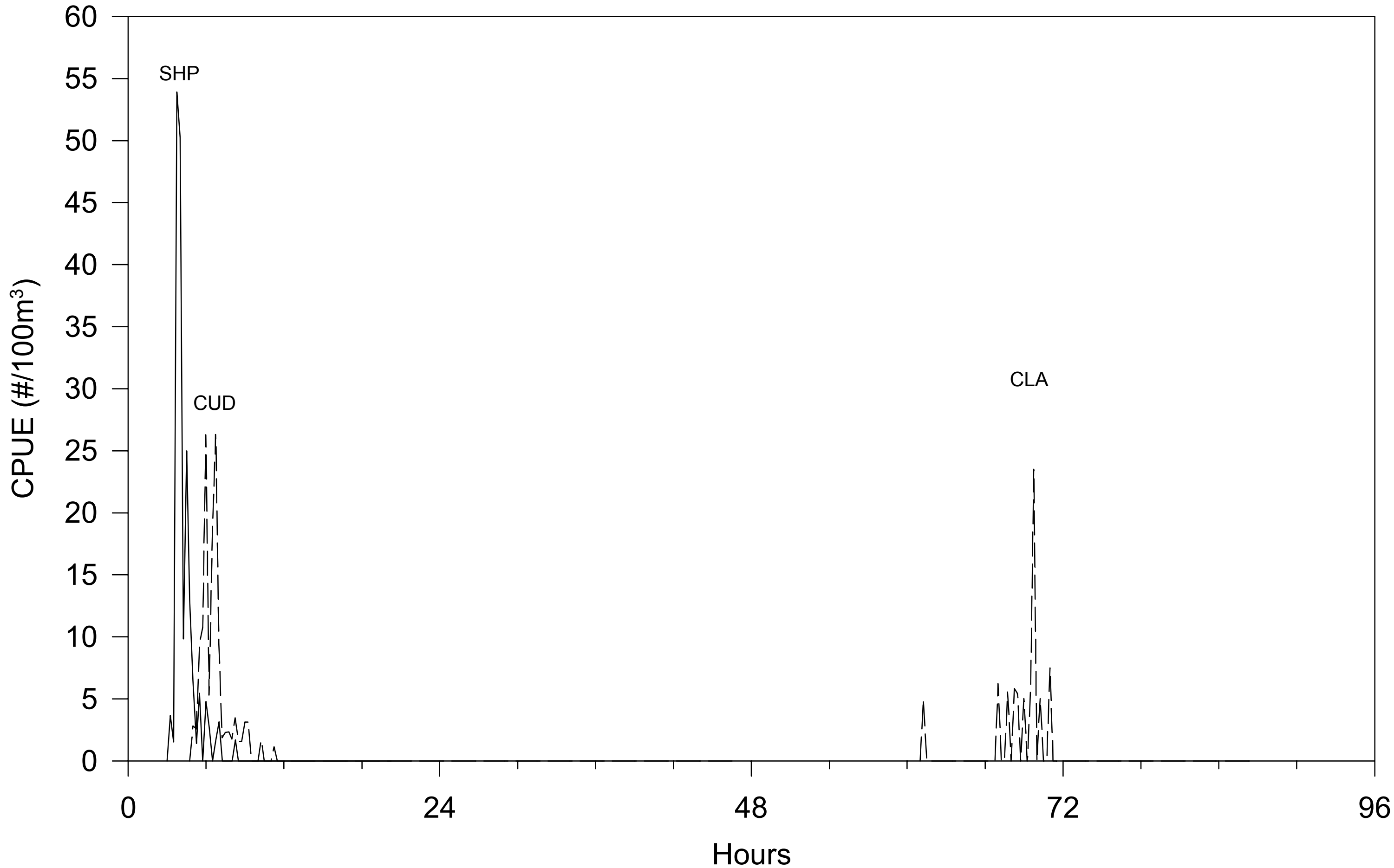

Figure 6. Travel time and dispersion of larval Colorado pikeminnow released from below Hogback Diversion Dam (RM 159) at three downstream localities.

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 study sites in the San Juan River were similar (range for 50% rate of travel = 3.1 km $\cdot$ h^{-1} to 3.8 km $\cdot$ h^{-1}) despite reach-dependent differences in mesohabitat conditions, sinuosity, substrate composition, and channel slope. Although study sites were located from reach 1 to reach 6, differences in geomorphological variables between these reaches (Bliesner, 1999) appeared to only moderately affect downstream displacement rates. The 50% rate of travel values within the upper portion of the study area (i.e., HBD-SHP and HBD-CUD) were slightly higher than those recorded in middle reaches (i.e., HBD-MEX). This difference could have resulted from the modestly increased river gradient and somewhat decreased abundance of low velocity mesohabitats in these upper reaches. The increased travel rate between HBD and CLA compared to HBD and MEX may have been caused by habitat changes in reach 2 (lower sinuosity, narrower channel width, and higher channel slope than in reaches 3 or 4). It appears that physical differences between reaches were not large enough to result in any substantial differences in drifting particle travel times.

