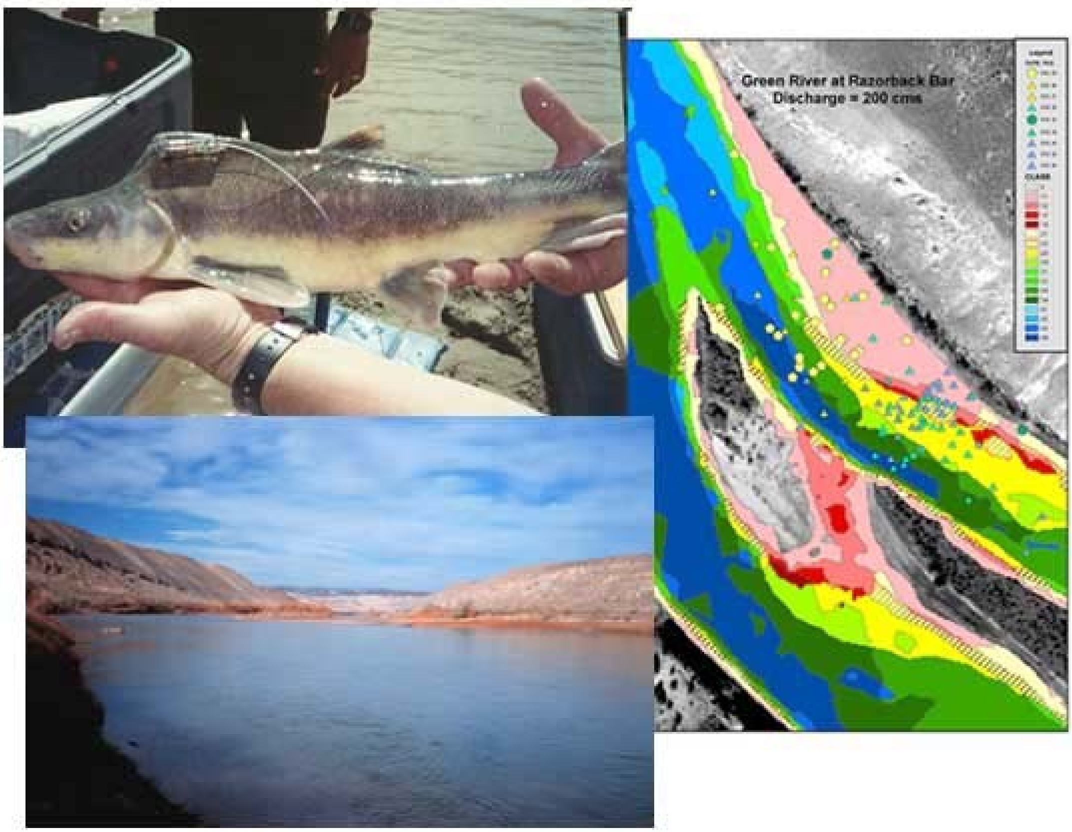
Habitat Measurement and Modeling in the Green and Yampa Rivers

Project Report

Natural Resources Preservation Program

December 2001



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Colorado Endangered Fish Recovery Program, Fort Collins, Colorado
U. S. Fish and Wildlife Service, Vernal, Utah
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Habitat Measurement and Modeling in the Green and Yampa Rivers

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EXECUTIVE SUMMARY

Populations of the endangered razorback sucker (*Xyrauchen texanus*) in the middle Green River have declined since closure of Flaming Gorge Dam in 1962. The apparent cause for the decline is a lack of successful recruitment. Recruitment failure has been attributed to habitat alteration and competition and predation by exotic fishes on early life stages of razorback sucker. This study was conducted to evaluate two of the potential reproductive bottlenecks that might limit recruitment of razorback sucker in the Green River Drainage; (1) reduced larvae production due to sediment deposition on spawning areas, and (2) reduced survival of larvae or juveniles due to lack of timely access to food-rich backwater and floodplain habitats.

A paired-site comparison of channel dynamics, hydraulics, temperature, and physical habitat characteristics between known spawning areas in the Green and Yampa Rivers was conducted. Hydrologic data from pre-and post Flaming Gorge time periods was used to assess long-term changes in relevant hydrologic characteristics and changes in the frequency of floodplain inundation. Repeated hydrographic surveys were used to examine patterns in sediment movement and to develop hydraulic models that were used to simulate habitat conditions at both study sites. Channel change was evaluated during water year 2000 and habitat conditions were simulated for runoff during 2000 and 1984. Telemetry was used to evaluate razorback sucker use of the spawning area during the ascending limb of the 2000 runoff cycle in the Green River. Habitat conditions over time

for 2000 and 1984 at both study sites were evaluated using maps and duration statistics to represent the period of time during the telemetry study (May 2000) and a period of time associated with known fish occupation of the bar that led to limited recruitment (May 1984).

Hydrologic analyses showed that since closure of Flaming Gorge Dam base flows were higher and less variable and the magnitude of peak flows was reduced. Reductions in the magnitude and duration of peak flows have reduced the frequency of floodplain inundation at suspected rearing areas downstream from the Green River spawning bar. Water temperatures near the Green River spawning area were within an acceptable range during the spawning period and probably did not directly limit reproduction during 2000. Repeated surveys showed variable patterns of scour and fill at Green and Yampa River cross sections including deposition of sediment in the Green River spawning area at flows less than 207 m^3/s. Cross section surveys suggested that lenses of sand move through both study areas over a range of discharges and that patterns of fill during high flow and scour during recession occur in both the main and side channels of the Green River site.

Habitat comparisons showed that the Green River site had a proportionally larger area of slow current velocity habitats over a range of flows than the Yampa River site due largely to differences in the size and elevation of channel features. Availability of shallow, moderate velocity habitats typical of those used by spawning razorback sucker in previous studies was higher during May 2000 than in May 1984 at both study sites. Conditions at spawning areas during 1984 were dominated by relatively deep and fast current velocity habitats. Year 2000 telemetry data showed that fish used a range of habitats during the spawning period but were often located in depths of less than 1.0 m and velocities between 0.4 and 1.2 m/s. Razorback sucker use of the Green River spawning area under very different conditions in 2000 compared to 1984 suggests that physical variables or cues other than depth and velocity influence use of the Green River spawning area. Use of the Green River spawning area by hatchery fish stocked previously at various locations in the Green River was documented by telemetry and indicates that mechanisms other than natal imprinting influence site selection.

Razorback sucker used the Green River spawning area during very different flow and habitat conditions during 2000 and 1984. This result is consistent with other studies showing flexibility in razorback sucker spawning behavior including the possible use of multiple spawning sites. Conversely, previous studies indicate that environmental requirements for survival of larvae are fairly narrow and must include access to food-rich backwater habitats. Although sediment deposition in spawning areas could limit recruitment during some years, it appears that larval access to floodplain habitats is potentially a more restrictive reproductive bottleneck over long periods of time.

INTRODUCTION

Review of physical studies

The Green River originates in the Wind River Mountains of Wyoming and flows 1,230 km southeasterly through Colorado and Utah until its confluence with the Colorado River near Moab, Utah. The Green River drains approximately 115,800 km^2 and is a principal tributary to the Colorado River. Elevations in the basin range from over 4,200 m in the headwaters to about 1,200 m at the Colorado River confluence (Muths et al. 1999). Climate is variable across the basin but most of the total annual stream flow is provided by snowmelt runoff during late spring and early summer resulting in a mean annual discharge of about 124 m^3/s at the Jensen, UT steam gage (1947-1999). Principal tributaries of the Green River include the Blacks Fork, Yampa, Duchense, White, Price, and San Rafael Rivers (Andrews 1986). The character and geomorphology of the Green River varies from steep and narrow canyons to low-gradient meandering reaches. Canyon reaches occur where highly resistant lithologies are exposed at the river level while meandering reaches are found in areas of moderate to low-resistance lithology (Grams and Schmidt 1999). Substrates are predominantly gravel or cobble in steeper reaches and sand in lower gradient reaches (Schmidt 1996). Meandering reaches contain an order of magnitude more alluvium per area than canyon reaches and store sediment in mid-channel bars and broad floodplains while in canyon reaches most sediment is stored in debris fan-eddy complexes (Grams and Schmidt 1999).

Flows and sediment transport in the Green River have been altered by the construction of dams and reservoirs. The two largest reservoirs in the Green River

Drainage are Strawberry Reservoir on the Duchense River and Flaming Gorge Reservoir on the upper Green River (live capacities of 1,364 and 4,625 million cubic meters, respectively). There are numerous other small reservoirs in the Green River Drainage but all are at least an order of magnitude smaller than Flaming Gorge, which has the capacity to store twice the mean annual inflow of the Green River. Operation of Flaming Gorge Dam has not reduced the mean annual discharge of the Green River; mean annual discharge at the Greendale, UT stream gage (less than 2 km downstream from the dam) was 59 m^3/s before (1951-1962) and 62 m^3/s after (1965-1999) closure of the dam. However, based on data for the same time periods, the average magnitude of annual peak flows decreased by about 54% (360 to 149 m^3/s) at Greendale, UT and 22% (653 to 509 m^3/s; pre-dam includes 1947-1962) 176 km downstream at Jensen, UT. Concomitant with closure of the dam were changes in annual suspended sediment yield. Andrews (1986) estimated annual suspended sediment yield was reduced from about 3.6 x 10^6 tons to zero at Greendale and from 6.92 x 10^6 to 3.21 x 10^6 tons at Jensen, UT following closure of the Flaming Gorge Dam.

Changes in flow and sediment regime have altered the morphology of the Green River. Reductions in peak flows and sediment load have resulted in a decrease in width of the bankfull channel from 6% to 10% (Andrews 1986; Lyons and Pucherelli 1992) and a reduction in effective discharge from 580 to 325 m^3/s in the vicinity of the Jensen, UT stream gage (Andrews 1986). Channel area has decreased due to the expansion of islands, the formation of new islands, and the filling of side channels with sediment (Lyons and Pucherelli 1992). Reduction in peak flows and decreases in channel area have been followed by invasion of riparian vegetation down to the base flow channel (Fisher et al. 1983). The effects of natural and man-made levees coupled with depletions and reduced seasonal variability in flows have reduced the frequency of floodplain inundation in the middle Green River from a 2 or 3 year recurrence interval to a 10 year recurrence interval (Wick 1997) and resulted in increased sediment storage at lower elevations in the channel (Wick 1997; Grams and Schmidt 1999). Mobilization of sediment at lower discharges (Wick 1997) and reduced floodplain connectivity (Stanford 1994; Tyus and Karp 1990; Modde et al. 2001) since closure of Flaming Gorge Dam are two physical alterations that are cited as important factors contributing to reduced recruitment of razorback sucker (*Xyrauchen texanus*) in the middle Green River.

Review of razorback sucker studies

The razorback sucker (*Xyrauchen texanus*) is an endemic catostomid of the Colorado River Drainage and one of four native species found in the Green River that are federally listed as endangered (U.S. Fish and Wildlife Service 1991). Razorback sucker were once widely distributed in warm water reaches of larger rivers from Wyoming to Mexico (Minckley 1973; Bestgen 1990) and were abundant enough in the lower basin of the upper Colorado River to support a commercial fishery (Minckley et al. 1991). Currently, razorback sucker are commonly found in only two areas; Lake Mohave and the middle Green River between the confluence of the Yampa and Duchense Rivers (Bestgen 1990). The Lake Mohave (AZ-NV) population has had near zero recruitment during the last 20 years (Mueller et al. 1998) and numbers declined from about 73,500 to 23,300 individuals during 1988 to 1992 (Marsh 1994). The middle Green River population is the largest extant population of razorback sucker that uses riverine habitat exclusively (Tyus 1987; Tyus and Karp 1990). Estimates for the middle Green River population suggest a population of about 500-1000 individuals (Lanigan and Tyus 1989; Modde et al. 1996) with very limited recruitment (Moode et al. 1996). The basin-wide decline in distribution and abundance of the razorback sucker has been attributed to habitat loss and modification as well as predation on early life stages by non-native fishes (Carlson and Muth 1989).

Razorback sucker are large (commonly 400-700 mm total length) and long-lived (30-40 year lifespan) fish (Minckley 1983; McCarthy and Minckley 1987) that evolved in the highly variable hydrologic conditions of the pristine Colorado River Basin (Minckley 1983; Lanigan and Tyus 1989; Bestgen 1990). The species derives its name from a prominent dorsal ridge found in adults. Wick (1997) suggested that the dorsal ridge acts as a keel and works in conjunction with large pectoral fins to provide stability when feeding in low-velocity backwaters and floodplains. Floodplain habitats and other warm backwater areas are important as nursery areas for juvenile fish and feeding areas for adult fish (Tyus 1987, 1990; Modde 1997; Wick 1997; Wydoski and Wick 1998).

Although razorback sucker are adapted to and frequently collected in lacustrine-like environments (Stanford 1994), other habitats used by adult razorback sucker vary widely and include runs, eddies, and pools (Tyus 1987; Tyus and Karp 1990; Modde and Wick 1997). Diet for all life stages varies but is typically plankton, algae, invertebrates, and detritus (Vanicek 1967; Marsh 1987; Muth et al. 1998). Adults congregate and spawn on the ascending limb of the hydrograph (Stanford 1994) at water temperatures ranging from 10 to 18 degrees C (Tyus 1987). In the middle Green River, Muths et al. (1998) described the spawning period generally as early or mid May through late May or early June. During spawning eggs are usually deposited in the interstices of gravel or cobble substrates where they develop unguarded (Muth et al. 1999). Incubation time and hatching success are temperature dependent (Marsh 1985; Bozek et al. 1990) with incubation time ranging from about 6 to 23 days (Bozek et al. 1990). After emergence, larval razorback sucker enter the drift and are transported downstream (Mueller 1989; Paulin et al. 1989) where the availability of low velocity, warm, and food-rich backwaters is likely a key determinant of recruitment success (Stanford 1994; Modde 1996; Modde et al. 2001). The long lifespan of the razorback sucker and high fecundity (up to 140,000 ova per fish, Minckley 1983) are presumed to be adaptations that allowed the species to persist in a highly variable environment where there might be several consecutive seasons without successful reproduction and recruitment (Bestgen 1990).

Studies reviewing collection data for razorback sucker in the middle Green River during the last ten years have demonstrated the use of two spawning areas; Green River kilometers (RKM) 492-501 near the town of Jensen, UT and the Yampa River near the Green River confluence in Echo Park, CO (Tyus and Karp 1990; Modde et al. 1996). Because of the relatively high capture rate of spawning sucker at the Jensen spawning area (Tyus and Karp 1990) and the potential deleterious effects of Flaming Gorge Dam operations on endangered fishes, most research has focused on the Green River spawning area. During 1992-1996 Wick (1997) conducted an intensive study of physical and biological processes at the Green River spawning area and found that sediment was deposited on the area used by razorback sucker during the spawning season beginning at flows of about 325 m^3/s which corresponds to the post-dam effective discharge estimated by Andrews (1986). The cause of sediment deposition was described as a backwater effect from a downstream constriction that reduced water surface slope in the spawning area during discharges over 325 m^3/s. Wick (1997) hypothesized that reduction in peak discharges since closure of Flaming Gorge Dam has resulted in sediment storage at lower elevations in the channel and sediment transport occurring at a narrower range of lower peak flow levels. Subsequent work using in-channel load sensors at the Green River spawning site found deposition of about 20 cm of sediment occurred during the spawning season (June 1999) at flows of about 500 m^3/s at the Jensen, UT stream gage (Carpenter et al. 2000). These studies support the hypothesis that during some years sediment deposition on the spawning bar could adversely affect incubating eggs or pre-emergent larvae.

Synthesis of larval and adult collection data (Modde 1996; Wick 1997) suggests that a second reproductive bottleneck affecting recruitment of razorback sucker is limited access to backwater and floodplain habitats. Based on length-frequency data, Modde et al. (1996) found that the only recruitment observed since closure of Flaming Gorge Dam has occurred following high flow years. Access to backwater and floodplain habitats during high flows provides conditions needed for recruitment (Stanford 1994; Modde et al. 2001) and may mediate predation by nonnative fishes on razorback sucker juveniles (Modde 1996). High flows may directly reduce the density of nonnative cyprinids that prey on young razorback sucker (Valdez 1990; Osmundson and Kaeding 1991) and also facilitate faster growth by razorback sucker in food-rich backwaters which could reduce vulnerability and increase survival (Modde et al. 1996; Modde et al. 2001).

Both of these potential bottlenecks are affected by the timing, frequency, magnitude, and duration of annual and inter-annual flows. On an annual basis, migration and spawning behavior are likely initiated by a series of cues related to the magnitude of flows, water temperature, and other physical variables (Tyus and Karp 1990; Modde and Wick 1997). Prior to spawning, flows of a particular magnitude are also thought to be necessary to remove fine materials from gravel and cobble spawning bars (Wick 1997). Subsequently, flows must provide nursery habitat for juveniles in backwaters and floodplain areas to obtain recruitment in a given year (Modde et al. 1996; Wick 1997; Modde 2001). Interannually, extreme high flows, although possibly associated with limited recruitment, are required to redistribute sediment, cycle nutrients, reduce non-native plant encroachment, and maintain channel connections with the floodplain (Stanford 1994).

There have been extensive geomorphological studies (e.g., Andrews 1986; Andrews and Nelson 1989; Lyons and Pucherelli 1992; Harvey et al. 1993; Grams and Schmidt 1999) and biological studies focusing on the razorback sucker (e.g., Tyus 1987; Tyus and Karp 1990; Modde et al. 1996; Muth et al. 1998; Modde et al. 2001) conducted in the Green River that have contributed vast amounts of information to our understanding of the physical processes at work in the river and the biology of the razorback sucker. The substantial amount of knowledge gained on the life history, population demographics, and habits of the razorback sucker is notable because many of these studies were initiated after the fish was very rare and federally protected. The goal of the current study is to assess relations between physical variables and potential reproductive bottlenecks for the razorback sucker by investigating and comparing spawning areas in the Green and Yampa Rivers. Specifically, our objectives are to: (1) describe long term trends in hydrology that relate to reproduction of razorback sucker, especially access to floodplain habitats; (2) characterize physical conditions (i.e., hydrology, temperature and the distribution of depths and velocities) over one snowmelt runoff hydrograph at sites used by razorback sucker in the Green and Yampa Rivers; and (3) document movement and habitat use by adult razorback sucker in relation to patterns in flow and habitat availability over time in the Green River. This study plan addresses a National Park Service, Natural Resources Program for Parks (NRPP) Project Statement titled *Impact of Altered Green River Flow on Sediment Deposition and Spawning Behavior of the razorback sucker (Xyrauchen texanus)*. This project was ranked by the National Park Service as a priority project for funding starting in 1998 and continuing through 2000.

METHODS

Study areas

Two sites were investigated; one on the mainstem Green River and one on the Yampa River, both in the Dinosaur National Monument near the Utah-Colorado border (Figure 1). These sites were selected because they represented two of the known spawning locations for razorback sucker in the Colorado River system, and both had been surveyed and sampled by previous researchers (e.g., Tyus 1987; Tyus and Karp 1990; Wick 1997; Modde et al. 1996). The Green River site was located in eastern Utah, about 5.6 km northeast of Jensen, Utah. This site was 1.75 km in length, and located about 4.7 km downstream from the Jensen, UT stream gage. The Green River site (Figure 2) was dominated by a large island that slit the river into a main channel on the south side of the island and a smaller side channel to the north. The side channel contained a gravel bar

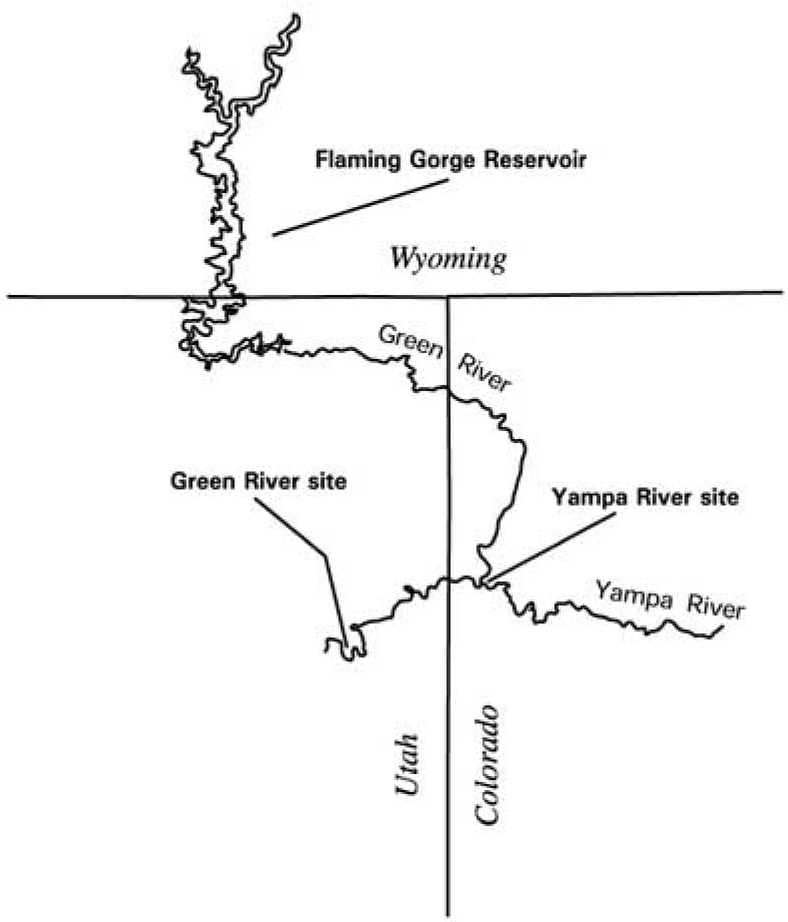

Figure 1. Study area locations on the Green and Yampa Rivers.

near the bottom of the island, where razorback sucker were known to congregate, and presumably spawn, between April and June. A small high-flow channel existed at the upstream end of the side channel, where it was suspected that deposits of sand collected on the declining limb of the runoff hydrograph. A working hypothesis (Wick 1997) suggested that this stored sand was transported downstream to the spawning bar during the rising limb of the hydrograph.

The Yampa River site was located in Echo Park, near the confluence of the Green and Yampa Rivers. The downstream-most boundary of the site was approximately 200 m downstream from the Yampa-Green confluence; the site extended up the Yampa River

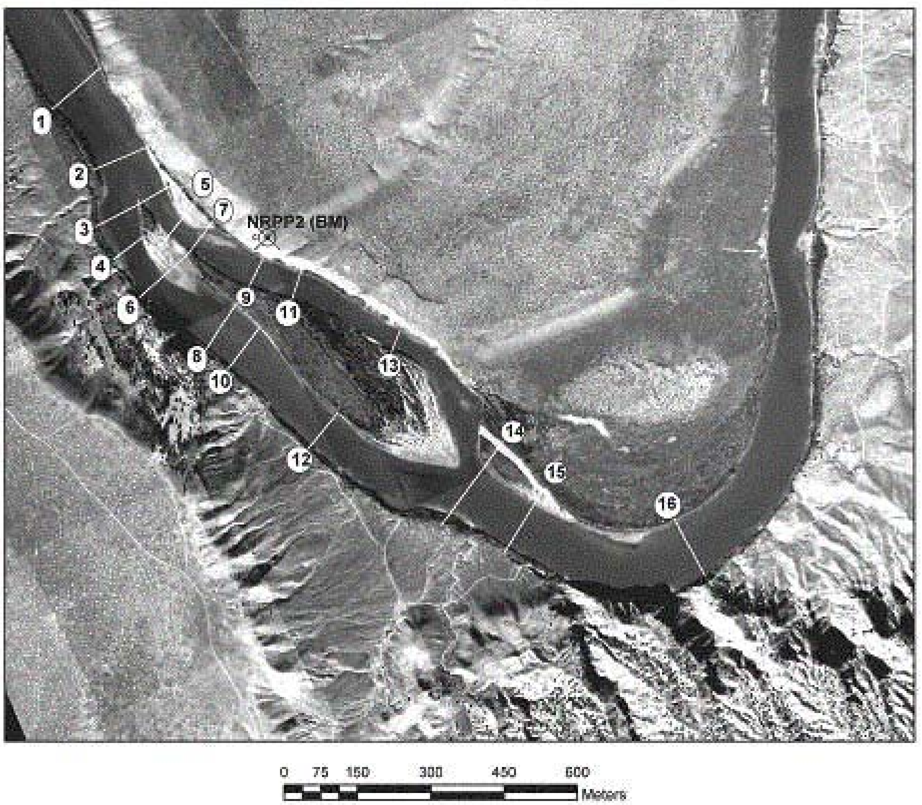

Figure 2. Orthorectified image mosaic of the Green River study area showing transect locations (numbered) and location of the permanent benchmark (NRPP2). Photographs were taken in October 1999 during base flow (73.5 m^3/s). Razorback sucker observations were concentrated near transects five and seven. River flow is from right to left.

for 990 m above the confluence. The study site also included a 350 m section of the Green River above the confluence, and incorporated a high-flow cutoff channel connecting the two rivers at a point on the Yampa River approximately 220 m upstream from the confluence (Figure 3). The Yampa River site had many features in common with the Green River site, including a large sand bar that split the flow into a main channel-side channel configuration. Congregations of razorback sucker had also been observed in the smaller side channel at this site during the spawning season. A primary

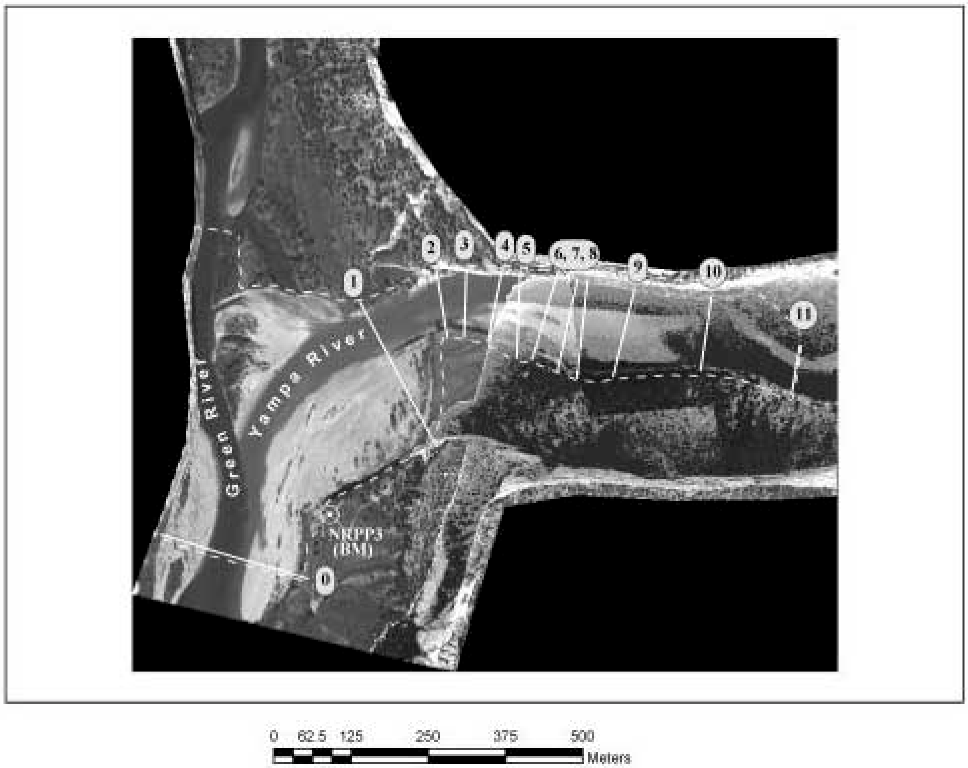

Figure 3. Orthorectified image mosaic of the Yampa River study area showing transect locations (numbered) and location of the permanent benchmark (NRPP3). The study area (dashed line) included a short reach of the Green River. Photographs were taken in October 1999 during base flow (10 m^3/s). Razorback suckers were suspected to spawn in the south side channel in the vicinity of transects four through eight. The eastern part of the image was in shadow when the photographs were taken.

difference between the two sites was the absence in the Yampa River of the sand-channel feature upstream from the spawning bar.

Study approach

A paired-site comparison of channel dynamics, hydraulics, temperature, and physical habitat characteristics between the Green and Yampa River study sites was conducted. The study approach entailed repeated hydrographic surveys at both locations to quantify changes in channel morphology that occurred over the course of one snowmelt runoff hydrograph during 1999-2000. Transects were surveyed before, during, and after the snowmelt runoff to monitor changes in cross-sectional profiles resulting from scour and fill. Topographic and bathymetric data, which served as input to a 2-dimensional hydrodynamic simulation model, were collected. The 2-D hydraulic model was used in conjunction with the Arc/Info Geographic Information System (GIS - ArcInfo V8.0.1, ESRI 2000) to evaluate habitat for the razorback sucker during the spawning season for water years 1984 and 2000. In addition to the hydrographic surveys, continuous temperature recorders were installed at both sites in order to compare the thermal regimes of the two rivers during the 2000 water year. Biological data on habitat use by razorback sucker were obtained from existing literature and a radio telemetry study of fish habitat use and movement.

Physical data collection

Hydrology

The pertinent hydrologic records for our study sites included data from the USGS gages on the Green River at Jensen (# 9261000) and the Yampa River at Deer Lodge Park (#9260050). The Jensen gage had the longer period of record, extending from water year 1947 to present, whereas the Yampa gage at Deer Lodge Park existed only from 1982 to present. The Yampa River record at Deer Lodge Park was extended by summing daily flows from the Yampa River at Maybell and Little Snake at Lily. The mean error between calculated and measured daily discharges at Deer Lodge Park was –1.5%. Errors were normally distributed, with over 70% of the calculated daily discharges within ± 15% of the measured value for each day.

For comparisons of long-term changes in flow regime we partitioned the periods of record for both streams into pre-Flaming Gorge and post-Flaming Gorge segments. The pre-Flaming Gorge period was defined from water years 1947 to 1962, and post-Flaming Gorge from water years 1964 to 2000. The years 1962 and 1963 were omitted from the series because the reservoir was being filled, resulting in atypical hydrographs during that period. Our goal was to select from each of the pre- and post-Flaming Gorge series, annual daily flow hydrographs that represented wet, normal, and dry water years, respectively. This partitioning made it possible to examine differences in daily flow patterns, pre- and post-Flaming Gorge, during years having comparable water supplies.