First arrival rates of travel for drifting particles and fish in the upstream reaches were notably higher than those recorded in downstream reaches. This difference, however, is most likely a result of the greater densities of drifting particles and fish closer to the point of release as compared to several hundred river kilometers downstream. It is possible that the first arrivals at MEX or CLA were not detected because of their low densities in the river. Maximum travel rate calculated from grey and purple particles at SHP and CUD were lower than for white, yellow, and blue particles. However, only about half the number of the purple and grey particles were released (compared to SG 1.005 beads). The result was lower densities of the non-SG 1.005 beads than SG 1.005 bead and thereby, a decreased probability of catching the first arriving particles. First arrival travel rate provides an estimate of the rapidity in which particles and fish can be displaced downstream. The 50% rate of travel is more appropriate when comparing travel rate of drifting particles and fish between reaches.

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).

Estimates of magnitude of displacement indicate that a substantial proportion of the passively drifting particles and protolarval fish released just below Hogback Diversion Dam were displaced downstream of MEX and CLA. However, the between site accuracy of magnitude of displacement estimates is not known. The lower density and extended distribution of particles and protolarval fish at downstream sites made it difficult to assess the absolute magnitude that passed a particular site. It is possible that at more downstream sites, CPUE values would naturally be lower in part because lower density levels are more difficult to measure.

These magnitude of displacement estimates provide a very conservative determination of the percent of Colorado pikeminnow being displaced. It appears that a large magnitude of displacement occurred between SHP and CUD as a result of larval Colorado pikeminnow and passively drifting particles being entrained in the Cudei Diversion Ditch. Catch rates at CUD were similar to those recorded in the river at SHP indicating that displacement into the ditch was probably occurring as a function of the volume of water being diverted. This study provides, in the form of the loss of fishes into Cudei Diversion Ditch, a quantifiable impact to San Juan River native fish populations.

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 2,000-3,000 cfs) 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 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.

Flows in 1999 during the study period were about 1,000 cfs higher than those recorded during the previous 1998 effort to quantify downstream displacement of passively drifting particles (Dudley and Platania, 2000). As sampling release and collection localities differed between studies due to discrete research objectives, it was not possible to directly compare the travel rates of particles between specific reaches. For example, the HBD-CLA reach included areas upstream and downstream of the 1998 study area. The travel rate of passively drifting particles in upstream reaches (HBD to SHP and HBD to CUD) were higher than those recorded during the 1998 study suggesting that increased flow resulted in increased travel rates. Likewise, the higher travel rates in upstream reaches may have been due to habitat differences (e.g., gradient, sinuosity, channel width, habitat composition etc.) that typify the upper reaches. It is most likely that higher travel rates were a combination of the two factors as moderately higher flows within these relatively static areas (bottom of Reach 5 and top of Reach 4) would not be expected to result in overbank flow or notably increased habitat heterogeneity. Downstream reaches (HBD-MEX) resulted in a travel rate (3.1 $km \cdot h^{-1}$) that did not differ that markedly from rates recorded from RM 133.4 to Mexican Hat during the 1998 study (range=2.6 $km \cdot h^{-1}$ to 3.2 $km \cdot h^{-1}$). The increased flow during the 1999 study might not have altered travel rates substantially because changes in the relative abundance of various habitat types would be expected to be minor.

There were only slight differences between travel rates of the different types of passively drifting particles (i.e., SG=0.97, 1.005, and 1.01). The purple particles (SG=0.97) had a slightly faster 50% rate of travel (3.5 km · h^{-1} versus 3.3 km · h^{-1}) through the uppermost section (HBD-SHP) compared to the nearly neutrally buoyant white, yellow, and blue particles (SG=1.005). The increased rate of travel of purple particles was not surprising because previous field trials (Dudley and Platania, 1999) indicated that some level of increase could be expected. Also, because the purple particles were positively buoyant and float in areas of low or no velocity, they would be more likely to be stranded along the shoreline or water-air interface of debris piles. This would result in fewer purple particles reaching downstream localities. Grey particles (SG=1.01) had a slightly slower travel rate (3.7 km · h^{-1} versus 3.8 km · h^{-1}) from HBD to CUD compared to the SG 1.005 particles. There was no noticeable shoreline stranding of grey particles, as was observed for purple particles, but these negatively buoyant particles sank in low or no velocity aquatic habitats.

Particles with a specific gravity SG 1.005 provided the best estimate of travel rate of larval Colorado pikeminnow. This was true, not only for relatively short reaches, but also for the entire 250 km (HBD to CLA=250 km) study area (3.5 km · h^{-1} beads versus 3.6 km · h^{-1} larval Colorado pike-minnow). The one exception to this pattern was for the 50% rate of travel of beads and larvae between HBD and SHP, the shortest (16.7 km) study reach. This difference suggests that beads and larval fish need more time (and distance) to achieve homogenous distribute throughout the river. The extremely similar travel rates of passively drifting particles and larval Colorado pikeminnow is very encouraging and provides a mechanism for future research. Establishing a methodology to predict the downstream movement of this very vulnerable life-stage through different river reaches and at various flows will prove pivotal to its recovery.

Passively drifting particles released from near the upper portion of the distribution for Colo-rado 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 to Lake Powell was about 17 h. More than 50% of larval fish collected at CLA arrived at this site in <3 d from the time when they were released.

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. Upstream reaches of the mainstem are blocked by water diversion structures near Farmington, New Mexico. The results of this study suggest that, under normal annual 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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