The partitioning process was conducted in the following manner. Recurrence intervals (Dunne and Leopold 1978) of mean annual flows from 1947 to 2000 for both gages were determined. Normal water years were defined by the median of the ranked data (having a 2-year recurrence interval). Water years having mean annual discharges closest to the long-term median were then selected from the pre-1962 and post-1964 subsets to represent normal or near-normal years. Above-normal water years were determined by ranking the mean annual discharges from highest to lowest and calculating the recurrence intervals for each year. Years having a 6-year recurrence interval were selected to represent above-normal water supplies. A similar process was used to select below-normal water years. In this case, the annual data were ranked from lowest to highest and an 8-year interval used to select years that were drier than normal. Above- and below-normal water years with moderate recurrence intervals were selected because in a historical context these flows were probably important for maintaining habitats relevant to razorback sucker reproduction. The 10-year recurrence interval would have been ideal for this analysis, but owing to differences in the pre- and post-Flaming Gorge periods of record, it was not possible to find years that met the criteria of comparable, moderate return periods having similar mean annual discharges. Thus, selection of the 6-year return period for wet-years and the 8-year interval for dry years was a compromise to meet all of our criteria. Table 1 provides a summary of the selected water years and

Table 1. Water years selected to represent wet, normal, and dry conditions for the pre-Flaming Gorge and Post-Flaming Gorge time periods in the Green and Yampa Rivers. Numbers in parentheses are the mean annual discharges (m^3/s) for each year.

	Green River		Yampa River	
Condition	**Pre-1962**	**Post-1964**	**Pre-1962**	**Post-1962**
Above-normal	1947 (159)	1998 (157)	1952 (84)	1971 (82)
Normal	1956 (132)	1976 (129)	1958 (64)	1973 (68)
Below-normal	1955 (81)	1991 (81)	1963 (32)	1994 (32)

the conditions that they represent. This analysis also included 1984, although this year met none of our selection criteria. During 1984, both the Green and Yampa Rivers experienced the largest mean annual and peak discharges on record. This was also one of few years in recent history when successful recruitment of razorback sucker has been documented (Wick 1997; Modde et al. 1996). Therefore, 1984 was included in the analysis because of its perceived biological importance.

Each of the selected water years was then sub-divided into hydro-periods considered to be hydrologically and biologically distinct. The base flow period was delineated as October 1 through March 31. A runoff period was defined from April 1 through June 30, and a recession period from July 1 through September 30. Flow duration statistics (Dunne and Leopold 1978), were then calculated for each water year type and hydro-period. From a biological perspective, razorback sucker spawn on the ascending limb of the runoff hydrograph, and young fish are transported downstream during runoff and recession. Sediment transport and channel dynamics are also most significant during these two hydro-periods. The base flow period represents a long interval of low flows encompassing the winter months, when young fish may be concentrated among the numerous predators that occur in this system.

Temperature data collection

Continuous-recording temperature data loggers were installed during March 2000 at the Green River site and April 2000 at the Yampa River site. Four temperature recorders were placed in the spawning channel at the Green River site and two each in the Green River upstream from the Yampa confluence, the Yampa River upstream from the Green confluence and in the Green River about 2 km downstream from the Yampa confluence. At each site temperature recorders were installed on both sides of the channel and hourly water temperatures were recorded. Temperature recorders were retrieved in August 2000. Hourly temperatures were reduced to daily means for each temperature recorder. Daily mean water temperatures for each recorder were used to calculate a mean daily temperature for each site.

Control survey

All of the survey techniques used in this study were dependent upon a reliable network of survey control points. During September 1999 three permanent benchmarks were established using survey-grade global positioning system (GPS) equipment. These benchmarks were surveyed from a National Geodetic Survey (NGS) Federal base network control station in Moffat County, Colorado (designation Y 419, PID LN0394) and were used as survey control at the study areas. The primary control point, designated as NRPP1 was established near the headquarters for Dinosaur National Monument. The other benchmarks were established at strategic locations (e.g., where good GPS reception was most likely) near the midpoints of both study sites. A repeat survey from the NGS control point to the primary control benchmark was conducted by a contractor as a check prior to starting airborne laser mapping work. The independent surveys were in relatively close agreement; deviations between the USGS and contractor survey for NRPP1 were 0.036 m (x, y) and 0.012 m (z).

Transect surveys

Initial transect surveys were performed at the Green River site during November 1999 and at the Yampa River site in April 2000. The discharge in the Green River during the November survey was 73 m^3/sec and the discharge during the Yampa survey ranged from 137 to 142 m^3/s. GPS, wading, and boat-mounted sounding systems were used to measure cross sections. A high-tension cable was stretched between anchorages established at the ends of each cross section, and depth measurements were made at regular intervals along the cable. Where wading was possible, the depth was measured with a top-setting wading rod. Otherwise, depths were sounded using a calibrated sounding reel and weight from a boat that was attached to the cable (Buchanan and Somers 1969). The water surface elevation was measured at each cross-section using GPS or differential leveling. Submerged streambed elevations were calculated by subtracting the depth at each interval from the water surface elevation for the transect.

Additional sets of transect data were collected during April and May using a boat-mounted GPS receiver in conjunction with a high-precision echo sounder and acoustic doppler current profiler (ADCP). The Green River survey was conducted during April 25-27 at flows of 200-207 m^3/s, May 16-18 at about 204-238 m^3/s, and during May 27-28 at 405-441 m^3/s. The Yampa River was re-surveyed May 24-25. During this period, the Yampa River was experiencing a secondary peak runoff (the first occurring about two weeks earlier). Discharge increased steadily from 194 m^3/s on May 24 to 248 m^3/s on

May 25. Positions, antenna elevations, depths, and velocities were logged for each cross-section, and streambed elevations calculated by subtracting the measured depth and the distance from the transducer face to the base of the GPS receiver from the measured elevation of the receiver. This procedure eliminated the need to correct for the submersion depth of the transducer, which varied depending on the weight and loading of the boat.

The post-runoff transect surveys were conducted between July 25-26 on the Yampa River and August 8-10 on the Green River. Discharge was 7 m^3/s and 38 m^3/s in the Yampa and Green Rivers, respectively, during these surveys. Transect data in the Yampa were collected primarily with GPS and conventional total station survey equipment, as the flow was sufficiently low to allow wading throughout the study site. Transect data in the Green were collected by GPS and echo sounding, as in the May survey.

Airborne laser mapping

Both study areas were surveyed using airborne laser mapping (LIDAR; Measures 1991) to describe topography for floodplains, tops of banks, tops of islands, and other near-channel features. LIDAR data were collected during October 23-24, 1999 by a contractor using a proprietary airborne laser mapping system from a small, fixed-wing aircraft. Distancing was accomplished by scanning a laser (4 kHz pulse rate) across the flight path of the aircraft. Aircraft position was measured using an on-board dual frequency GPS receiver. During the airborne survey a second dual frequency receiver collected measurements over benchmark NRPP1. Laser distances and differentially corrected GPS data were post-processed in conjunction with data from an inertial measurement unit and a geoid model (GEOID 96) to calculate ground positions and elevations. During final processing a program was used to identify and remove laser returns from tops of vegetation. All LIDAR data processing was completed by the contractor using proprietary algorithms and programs. Hand editing of the final data file was not performed by the contractor. Imagery was also collected during the airborne survey using a 2,000 x 2,000 pixel digital camera. The digital images were co-registered and georeferenced to the laser data. Accuracy of LIDAR elevation data collected for this study varied from 9 cm to over 100 cm root mean square error across different types of terrain. Small errors were associated with relatively flat terrain and large errors were observed on very steep, rocky slopes (Bowen and Waltermire 2002 in press).

Bathymetry

Bathymetric data were collected concurrently with the transect data using the boat-mounted GPS and echo sounder method described previously. Whereas the transect data were collected by traversing the stream at a right angle to the stream flow, bathymetry data were logged longitudinally and along diagonals between transects, moving from upstream to downstream for each course. Additional point data were collected with GPS and conventional surveying instruments to define topography of bars, islands, secondary channels, and shorelines, and to provide for interpretation of LIDAR data.

Composite habitat mapping

As a general procedure, a two-dimensional hydrodynamic simulation model (Ghanem et al; 1994, 1996) and a GIS were used to generate habitat classification maps for a range of discharges at each site. Output from the two-dimensional hydraulic model was exported to the GIS, where it was converted into a raster (grid) format and re-classified. The result of rasterization was a mosaic of aquatic habitat patches having specific characteristics defined by depth and velocity. The GIS was used to quantify the area of different habitat class types at each of the simulated discharges. These results were used to generate a graph of habitat class area versus discharge for both study sites.

Spawning bar substrate characterization

Ten transects were established to characterize substrate at the Green River spawning bar. Transects were placed 10-20 m apart and extended from the north bank of the spawning channel to the north bank of the large mid-channel island. During the recessional limb of the 2000 runoff, substrate was determined at 0.5 m intervals along each transect. Substrate was coded using a modified Wentworth particle size scale

(Bovee 1986). Substrate data were mapped and plotted with fish positions to examine patterns in substrate use.

Biological data collection

Collection of Razorback sucker

Razorback sucker were captured by electrofishing (Smith Root GGP transducer mounted in a jon boat). Three to six passes were made over the spawning bar weekly from May 1 - 22 2000. All razorback sucker captured were placed into a live well after each pass. Each fish was examined for a Passive Integrated Transponder (PIT) tag, weighed (nearest 0.1 of a gram), measured (TL mm), and sexed for identification (i.e., presence of tubercles, express milt or eggs); those fish without a PIT-tag were tagged. Prior to release, records were consulted for the origin of the fish (i.e., wild or hatchery). As part of an independent recovery program element related to development of genetic refugia and brood stock for a future stocking program, all wild females and a limited number of wild males were removed from the river and taken to Ouray National Fish Hatchery.

Implantation of radio transmitters

Radio transmitters were externally attached to razorback sucker collected from the spawning area. The transmitters were 149 Mhz with a 44 day life span (Lotek Engineering Inc.) and weighed approximately 6.5g. Each transmitter was attached externally to the keel (anterior of the dorsal fin) on the dorsal surface of the fish. Each transmitter had four small holes to allow attachment. Prior to attachment fish was anesthetized with tricane methanesulfonate (MS-222). Unconscious fish were placed on their ventral surface in a square shaped wooden platform (41 x 33 cm) and the gills irrigated with dilute MS-222. Two holes were drilled into the keel of each fish using a cordless drill with a 0.23 cm bit. The distance between the holes was approximately 3.5 cm. A 20-gage needle was inserted into the transmitter and through each hole to keep the transmitter fixed onto the keel. Absorbable violet monofilament suture (Ethicon 3-0) was fed through a 20 gage needle until it was exposed on the opposite end. The transmitter was fastened tightly to the keel with a combination of knots. Neosporene was applied to the wound to reduce possible infection. After attachment, the fish was placed into a live well to recover for a minimum of 10 minutes. All fish were released near the spawning site.

Attachment instruments (forceps, scissors, grooved directors, and tweezers) were sterilized in isopropyl (90%) alcohol prior to each procedure. Prior to attaching the external transmitter to the keel of the fish, the frequency (i.e. 149.740 or 149.760) and the code were documented.

Data logging stations

A data logging station was setup on the large island south of the spawning area. The station consisted of three, four-filament Yagi antennas. One antenna faced upstream, the second faced downstream, and the third pointed directly at the spawning bar. The antennas were connected to a Lotek model SRX 400 logging receiver. The receiver was powered by a photovoltaic panel equipped with a battery. The stationary logger operated between May 1 and June 6, 2000.

The station continually scanned for the nine razorback sucker frequency-code combinations. When a fish was within range the transmitter frequency, code, time, and signal strength were recorded. From these data it was determined when each razorback sucker approached and departed the spawning area (i.e. time; date; and time period of activity - nocturnal, diurnal, and crepuscular) and how long each fish remained in the spawning area.

Ground Survey Telemetry

The spawning bar was monitored for a 24-h period to determine specific locations of transmitter attached fish on four dates; May 16-17, May 18-19, May 23-24 and May 24-25. Locations of fish were recorded hourly over each 24-h period. Specific fish locations were obtained by triangulation. The shoreline was walked with a hand held three-element Yagi antenna until a signal was detected. Then bearings were taken using a compass to locate each fish. The locality was triangulated from two of the five known reference locations on the island to provide accurate locations and mapping. The reference location pins were surveyed in by GPS.

Data analysis

Channel change comparisons

Evaluations of change in channel geometry during water year 2000 were conducted at both Green and Yampa River study sites. At both sites a pre- and post-runoff profile was measured at each transect location (Figures 2 and 3) using a combination of conventional and hydrographic surveying methods described previously. For the Green River site, additional measurement data collected during trips between base flow and peak flow were used to describe channel geometry at intermediate flows. Points used for the intermediate flow profiles were selected from hydrographic survey data collected during repeated channel crossings at transect locations. Only survey points within ± 20 cm on either side of the true transect line were included in the intermediate flow data sets. If data for a particular flow and date within 20 cm were not available, survey data from the closest survey date were used to fill in gaps. This approach depicts no change in channel geometry for cases where data were not available. In addition to transect measurements, the topography of the central part of the high flow channel near the upstream boundary of the Green River site was mapped before, during and after peak flow.

Two-dimensional hydraulic modeling

The River_2D two-dimensional (depth-averaged) model developed at the University of Alberta (Ghanem et. al. 1994; 1995; 1996) was used to simulate depths and water velocities at unmeasured flows. This model uses a Petrov-Galerkin upwinding scheme for stability and jump capturing. It can therefore predict, without intervention, regions of supercritical flow and associated transitions. The model also incorporates a highly simplified groundwater flow model for flow in dry (water surface below ground surface) areas. A continuous water surface elevation over the entire domain is predicted. The groundwater component does not attempt to accurately represent subsurface flow fields, but is used merely as a convenient way to handle the lateral wetting/drying boundaries of the surface flow. As such, the groundwater parameters of storativity and permeability are set to arbitrary but small values over the entire solution domain to minimize the groundwater discharge. The model uses a physical description for lateral eddy diffusivity, limited to 0.14 times the bed shear velocity and depth (Fischer, et al. 1979).

A two-dimensional finite element computational mesh consisting of linear triangular elements was generated for each site. The mesh was created in an unstructured fashion with the primary criteria for refinement being topographic matching. For both study sites the pre-runoff channel geometry was used to define bed elevations. Topographic matching was assessed visually by overlaying contour maps in the mesh generation program. At each node the bed elevation and roughness height were specified. Following the model's discretization scheme, these parameters were assumed to vary linearly over each triangle. The computational domain was extended about 120 m in the upstream and downstream directions to minimize the effect of inflow and outflow boundary conditions that were supplied to the model as a uniformly distributed inflow discharge and either a fixed downstream elevation or a function of discharge per unit depth. Hydraulic models were calibrated by comparing observed and predicted water surface elevations for measured flow conditions. Depths calculated from predicted water surface elevations were generally within 3-5% of measured depths and predicted velocities were typically within 5-10% of ADCP measured values.

A range of flows bracketing the discharges observed during the study at each site were simulated. For the Green River site, simulations were run for discharges of 50 m^3/s, 50-750 m^3/s in increments of 50 m^3/s, and 1100 m^3/s. Flows of 6, 30, 50, 100, 150, 250, 300, 350, 400, 500, 750, and 900 m^3/s were simulated for the Yampa River site. The highest discharge simulated at each site corresponds closely to the peak flow of record measured during 1984.

Stream power map development

Maps depicting an approximation of stream power (calculated as depth times mean column velocity) for the range of discharges above were generated to provide a simple evaluation of the potential for sediment transport at different discharges. Because this measure of stream power alone is not useful for making quantitative predictions of sediment transport, comparisons of stream power maps for different flows combined with observed changes in channel geometry at cross sections were used to evaluate the ability of stream power to predict potential sediment movement.

Developing habitat time-series

Habitat mapping and time-series development focused on two potential reproductive bottlenecks for successful reproduction and recruitment of razorback sucker; habitat conditions at the spawning bars in the Green and Yampa Rivers during runoff and subsequent availability of floodplain habitat downstream from the Green River spawning bar. These potential bottlenecks were evaluated by examining: (1) habitat time series for the runoff hydroperiod during water years 2000 and 1984 for both study areas and (2) the availability of floodplain habitat downstream from the Green River site near Ouray, UT. Output from hydraulic simulations was classified based on habitat class definitions (Table 2) to develop maps of habitat for the range of flows simulated. Spawning habitat used by razorback sucker was broadly defined based on data collected by Tyus and Karp (1990). Ninety-five percent confidence intervals were calculated for depth and velocity measurements (Tyus and Karp 1990) and expanded by about ten percent to describe a conservative range of depth and velocity that would represent habitat where spawning was documented based on historical data. The spawning habitat type was designated class 22. Other habitat classes were defined arbitrarily. The resulting relations between flow and habitat area were combined with daily hydrograph data to develop a time series of habitat availability (Bovee 1998). For each site, time series of habitat availability were constructed for the ascending limb of the runoff hydroperiod (1 April – 30 June) for water years 2000 and 1984. The area and persistence of habitat classes over time were summarized graphically using duration curves and compared. Flows during the runoff and recessional hydroperiods combined with area of floodplain inundation curves for the Green River near Ouray, UT (Muths et al. 1999) were used to estimate the extent and duration of floodplain inundation for the years used in hydraulic simulations. Data from 2000 quantified conditions during the fish telemetry study and data from 1984 were used to represent conditions during a year when razorback sucker reproduced successfully. The habitat characteristics for congregations of fish observed during the telemetry study were determined by overlaying the positions of individual fish with a composite habitat

Table 2. Habitat classes used in habitat mapping and time series development. Class 22 was broadly defined based on measurements of depth and velocity associated with spawning razorback suckers in the middle Green River (Tyus and Karp 1990). First digit in class code increases with increasing depth and second digit increases with increasing velocity.

Depth range	Velocity range	Habitat class
0.0 – 0.5	0.0 – 0.4	11
	0.4 – 0.8	12
	0.8 to 1.2	13
	>1.5	14
0.5 – 1.0	0.0 – 0.4	21
	0.4 – 0.8	22
	0.8 to 1.2	23
	>1.5	24
1.0 - 1.5	0.0 – 0.4	31
	0.4 – 0.8	32
	0.8 to 1.2	33
	>1.5	34
>1.5	0.0 – 0.4	41
	0.4 – 0.8	42
	0.8 to 1.2	43
	>1.5	44

map of the Green River site, developed for the discharge at which the fish observations were made.

RESULTS AND DISCUSSION

Hydrographic analysis

Since the construction of Flaming Gorge Dam, peak flows have been reduced and base flows increased in the Green River. Post-dam discharges were lower about 25% of the time, and higher 75% of the time (Figure 4). No such trend was observed in the

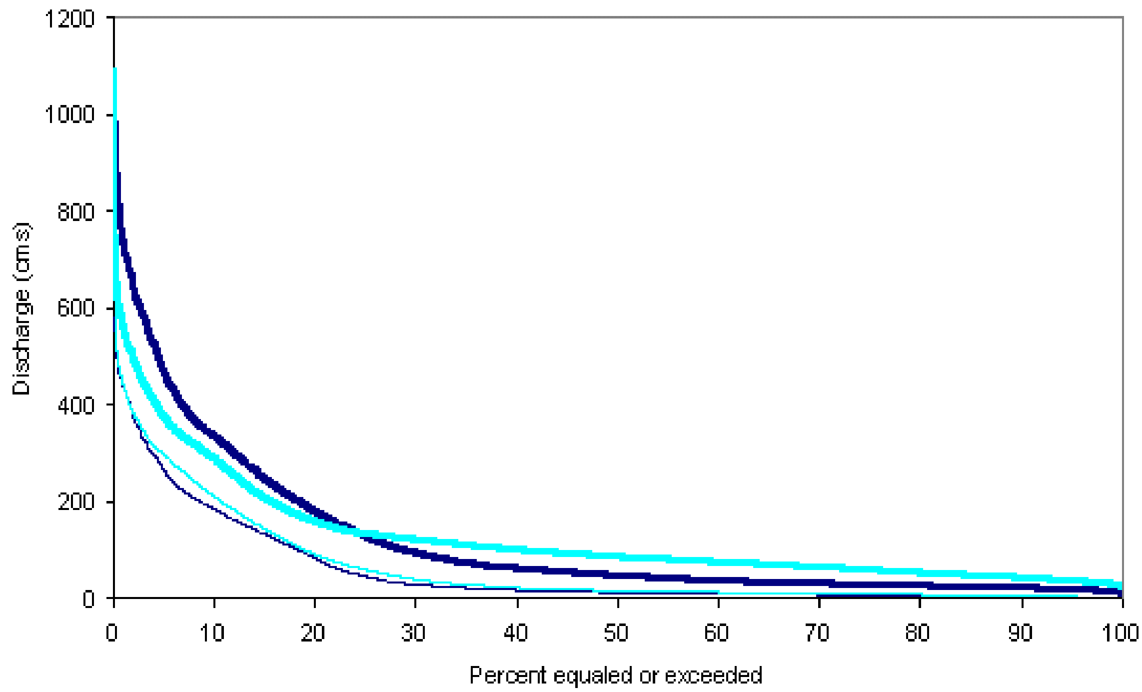

Figure 4. Duration curves for the Green and Yampa Rivers; Jensen, UT stream gage before (dark bold line), after (light bold line); Yampa River near the Green confluence before (dark thin line), and after (light thin line) closure of Flaming Gorge Dam

Yampa River, but the post-dam period was apparently somewhat wetter. The grand mean of discharges for the pre-dam period in the Yampa was 53 m^3/s, whereas the post-dam mean was 63 m^3/s. This is a difference of nearly 19% between the two periods. In the Green River at Jensen, the difference between the pre- and post-dam means was smaller: the pre-dam mean discharge was 124 m^3/s and the post-dam mean was 127 m^3/s, a difference of around 2%.

Differences in daily discharges for normal, wet, and dry years are summarized below by hydro-period. These summaries are based on the representative water years listed in Table 1, rather than all of the years of a particular type (e.g., wet water years are represented by 1947 and 1998 for the pre-dam and post-dam conditions and do not include all of the wet years in the two sub-series). Daily flow hydrographs and flow duration curves for each comparison are included in Appendix **A**.

Base flow period

In the Green River, base flows tended to be considerably higher and less variable across all types of water years during the post-Flaming Gorge period than in the pre-Flaming Gorge period (Figures **A1-A9**). Differences between average daily base flows for the representative water years are summarized in Table 3. In normal and wet years, lowland runoff events occurring near the end of the base flow period were likely responsible for infrequent periods of relatively high discharge under pre-dam conditions. To illustrate, pre-Flaming Gorge base flow was higher than the post-dam flow for 20 days (out of 182) during the normal water years, and for 11 days during the wet years (Figures **A7** and **A8**). After the construction of Flaming Gorge Dam, these lowland runoff spikes occurred less frequently, probably as a result of their storage during February and March.

Table 3. Summary of base flows in the Green and Yampa Rivers for representative wet, normal, and dry years under pre- and post-Flaming Gorge conditions. Percentage differences refer to the amount and direction of change from the pre-dam condition.

	Green river			Yampa River		
Condition	Pre-dam (m^3/s)	Post-dam (m^3/s)	Difference (%)	Pre-dam (m^3/s)	Post-dam (m^3/s)	Difference (%)
Wet	54.3	117.7	+117	10.5	20.5	+95
Normal	44.9	84.6	+88.7	17.7	16.8	-5
Dry	32.6	46.4	+42.4	10.9	16.4	+50

Some fairly large differences in base flow between the pre- and post-dam periods were also observed in the Yampa River. These differences could be partially the result of our selection process. This possibility seems most likely for the wet year pre-dam base flow, which was actually lower than the base flow during the dry year. Although somewhat counterintuitive, it is not uncommon for rivers to experience drier-than-normal base flows during a wetter-than-normal water year. A second possible cause for the differences may be climatic; the post-Flaming Gorge period having been slightly wetter than the pre-dam period in the Yampa River system.

Runoff period

Average daily discharges in the pre-dam Green River were higher in all water year types than during the post-dam period, although the differences were greater during wet and normal years (Table 4, Figures **A1-A6, A10-A12**). Differences in peak discharges between pre-and post-Flaming Gorge were even larger, but the same pattern was observed (Table 5). In the Yampa River, differences between pre- and post-Flaming Gorge runoff hydrographs were more subtle. During the representative normal water

Table 4. Summary of runoff flows in the Green and Yampa Rivers for representative wet, normal, and dry years under pre- and post-Flaming Gorge conditions. Percentage differences refer to the amount and direction of change from the pre-dam condition.

	Green river			Yampa River		
Condition	Pre-dam (m^3/s)	Post-dam (m^3/s)	Difference (%)	Pre-dam (m^3/s)	Post-dam (m^3/s)	Difference (%)
Wet	389.4	319.1	-22.0	295.5	319.1	+43.1
Normal	368.5	241.0	-34.6	220.2	205.0	-6.9
Dry	180.8	164.9	-8.8	100.8	99.3	-1.6

Table 5. Summary of annual peak discharges in the Green and Yampa Rivers for representative wet, normal, and dry years under pre- and post-Flaming Gorge conditions. Percentage differences refer to the amount and direction of change from the pre-dam condition.

	Green river			Yampa River		
Condition	Pre-dam (m^3/s)	Post-dam (m^3/s)	Difference (%)	Pre-dam (m^3/s)	Post-dam (m^3/s)	Difference (%)
Wet	816	510	-37.5	581	555	-4.5
Normal	751	470	-37.4	479	496	+3.5
Dry	337	314	-6.8	254	217	-14.6

years average daily and peak discharges were about the same for both pre- and post-dam periods. The peak discharges in the wet year comparison were also similar, but the mean daily discharges were considerably higher for the post-dam runoff period. The opposite phenomenon was observed in the dry year comparison, where the average daily flows for the period were essentially the same, but the peaks differed by nearly 15%.

Several aspects of the runoff period are noteworthy. First, the runoff hydrographs for the Yampa River and the Green River were commonly bimodal or polymodal. These multiple spikes were more dramatic during normal and dry water years, and represented two or more distinct snowmelt periods. Early-season peaks were probably associated with snowmelt from the south-facing drainages, and late-season peaks from north-facing drainages. The timing and sequencing of these spikes may or may not have biological and geomorphic implications but it is clear that the flow pattern observed in the Green River mirrored that of the Yampa (Figure 5).

A second interesting aspect of the pre- and post-Flaming Gorge comparison relates to water year 1984, the largest water year on record in the Green River basin. The 1984 peak flow was also the highest on record for the Green River, (1,133 m^3/s in the Green River and 915 m^3/s in the Yampa). Taken over the period of record (1947-2000), the recurrence interval for the 1984 peak flow at Jensen was 54 years. However, Green River flow records indicated that discharges approaching 1984 levels occurred frequently prior to the construction of Flaming Gorge Dam. Between 1947 and 1962, the peak discharge exceeded 1,000 m^3/s one year (1957), 900 m^3/s one year (1952), and 800 m^3/s two years (1947 and 1958). Considering only the pre-Flaming Gorge series, the recurrence interval was 17 years for flows over 1,000 m^3/s, and 8.5 years for flows over 900 m^3/s. During those same years, the Yampa River peak flows were 940 m^3/s, 581 m^3/s, 492 m^3/s, and 479 m^3/s, respectively. For the period of record, the peak flow in the Yampa River exceeded 500 m^3/s in 10 out of 52 years, 8 of which occurred during the post-Flaming Gorge period. In contrast, peak flows in the Green River have exceeded 700 m^3/s only three times during the post-Flaming Gorge era. One of those years was 1984, when the Green would have flowed over 900 m^3/s, due solely to discharge from the Yampa.

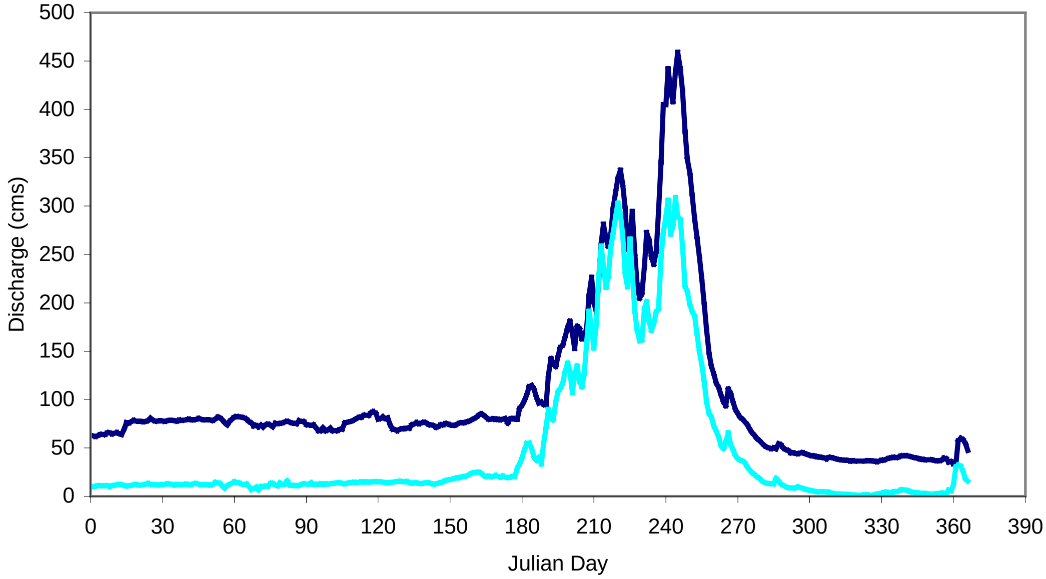

Figure 5. Annual hydrographs for the Green (dark line) and Yampa (light line) Rivers during water year 2000, showing the temporal correspondence in discharges between the two streams. Green River discharge measured near Jensen, UT and Yampa discharge from Deerlodge Park.

It is clear that operations at Flaming Gorge have reduced peak flows in the Green River. Of greater biological significance, however, may be the reduced frequency of moderate-to-large floods, which historically had recurrence intervals of about 5 to 10 years. For example, the pre-Flaming Gorge peak flow with a recurrence interval of 5 years in the Green River was approximately 820 m^3/s. Excluding 1984, the peak discharge has never achieved 820 m^3/s in this reach since the construction of Flaming Gorge Dam. In contrast, the 5-year peak flow in the Yampa prior to 1962 was approximately 485 m^3/s. During the post-Flaming Gorge period, the 5-year peak flow in the Yampa was actually higher, around 520 m^3/s.

The importance of relatively large floods with moderate recurrence intervals to recruitment of razorback sucker has been documented (Wick 1977, Modde et al. 1996, Muth et al. 1999). A primary resource for successful year classes of razorback sucker is the sustained presence of inundated floodplain, where young fish can grow quickly and avoid predation. Muth et al. (1999) provide evidence that this type of habitat is available at the Ouray National Wildlife Refuges when the discharge is greater than 500 m^3/s. Maximum inundation occurs at flows in excess of 640 m^3/s, and decreases rapidly between 640 and 500 m^3/s. Prior to construction of Flaming Gorge Dam, flows in excess of 600 m^3/s occurred for 10 days or longer in 6 of 16 years (37.5% of years, Figure 6). After Flaming Gorge, flows of this magnitude and duration occurred in 3 years out of 37 (8.1% of years, Figure 6). In 1983, flows in the Yampa River alone exceeded 600 m^3/s for 3 days, and in 1984, for 21 days.

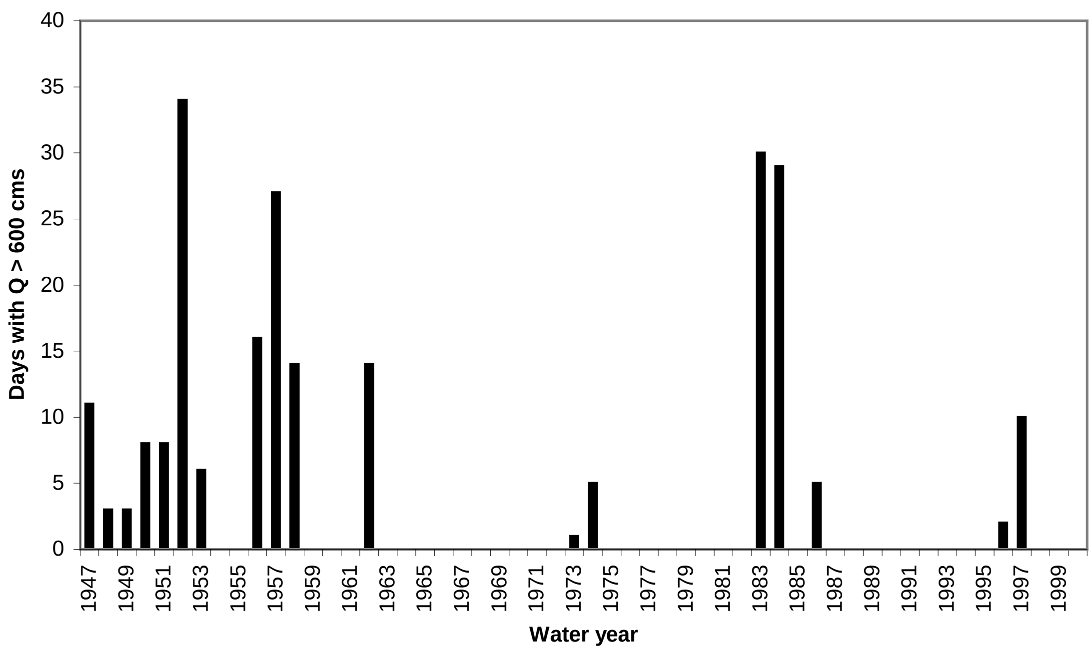

Figure 6. Number of days per water year, with discharges in excess of 600 m^3/s at the Jensen gage on the Green River.

Recession period

The recession period was arbitrarily defined as the interval from July 1 to September 30. During this time stream flow decreases to base flow. Because of the inherent variability of discharge during the recession, average flows for the period may have less meaning than during the base flow and runoff periods. The more relevant aspects of the recession period may be the difference in discharge between runoff and base flow and the rate of decrease. Historically, the recessions in both rivers were typified by large differences between the runoff peak and the base flow, with a rapid decline during July followed by a more gradual reduction during August and September. Stanford (1994) and Wick (1997) have both implicated a reduction in amplitude between peak flows and base flows as a likely contributor to the decline of native fishes in the upper Colorado River basin. Although the cause and effect relationship is complicated, the underlying importance of the amplitude of the peak-base cycle appears to be related to competition and predation by introduced species. Stanford (1994) suggested that native species are better adapted than non-natives to the naturally high variability of stream flow typical of pre-development Great Basin Rivers. Reduction of this variability may favor recruitment and survival of non-native species and alter food web dynamics. The rate of decline from the peak flow may also be important in the same context. Young razorback sucker are known to rear successfully in embayments and depressions on floodplains. If the peak flow is sustained and the rate of decline to the base flow is rapid, the potential for occupancy of these areas by non-native fishes may be reduced, thereby mediating predation on young razorback sucker. Table 6 summarizes the changes in amplitude of the recession, both in terms of absolute differences and as the peak-to-base ratio. The rates of decline are depicted in Table 7 as the negative exponents of a power curve fit to the daily data for the recession period: the smaller the exponent (i.e., the larger the value of the negative number), the more rapid the rate of decline.

Table 6. Summary of recession period amplitude differences (m^3/s) in the Green and Yampa Rivers for representative wet, normal, and dry years under pre- and post-Flaming Gorge conditions. Ratios are expressed as peak flow divided by base flow.

	Green river				Yampa River			
Condition	Pre-dam amplitude (m^3/s)	Post-dam amplitude (m^3/s)	Pre-dam ratio	Post-dam ratio	Pre-dam amplitude (m^3/s)	Post-dam amplitude (m^3/s)	Pre-dam ratio	Post-dam ratio
Wet	665	431	15.8	9.0	559	502	105	96
Normal	681	399	29.9	8.8	472	444	179	65
Dry	291	256	11.5	7.1	171	177	121	174

Table 7. Exponents for power curves fit to daily discharges during recession periods in the Green and Yampa Rivers for representative wet, normal, and dry years under pre- and post-Flaming Gorge conditions.

	Green River		Yampa River	
Condition	Pre-dam	Post-dam	Pre-dam	Post-dam
Wet	-7.87	-4.80	-11.52	-12.58
Normal	-8.52	-4.13	-12.41	-10.70
Dry	-6.95	-4.21	-7.22	-11.02

In the Yampa River, the differences between peak and base flow values are remarkably similar for pre- and post-dam periods in all water year types, although there is considerable variation among the ratios (Table 6). It is noteworthy that the recessional amplitudes for the Yampa are similar to those for the Green, and the ratios are an order of magnitude higher. This phenomenon can be interpreted to mean that the relative difference between the runoff peak and base flow is much larger in the Yampa River than in the Green. Likewise, the power function exponents in Table 7 are roughly 50% steeper in the Yampa for nearly all cases, indicating that the transition from peak flow to base flow is precipitous in the Yampa compared to the Green. The pre-dam to post-dam comparison for the Green shows pre-dam amplitudes and ratios in the Green River were 50% to 100% higher than those during the post-dam period, except during dry water years. Power function exponents indicate that the recession was more gradual during the post-Flaming Gorge period than it was prior to construction. For example, during a normal water year, the pre-dam rate of decline was over twice that of the post-dam period.

Water temperatures

Water temperatures measured during April - June 2000 in the Green and Yampa Rivers upstream from the confluence were about 1.6 degrees C lower in the Green River based on the mean of daily differences (Figure 7). Mixing of the Yampa and Green flows resulted in an average increase of one degree C in Green River water temperature about 2 km downstream from the confluence. At the spawning bar, about 50 km downstream, water temperatures in the Green River were very similar to temperatures in the Yampa River near the confluence (mean difference = -0.01 degrees C, standard deviation of differences = 0.47 degrees C). Because water temperatures were within the range measured during previous spawning observations (10-18 degrees C; Tyus 1987) and very similar to those in the unregulated Yampa River, it is unlikely that water temperature directly limited razorback sucker reproduction in the Green River during the 2000 runoff. The difference in water temperatures during runoff at the Green River spawning area between the pre- and post-Flaming Gorge periods was not quantified. However, based on water temperatures measured at the Green – Yampa confluence some level of water

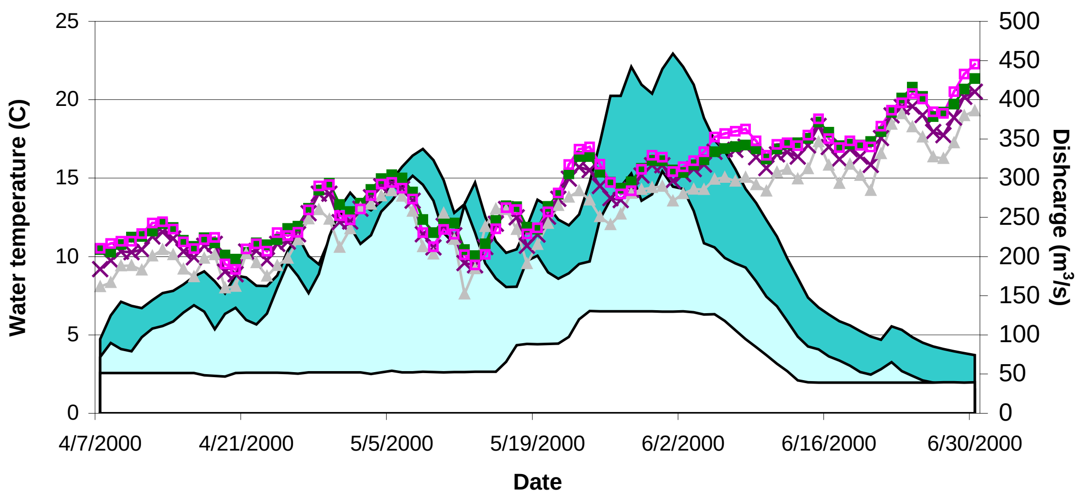

Figure 7. Mean daily water temperatures measured during April – June 2000 in the Yampa River 800 m upstream from the Green confluence (open squares), Green River 1 km upstream from the Yampa confluence (filled triangles), Green River 2 km downstream from the Yampa confluence (x), and Green River 50 km downstream from the Yampa confluence (filled squares) at the razorback bar spawning area near Jensen, UT. Dishcarges are also depicted for Green River flow at Greendale (white area), Yampa River discharge at Deerlodge Park (light shaded area), and Green River near Jensen (dark shaded area).

temperature depression at the Green River spawning area resulting from Flaming Gorge operations is suspected. Potential effects of slightly lower water temperatures in the reach near Jensen, UT include increasing the time needed for razorback sucker egg incubation (Bozek et al. 1990) and decreasing rates of primary and secondary production in backwaters (Stanford 1994). These effects could alter timing of emergence, and subsequent food availability for juvenile razorback sucker.

Channel change comparisons

Repeated cross section measurements in the Green River demonstrated that patterns of scour and fill over the course of runoff are variable and complex (Appendix **B**, Figures **B1-B8**). In general, cross sectional elevations were higher after the 2000 runoff (August 2000) than before runoff (November 1999). The largest pre- and post-runoff changes in channel geometry were observed at cross sections one and two near the downstream end of the site: cross section one showed greater than 0.75 m of scour near the north bank and a smaller amount of fill in the center of the channel (Figure **B1**) while cross section two filled greater than 0.5 m for over half its length (Figure **B1**). Both of these cross sections are in an area of the channel dominated by large lenses of sand that are visible as light areas under the water surface in Figure 2.

Cross sections in the spawning bar area of the side channel (three, five, and seven) showed filling over the course of runoff (Figures **B2-B4**). Data from cross section seven in the center of the spawning area indicate that fill observed at this cross section had occurred by late April at flows not greater than 207 m^3/s. The depth of fill at cross section seven measured during April and August (20-25 cm) was corroborated by depth of fill over a temperature logger installed near the cross section in March and recovered during August 2000. Sediment deposited during April at cross section seven did not originate in the high flow sand channel; cross section measurements showing deposition at transect seven were completed prior to inundation of the high flow sand channel. Data from cross section five, also near many of the fish telemetry observations, show a smaller amount of deposition during April and less overall change in channel profile over time. These findings suggest that some deposition of sediment over areas most frequently used by razorback sucker during 2000 occurred prior to their arrival at the spawning area in May. Cross sections 8, 9, 10, 12, 13, and 16 all showed relatively large changes in bed elevation, predominated by filling, during May then returned to a condition similar to the pre-runoff channel geometry by August (Figures **B4-B8**). Cross sections 4, 6, and 11 exhibited relatively small changes during the 2000 water year (Figures **B2**, **B3**, and **B6**).

The high flow, sand filled-channel near the upstream boundary of the Green River site scoured and refilled during the course of the study. Based on observations during data collection trips, the sand channel began flowing in April 2000 at a discharge between 207 and 210 m^3/s (Figure 8). Repeated topographic surveys and cross section measurements indicated a net outflow of 982 m^3 of sediment from the sand channel between November 1999 and May 2000. During recession (May – August 2000) the sand channel refilled with 343 m^3 of sediment. These volumes divided by the area mapped (approximately 1550 m^2) correspond to an average change in bed elevation of –0.64 m and +0.22 m for the high flow sand channel during runoff and recession, respectively. These estimates are conservative because the channel margin on each side was excluded from the mapped area to maintain a relatively planar surface.

Simulated water surface profiles for the Green River study site showed a backwater effect encroaching on a riffle near the spawning area at a flow of 100 m^3/s. At a discharge of 200 m^3/s the riffle was drowned and by 400 m^3/s the entire study site was behaving as a low gradient run (Figure 9). Wick (1997) observed a pattern of filling during runoff and subsequent scouring during recession at transect nine located in the vicinity of the spawning area. Reduced water surface slope at flows of 325 m^3/s and larger combined with an available supply of mobile sediment (e.g., the high flow sand-filled channel near the upstream site boundary) were reported to be responsible for deposition. Noticeable sedimentation was reported at 410 m^3/s (Wick 1997) which corresponds closely to the flow (400 m^3/s) at which the site behaved as a low gradient run based on year 2000 hydraulic simulations. Results from the 1999-2000 survey at transect nine demonstrated a pattern of fill and scour similar to that observed in 1993 (Wick 1997) with the largest amount of fill measured during late May 2000 at flows of 405-441 m^3/s (Figure **B-5**). Measurements during August 2000 showed that deposits had scoured and the cross section profile was very similar to the pre-runoff condition. A similar pattern of fill and scour during 1999-2000 was observed at cross sections 8, 9, 10, 12, 13, and 16 in both the main and side channels (Figures **B4-B8**). These observations indicate the pattern of fill and scour first observed by Wick (1997) is not uncommon throughout the site and that sediment is being supplied from upstream sources not limited to the high flow sand-filled channel near the upstream site boundary.

Figure 8 bottom. Photographs of the high-flow, sand filled channel entrance (top) and exit (bottom) near the upstream boundary of the Green River study site. The channel was just beginning to carry water during April 2000 at a flow of about 207 m^3/s.

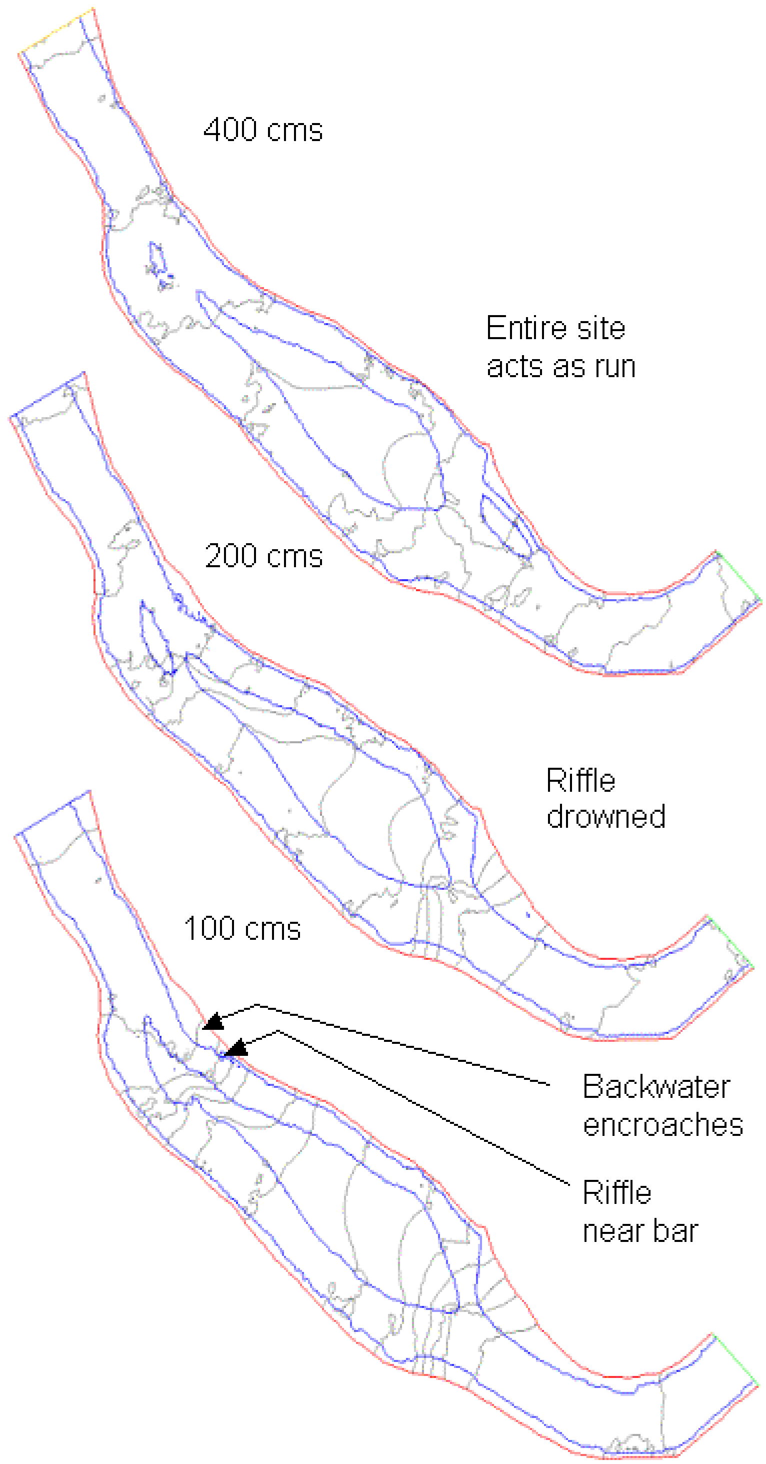

Figure 9. Simulated water surface contours (0.1 m interval) for the Green River study site at three discharges. Contour lines crossing island boundaries represent groundwater. River flows from right to left.

Sediment deposition occurred at cross section seven in the spawning bar area before April 27, 2000 at flows less than 207 m^3/s. This deposition occurred prior to inundation of the high flow, sand channel near the top of the site suggesting movement of existing in-channel sediment, probably as bedload. The discharge associated with inundation of the high flow, sand filled channel at the upstream end of the Green River study area was near 210 m^3/s during 2000. The flow required for inundation of the high flow channel is related to the elevation of the sand deposit which is determined by flows during the previous year; lower peak flow during 2000 compared to 1999 resulted in a net loss of sediment from the high flow channel during the water year 2000. Although the high flow channel contributes sediment to the side channel spawning area, data from repeated cross section surveys in the side channel and main channel suggest that lenses of sand move through the study area at a range of discharges and that upstream sources other than the high flow channel are also contributing sediment to the study area. The high flow channel is a relatively limited source of sediment but its behavior demonstrates at a small scale the important interaction of antecedent and current year conditions in determining sediment transport and deposition in the Green River spawning area.

The overall trend in the Yampa River between the pre-and post-runoff surveys was one of scour, with fill in a few localized areas (Figures **B9-B13**). Most of the scour occurred in the main (north) channel, where the change in streambed elevation ranged from essentially zero at cross-sections six through nine to nearly a meter at locations on cross-sections one, three, and four (Figures **B9-B11** and **B13**). The maximum scour was observed at cross-section ten, where the main channel thalweg elevation shifted position and decreased by nearly 1.2 m (Figure **B13**). The most significant areas of fill occurred at cross-sections two and three (Figures **B9** and **B10**). The average elevation of the streambed at cross-section two increased by 0.73 m between the main channel thalweg and the south bank of the side channel. At cross-section three, both the main and side channels were scoured, but an average elevation increase of nearly 0.5 m had apparently occurred at the downstream end of the sand bar that divided the two channels. The localized deposition at these two cross-sections might indicate the transport of a slug of sediment, in the form of a lens or a dune, through the study reach during the runoff period. It is noteworthy that the survey conducted during May indicated streambed elevations comparable to those measured during July. This finding suggests that the bulk of the channel movement had occurred prior to the secondary peak runoff in late May, and probably occurred during the initial runoff period in early May.

Stream power

For a particular discharge the range of stream power values generally was twice as large at the Yampa River study area compared to the Green River site (Figures **C1-C26**). Additionally, the proportion of the study area with relatively high stream power values was consistently larger at the Yampa site suggesting that if sediment inputs to the Green and Yampa study reaches were equal, the Yampa River site would have a higher sediment transport rate. At both sites the side channel spawning areas were characterized by low stream power relative to the main channel; values were typically 50-75% lower in the side channel at both sites compared to the maximum stream power value for a particular discharge. In some cases there was reasonable correspondence between stream power for water year 2000 discharges and observed channel change (e.g., Yampa River cross sections three and four) but generally stream power was a mediocre predictor of channel change at individual cross sections.

Physical habitat

Relations between discharge and area of 16 habitat classes indicated that the Green River site had a proportionally larger area of slow current velocity habitat classes across all depth ranges than the Yampa site for the discharges simulated (Figures **D60-D63**). The Yampa River site was dominated strongly by deeper and faster habitat classes at flows over 250 m^3/s (Figures **D62 and D63**). At the Green River site slow velocity habitats were associated with the side channel, margins around the large central island, the spawning bar, and the area around the high flow channel near the upstream end of the study area (Figures **D1-D15**). Persistence of slow current velocity habitats at discharges over 250 m^3/s at the Green River site was due largely to the size and elevation of the central island, spawning bar, and side channel bed as well as the elevation of the island associated with the high flow channel (Figures **D6-D15**). The Yampa River site was smaller overall than the Green River study area and had a narrow, constrained channel.

Additionally, the island in the Yampa River site was smaller and lower in elevation relative to bank height than the island in the Green River study area resulting in inundation at lower discharges and reduced effects on nearby current velocities (Figures **D32-D43**).

Comparison of habitat duration curves for the ascending limb of the runoff period (April 1 - May31) between 1984 and 2000 revealed patterns in habitat availability at both sites. In the Green River study area there were larger areas of habitat available for longer periods of time during 2000 compared to 1984 for 12 of the 16 habitat classes (Figures **D16-D31**). With the exception of class 43, the area of deep (>1.5 m) habitat classes was larger during 1984 than in 2000 at the Green River site (Figures **D28-D31**). Area of shallow (0.5-1.0 m), moderate velocity (0.4-0.8 m/s) habitat (class 22) in the Green River, which encompasses the general range of depths and velocities where ripe razorback sucker were collected during 1981-1989 (Tyus and Karp 1990), was consistently larger over time during 2000 compared to 1984. At the Yampa River site, differences between habitat duration curves for 1984 and 2000 generally were smaller (Figures **D44-D59**) compared to the Green River site owing to similarity in the shape of habitat versus flow functions for many of the 16 habitat classes (Figures **D62 and D63**). Similar to the Green River results, area of very shallow (0.0-0.5 m), shallow (0.5-1.0 m), and moderately deep (1.0-1.5 m) habitat classes typically were larger during 2000 compared to 1984 (Figures **D44-D55**) and excluding class 43, the area of deep habitat classes was larger over time during 1984 (Figures **D56-D59**). During 2000 there was a slightly larger area of habitat class 22 available at the Yampa site compared to 1984 (Figure **D49**). Generally, the larger differences in very shallow, shallow, and moderately deep habitat duration curves at the Yampa site occurred in the 50-100% exceedence range whereas at the Green site differences were more evenly distributed across exceedence probability.

Habitat conditions during the time fish were detected in the spawning area at the Green River site were very different between 2000 and 1984. During 2000 fish were observed in the spawning area from May 1 through May 25. In 1984, razorback sucker were collected in the vicinity of the spawning area during May 3 through June 14 (Tyus and Karp 1990; Tyus 1987). During both 2000 and 1984 flows increased and peaked during May; mean daily May discharges were 682 m^3/s and 301 m^3/s for 1984 and 2000, respectively. Based on hydraulic simulation results and the mean May discharge, in 1984 the Green River side channel and the area over the spawning bar would have been dominated strongly by deep and fast habitat classes (Figure **D13**). In contrast, the mean May discharge during 2000 provided relatively high habitat diversity and large areas of shallow to moderately deep habitat classes in the side channel (Figure **D6**). During May 2000 the area including the spawning bar contained shallow, moderate velocity habitat and large areas with depths and velocities similar to habitat class 22.

Differences in habitat versus flow relations and the comparison of habitat conditions between 1984 and 2000 show that the Green River site maintains proportionally larger areas of diverse habitat classes over the range of discharges simulated compared to the Yampa River site. Relations between flow and habitat for the Yampa site strongly reflect the incised channel and relatively small size and low elevation of the island that creates the side channel spawning area. Because of these characteristics, deep and fast habitat classes predominate at flows typical of the ascending limb hydrograph in the Yampa River.

Comparison of habitat duration curves and habitat maps at the Green River site for the ascending limb of the 1984 and 2000 runoff shows that habitat conditions were considerably different between years. The 1984-2000 comparison was based on 2000 channel geometry only. Thus, differences in hydraulic model output and habitat maps resulting from using the 2000 channel geometry to represent conditions in 1984 were not accounted for in 1984 habitat estimates. However, because of the large difference in May discharges between years and the lack of recent channel migration near the site, the comparison was probably representative of general differences in habitat between years. There was more moderate depth and moderate current velocity habitat, typical of areas where spawning razorback sucker were collected in other studies (Tyus 1987; Tyus and Karp 1990), available during the ascending limb of the hydrograph during 2000 than in 1984. During the ascending limb of the 1984 hydrograph, habitat in the side channel and spawning bar area was characterized predominantly by relatively large depths (> 1.5 m) and fast current velocities (> 1.5 m/s). Razorback sucker were collected in the Green River study area during both 1984 and 2000 and recruitment was documented from 1984

(Modde et al. 1996). Presence of razorback sucker at the Green River spawning bar under very different hydraulic conditions during 1984 and 2000 suggests that use of the spawning area by razorback sucker is driven by physical variables or other cues besides the distribution of water depths and current velocities alone.

Relations between physical variables and year 2000 fish observations

Between May 1 and May 20, 2000, 19 razorback sucker were captured on the spawning area with electrofishing equipment (Table 8). Ten of the 19 fish collected were wild fish and the remaining fish were hatchery-produced fish ranging between ages 6-9 and stocked in 1998 and 1999. All but two small hatchery fish stocked in 1999 were identified as fish approaching spawning condition (i.e. tuberculate males, or females with inflamed genital region). Among the fish collected eight were implanted with radio transmitters; three wild males and five hatchery produced fish (four males and one female). Because wild fish were needed for development of a genetic refugia as part of the species recovery effort, both wild females and five wild males were removed from the river and taken to Ouray National Fish Hatchery to be used as broodstock for reintroduction efforts. Among the eight fish implanted, five fish were later detected for a minimum of at least 5 d on the spawning bar (Appendix **E**). Razorback sucker were present on the bar during the first electrofishing sampling date, but appeared in peak numbers on the May 5 sampling date, after which fewer fish were collected.

Fish collected by electrofishing and counted by the stationary telemetry logger indicated razorback sucker occupied the spawning area between May 1-25, 2000 (Figure 10). Because fish were present in the area on the first day of electrofishing, it is likely that fish were present in the spawning area before May 1. Telemetry logging data indicated that the duration of spawning was detected better by telemetry than electrofishing, suggesting that fish may be avoiding electrofishing boats after repeated passes through the area. On May 9 no fish were collected with electroshocking and the following day, a monitoring effort was conducted to determine the location of fish previously on the bar. Only two fish were located by telemetry equipment within six kilometers of the spawning area (code 39 = 498.7km, code 41=505.1 rkm).

Table 8. Dates, size, sex, capture status, reproductive condition, origin and disposition of razorback sucker collected form the Escalante spawning area (RKM 504.3) in the middle Green River between May 1-22, 2000.

Date	TL	WT	Recap	Sex	Sex Characteristics	Origin	Code	Disposition	Date Stocked	Year Class
05/01/2000	507	1389	Y	M	TUBERCLES	WILD	38	RELEASED		
	426	757	HAT	M	TUBERCLES	HATCHERY	39	RELEASED	1999	1994
	510	1452.8	Y	F	RIPE	WILD		HATCHERY		
05/02/2000	510	1475.5		M	TUBERCLES	WILD		HATCHERY		
05/05/2000	474	980	Y	F	TUBERCLES	HATCHERY	33	RELEASED	1998	1991
	518	1430.1	Y	M	TUBERCLES	WILD		HATCHERY		
	414	685	HAT	M	TUBERCLES	HATCHERY	40	RELEASED	1999	1993
	536	1649	Y	M	TUBERCLES	WILD		HATCHERY		
	492	1440	Y	M	TUBERCLES	WILD		HATCHERY		
	533	1578	Y	M	TUBERCLES	WILD	41	RELEASED		
	389	580	HAT			HATCHERY	32	RELEASED	1999	1993
	399	611	HAT			HATCHERY		RELEASED	1999	1993
05/08/2000	464	1135	Y	M	TUBERCLES	WILD	34	RELEASED		
	410	572	HAT	M	TUBERCLES	HATCHERY	36	RELEASED	1999	1993
	405	661	HAT	M	TUBERCLES	HATCHERY		RELEASED	1999	1993
	520	1452.8	Y	F		WILD		HATCHERY		
	400	607	HAT	M	TUBERCLES	HATCHERY		RELEASED	1999	1993
05/09/2000	no fish- 4 passes									
05/11/2000	468	998.8	Y	M	TUBERCLES	WILD		HATCHERY		
	471	954	HAT	F		HATCHERY		RELEASED	1999	1991
	recaptured from 5/5/00							RELEASED		
05/12/2000	no fish - 4 passes									
05/15/2000	recaptured from 5/5/00									
05/17/2000	recaptured from 5/8/00[1]					HATCHERY				
05/22/2000	no fish - 4 passes									Code

[1] Fish with transmitter code 35 was first captured on 5/8/2000 but on date the transmitter was not attached. It was recaptured on 5/17/2000 and a transmitter was attached on that date.

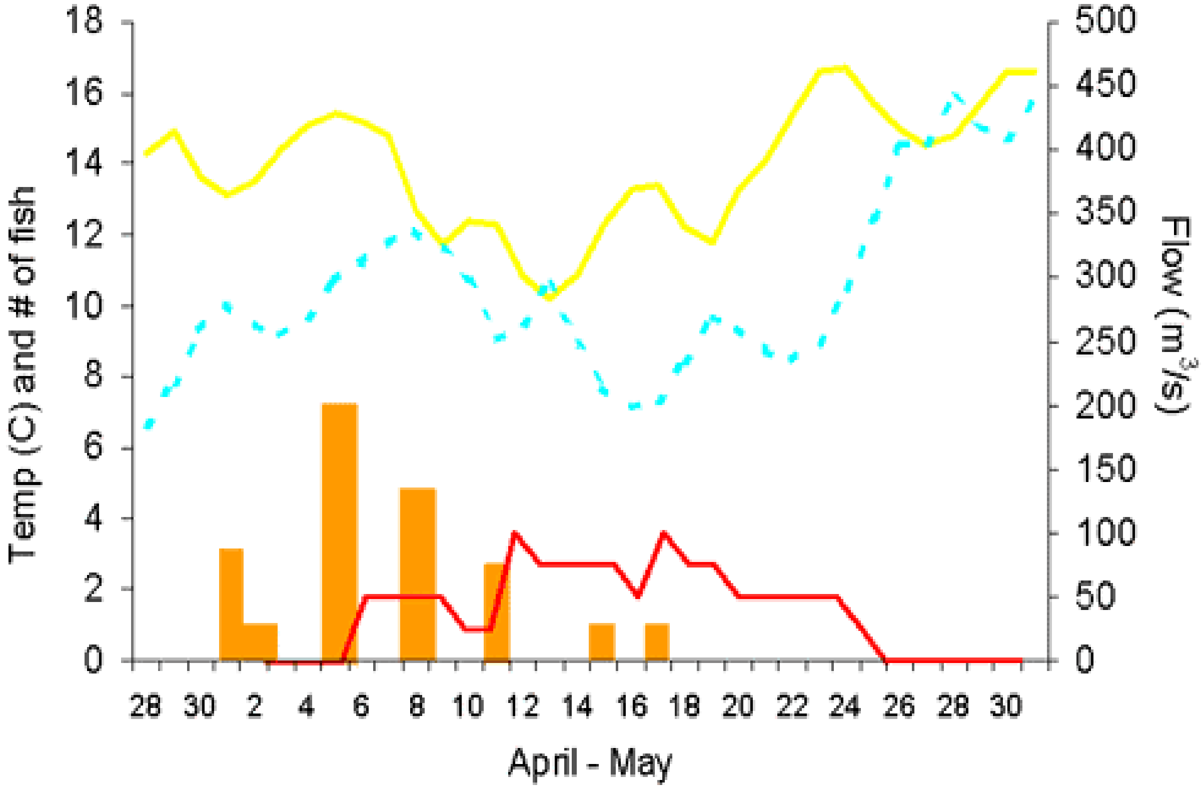

Figure 10. Numbers of razorback sucker collected with electrofishing (bars) and total hours that fish were detected in the spawning area (dark solid line) by a stationary telemetry logger compared with temperature (light solid line) and discharge (dashed line).

The movement of fish away from the spawning area was coincident with a rapid water temperature drop. The greatest number of fish detected by telemetry occurred on May 11 when four fish were detected, and at least three fish were detected between the 11th and 18th of May (Appendix **E**). No fish were detected in the spawning area after water temperature exceeded 17 degrees C.

The time fish spent in the vicinity of the spawning bar, as detected by the stationary telemetry logger, was equally divided between diurnal and nocturnal hours (Figure 11). Among the four diel monitoring efforts, four separate fish were monitored in

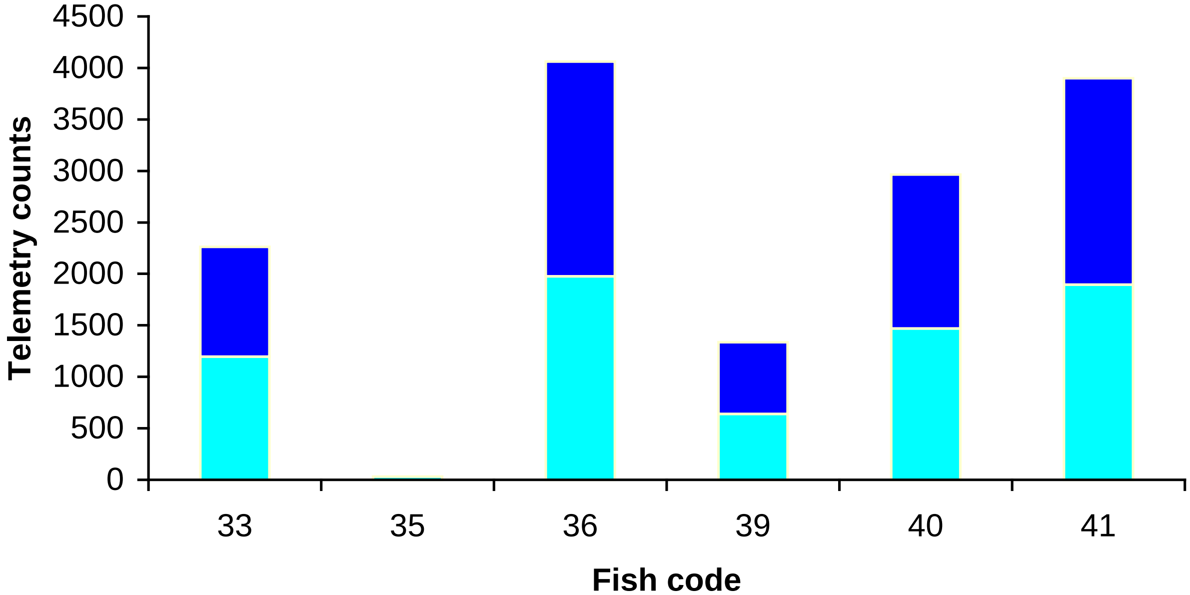

Figure 11. Number of telemetry counts in daylight (07:00-18:59, light bars) and darkness (19:00-06:59, dark bars) in which individual fish were recorded in the vicinity of the Escalante spawning bar (RKM 504.3) in the middle Green River between May 1 and June 6, 2000.

the spawning area. During the May 16-17 and May 18-19 surveys, transmitter codes 39, 40, 36 and 33 were located near the suspected spawning area. During these dates, fishes 39, 40 and 36 were located often in depths of less than 1.0 m and velocities between 0.4 and 1.2 m/s (Figures 12 and 13). However, fish were located in several different areas, including the main channel during the monitoring period. Fish 33, the only female implanted with a transmitter, was first located near the spawning bar on May 15 (implanted 10 d previously). During the diel monitoring, fish 33 was not located on the spawning bar between 23:30 and 02:50 on the 18th and 19th of May, respectively. During both the 18th and 19th of May, fish 33 was detected in the vicinity but was located upstream of the spawning bar. The two fish (codes 33 and 36) monitored on two successive days between 23-25 of May appeared to be moving away from the spawning area with fish located both downstream and in variable depths and velocities. During the last diel monitoring effort the last fish remaining in the spawning area (code 33) left the spawning area before the completion of the 24 hr monitoring period.

The base substrate of the area more frequently used by fish during the 16-17 and 18-19 May diel monitoring periods consisted primarily of gravel and cobble size particles. No distinct pattern of either substrate distribution or fish association with a particular substrate size was found (Figure 14). However, locations of fish 40, 36 and 39 appeared frequently in or near a small, shallow, side channel between two gravel/cobble bars near the north shoreline (Figures 2, 12, and 13).

Razorback sucker in the middle Green River were found at the spawning area near Jensen during the ascending limb of the 2000 hydrograph. Fish were already at the spawning area on the first collection date, May 1, and the last fish with an attached radio transmitter left the area on May 25. Modde and Irving (1998) reported that razorback sucker were collected at the same spawning area as early as April 20 and 25 in 1994 and 1995, respectively, and the greatest number were present during the first and second week of May. During the low flow year of 1994 (e.g., peak < 300 m^3/s) fish were not found on the bar after May 24, whereas, during the higher flow year of 1995 (e.g., peak ~ 550 m^3/s) fish were found as late as June 9. It is likely that fish had moved to the spawning area just prior to the start of this study. Therefore, although flows varied among the years of 1994, 1995, and 2000, fish appeared to migrate at approximately the same time, i.e., early in the ascending limb of hydrograph. Fish may remain in the spawning area for a longer time period if flows are higher such that spawning occurs at a time so that larvae emerge at or around peak flows (Muth et al. 1998). Although increase in discharge may initiate migration, temperature appeared to be a major factor in maintaining fish presence in the spawning area in the spring of 2000. When temperature declined rapidly during May 9, no fish were collected with electrofishing and all of the fish with attached transmitters left the vicinity of the spawning area. However, within 48 h, many fish had returned even though temperature had not increased appreciably. Therefore, the rate of temperature drop may be as important as absolute temperatures to spawning behavior.

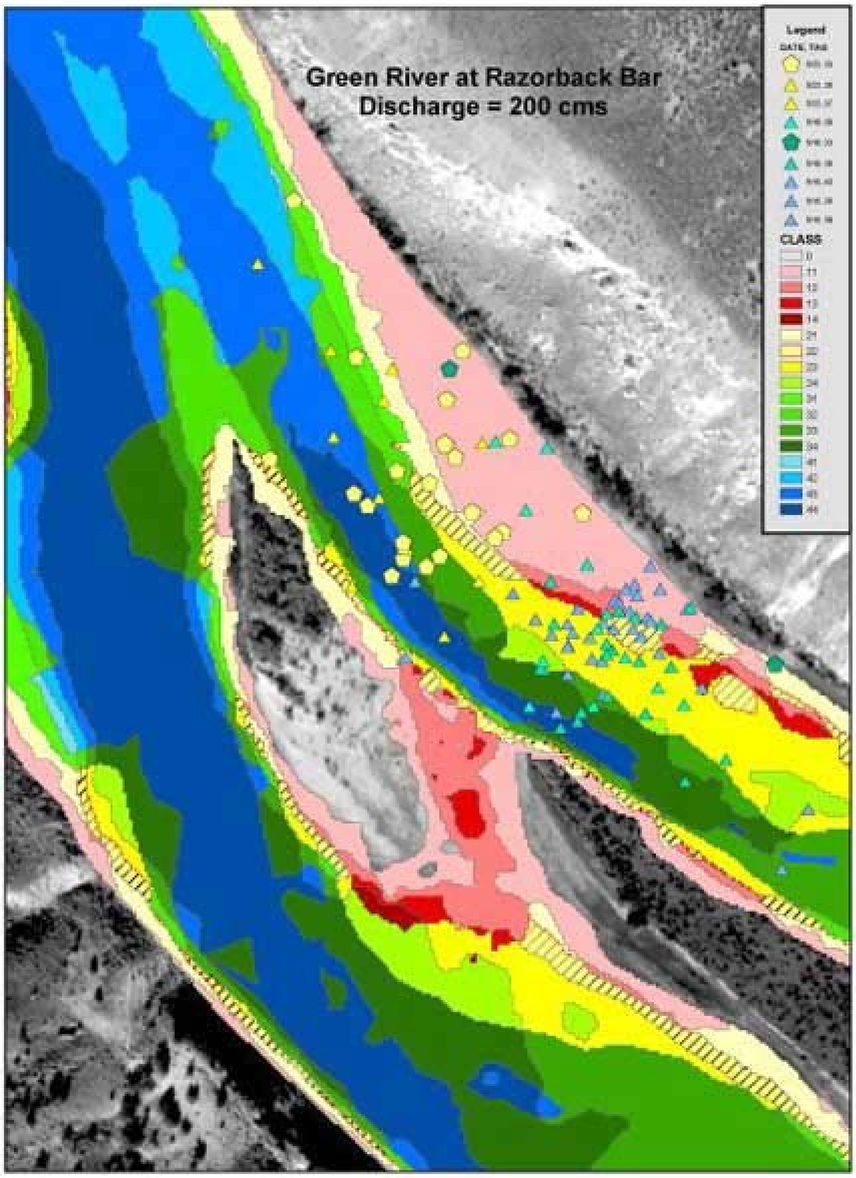

Figure 12. Habitat conditions at the Green River spawning bar at 200 m^3/s and fish locations from all telemetry observations during 16, 18, and 23 May 2000. Mean daily discharges measured near Jensen, UT were 204.0, 237.4, and 253.2 m^3/s for May 16, 18, and 23, respectively.

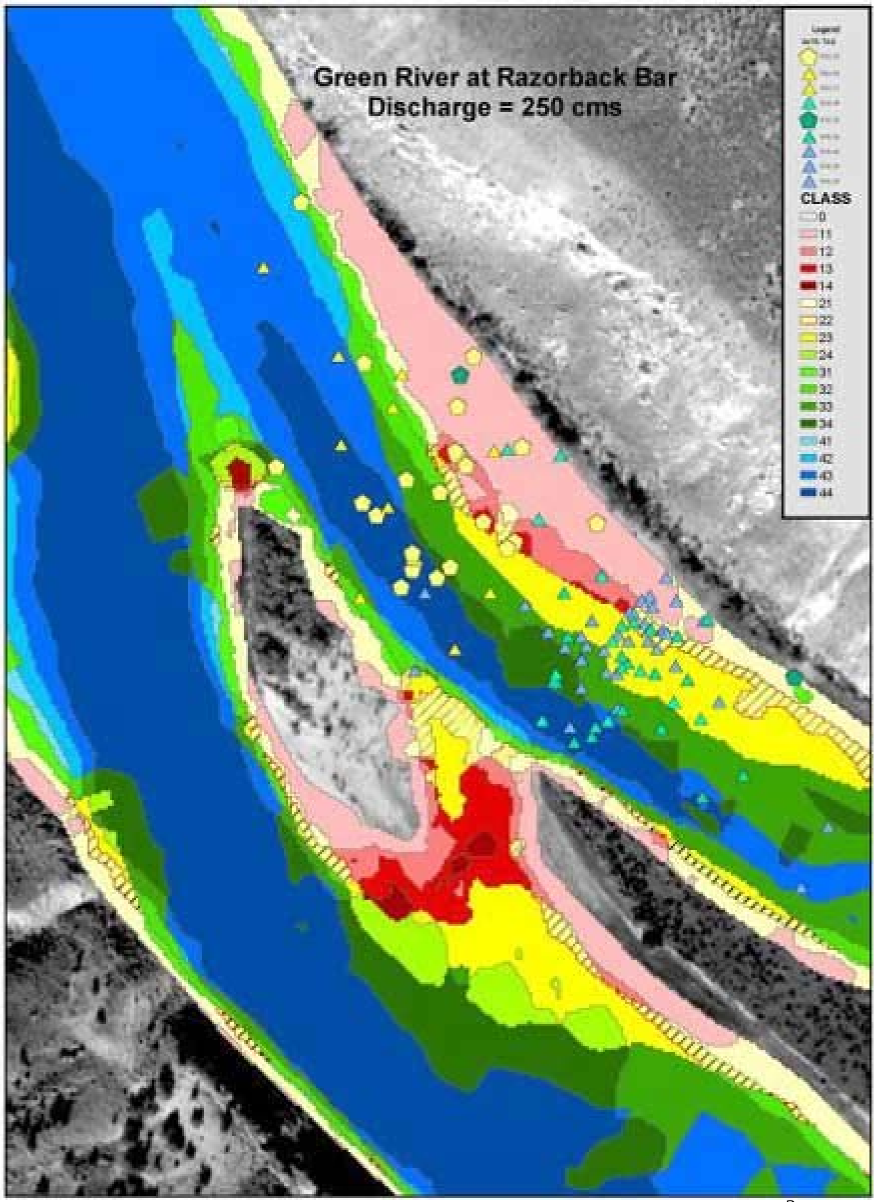

Figure 13. Habitat conditions at the Green River spawning bar at 250 m^3/s and fish locations from all telemetry observations during 16, 18, and 23 May 2000. Mean daily discharges measured near Jensen, UT were 204.0, 237.4, and 253.2 m^3/s for May 16, 18, and 23, respectively.

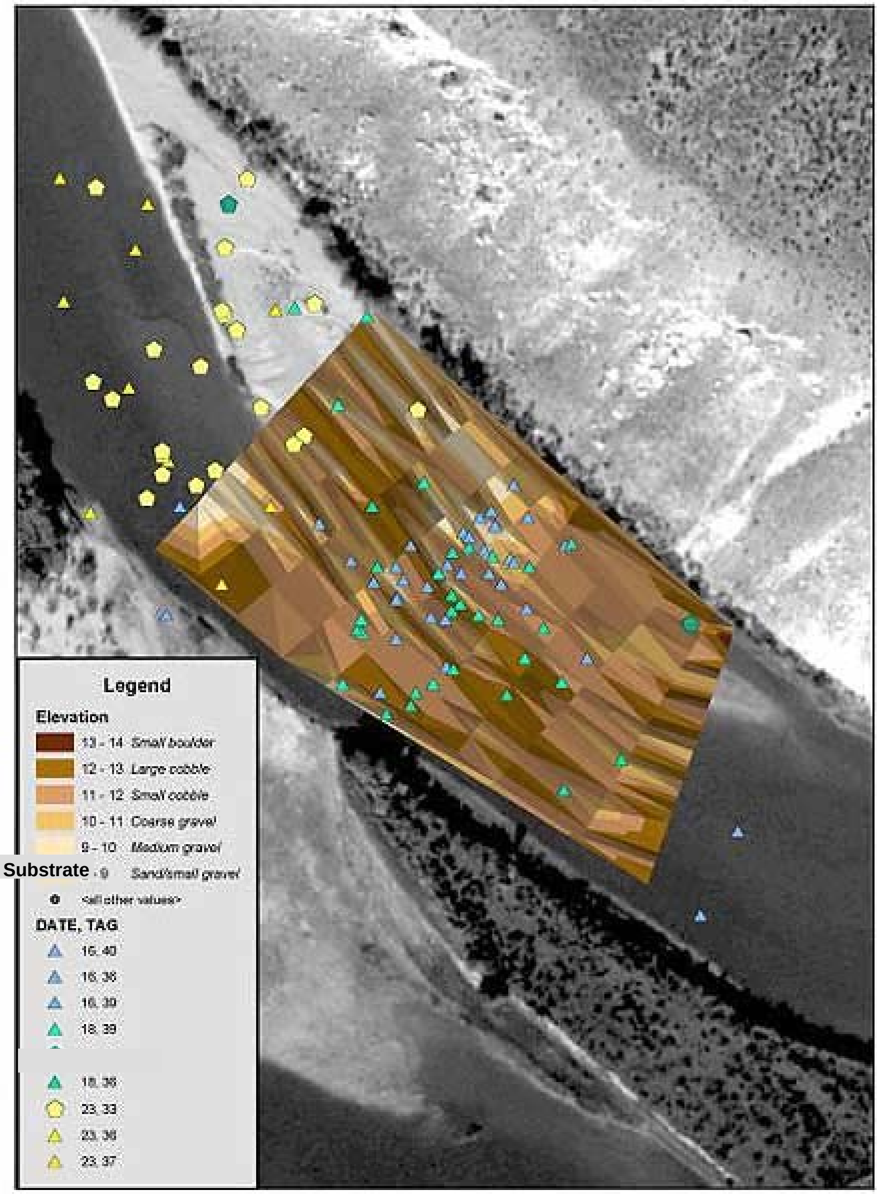

Figure 14. Substrate map of the middle Green River (RKM 504.3) around the Escalante spawning area compared with locations of fish from each 24 h survey period.

Nearly half of the fish collected on the spawning bar with electrofishing gear were hatchery-produced fish, and many were stocked the previous year in various locations in the middle Green River. This suggests that mechanisms other than natal imprinting are influencing fish use of the Green River spawning bar. Among the nine hatchery produced fish captured were two females, one (code 33) was the last telemetered fish to leave the spawning area. Among the eight fish with transmitters, three were wild and five were of hatchery origin. Only one wild fish with a transmitter attached remained in the study area for several days while four hatchery produced fish remained in the area during the spawning period. Thus, the greatest amount of information was gained from the behavior of hatchery fish in the spawning area. Only hatchery-produced fish were detected on the spawning bar during the 24 hr telemetry monitoring surveys, although the wild fish (code 41) was recorded to be in the spawning area for 11 d and overlapped temporally with three hatchery origin fish (codes 36, 40, and 36). Because both wild and hatchery fish were collected simultaneously in the same locations with electrofishing gear and the locations in which monitored fish were detected coincided with where most fish were collected both this year and in past years, it is likely that hatchery fish were using the same spawning areas as wild fish. There did appear to be some difference in the area used by the hatchery males and the hatchery female. The males appeared to spend most of their time in and around the suspected spawning area, whereas the single female tended to remain just outside of the spawning area during most diel monitoring.

The impacts of transmitter attachment on spawning behavior are unknown, however, external attachment was much less invasive and appeared to have less impact than surgically implanted transmitters. In a previous study using surgically implanted transmitters wild razorback sucker males left the spawning bar immediately and did not return during the same spawning event, but did return in subsequent years (Modde and Irving 1998). Response of the fish to transmitter attachment was variable. Two fish, one hatchery (code 40) and one wild fish (code 41) were found continuously on the bar after attachment, whereas code 36 left and did not return for 3 d, and code 33 was not detected in the spawning area for 10 d following attachment. It is apparent that transmitter attachment did not deter fish from being attracted to the spawning area, and in at least two cases fish did not leave the vicinity after transmitters were attached. Another uncertainty about the study is the specific location of the spawning area. Given that most fish were congregated in a narrow area of the river it is probable that the specific spawning area is located within the area occupied by the monitored fish, but the area occupied probably represents staging as well as spawning habitat. The most reliable information obtained during fish observations was the duration of individuals occupying the spawning bar and the determination that fish remained in the spawning area during both the daylight and dark hours.

The potential for sediment deposition to affect reproductive success on the spawning bar is a function of discharge, channel slope, and sediment availability. Although sediment transport was not measured directly in this study, results suggest that local changes in water surface slope begin at discharges of 100-200 m^3/s and that the site functions as a low gradient run at flows near 400 m^3/s with reduced water surface slope in the vicinity of the spawning bar. Repeated cross section measurements showed the pattern of fill during high flow and scour during recession observed during 1993 (Wick 1997) occurred during 2000 at the same side channel cross section as well as at other side and main channel cross sections. Sediment in the Green River side channel also was moved prior to April 27, 2000 and deposited in the spawning area at flows of less than 207 m^3/s. These observations suggest that sediment deposition in the Green River spawning area could occur under a range of flow conditions.

Razorback sucker have an extremely flexible reproductive behavior. Fish were observed using the Green River spawning area during very different flow conditions during 2000 and 1984. Based on relations between habitat and flow, conditions in the area where razorback sucker spawn in the Yampa River are also variable from year to year. Razorback sucker have successfully spawned in littoral windswept cobble shorelines of Lake Mohave (Minckley et al. 1991), deep cobble beds in Lake Meade (Holden et al. 1997), and a pond on Cibola National Wildlife Refuge (Gordon Mueller, USGS, Personal Communication), as well as in riverine habitats (Muth et al. 1998). Work by Modde (1998) also suggests that razorback sucker in the Green River use multiple spawning areas. Given the historical flood-flow variation of the major rivers in the Colorado River Basin in which razorback sucker were once abundant (Collier et al. 1996), spawning conditions would have varied substantially between years. Thus, razorback sucker behavior in response to changing conditions is no doubt adaptive to allow production of offspring. Conversely, larval razorback sucker survival is dependent upon a much narrower range of environmental conditions. Modde et al. (2001) related the inability of larvae to access off-channel floodplain depressions as a major factor in recruitment failure of razorback sucker in the middle Green River. Access to floodplain habitat is related to the timing, magnitude and duration of peak flows and the emergence of larvae from the spawning substrate. Razorback sucker larvae are shorter and have smaller yolk sacs than other mainstem catostomids (Snyder and Muth 1990) and are susceptible to starvation if they do not have access to prey densities between 13 and 50 zooplankters/l (Papoulias and Minckley 1990, 1992) in a timely manner. Invertebrate densities in the main channel of the middle Green River ranged between only 1.5 and 7.1 zooplankters/l compared to densities of 492 to 690 zooplankters/l in an off-channel floodplain depression (Mabey 1993). Thus over long time periods, timeliness of larval emergence and subsequent access to food-rich floodplain habitats is potentially a more restrictive reproductive bottleneck than specific conditions in the Green and Yampa River spawning areas.

CONCLUSIONS

The construction and operation of Flaming Gorge Dam has altered flows in the Green River in the vicinity of the razorback sucker spawning area near Jensen, UT. In the period of record after closure of the dam, base flows were higher and less variable during all water year types and average daily discharges were lower, particularly during wet and normal years. The magnitude of annual peak flows was about 22% lower and the frequency of moderate to very large floods was reduced. Recession was more gradual during the post-Flaming Gorge period than it was prior to dam closure; during a normal water year, the pre-dam rate of decline was over twice that of the post-dam period. Increased base flows and reduced peaks have resulted in an average decrease in base to peak amplitude of 29% across water year types. Reduction in peak flow magnitude and frequency of large floods has reduced the frequency and extent of floodplain inundation downstream from the spawning area; prior to construction of Flaming Gorge Dam, flows that inundate substantial floodplain habitat at Ouray National Wildlife Refuge (> 600 m^3/s) occurred for 10 days or longer in 6 of 16 years (37.5% of years) and in 3 years out of 37 years (8.1% of years) after closure of the dam. As documented in other studies changes in hydrology since closure of the dam have also altered sediment transport, channel morphology, and dynamics associated with habitat formation.

It is unlikely that water temperature directly limited razorback sucker reproduction in the Green River during the 2000 runoff. However, based on water temperatures measured at the Green – Yampa confluence some level of water temperature depression at the Green River spawning area resulting from Flaming Gorge operations is suspected. Potential effects of slightly lower water temperatures in the reach near Jensen, UT include increasing the time needed for razorback sucker egg incubation and decreasing rates of primary and secondary production in backwaters which could alter timing of emergence, and subsequent food availability for juvenile razorback sucker.

Repeated cross section measurements in the Green River showed variable patterns of scour and fill, with cross section elevations generally higher following runoff. A pattern of fill during high flow and scour during recession at several cross sections in both the main and side channels was observed. Sediment in the Green River side channel also was moved prior to April 27, 2000 and deposited in the spawning area at flows of less than 207 m^3/s. This deposition occurred prior to inundation of the high flow sand channel near the upstream end of the site suggesting movement of existing in-channel sediment, probably as bedload. Although sand from the high flow channel contributes sediment to the side channel spawning area, data from repeated cross section surveys in the side channel and main channel suggest that lenses of sand move through the study area at a range of discharges and that other upstream sources also contribute sediment to the study area. The overall trend in the Yampa River between the pre-and post-runoff surveys was one of scour, with fill in a few localized areas. Most of the scour occurred in the main (north) channel. Localized deposition at some Yampa River cross sections suggest the transport of a slug of sediment, in the form of a lens or a dune, through the study reach during the runoff period. Cross section surveys suggested that the majority of sediment movement in the Yampa had occurred prior to the secondary peak runoff in late May, and probably occurred during the initial runoff period in early May.

Stream power values generally were twice as large at the Yampa River study area compared to the Green River site and the proportion of the study area with relatively high stream power values was consistently larger at the Yampa River site. At both sites the side channel spawning areas were characterized by low stream power relative to the main channel; values were typically 50-75% lower in the side channel at both sites compared to the maximum stream power value for a particular discharge.

The Green River site had a proportionally larger area of slow current velocity habitat classes across all depth ranges than the Yampa site for the discharges simulated. The Yampa River site was dominated strongly by deeper and faster habitat classes at flows over 250 m^3/s. Persistence of slow current velocity habitats at discharges over 250 m^3/s at the Green River site was due largely to the size and elevation of channel features. The Yampa River site was smaller overall than the Green River study area and had a narrow, constrained channel and relatively small island-side channel complex resulting in predominance of deep and fast habitat types for much of the range of flows simulated.

Comparison of habitat duration curves for the ascending limb of the runoff period revealed that there were larger areas of habitat available for longer periods of time at the Green River site during 2000 compared to 1984 for most habitat classes, including shallow, moderate velocity habitat where spawning razorback sucker were commonly collected historically. At the Yampa River site, differences between habitat duration curves for 1984 and 2000 generally were smaller owing to similarity in the shape of habitat versus flow functions for many habitat classes. However, area of very shallow, shallow, and moderately deep habitat classes typically were larger during 2000 compared to 1984.

Habitat conditions during the time fish were detected in the spawning area at the Green River site were very different between 2000 and 1984. In 1984, the Green River side channel and the area over the spawning bar would have been dominated strongly by deep and fast habitat classes while flows in 2000 provided relatively high habitat diversity and large areas of shallow to moderately deep habitat classes in the side channel and near the spawning bar. Presence of razorback sucker at the Green River spawning bar under very different hydraulic conditions during 1984 and 2000 suggests that use of the spawning area by razorback sucker is driven by physical variables or other cues in addition to the distribution of water depths and current velocities.

Fish collected by electrofishing and counted by the stationary telemetry logger indicated razorback sucker occupied the spawning area between May 1-25, 2000. Telemetry data indicated that the duration of spawning was detected better by telemetry than electrofishing, suggesting that fish may be avoiding electrofishing boats after repeated passes through the area. No fish were detected in the spawning area after water temperature exceeded 17 degrees C. The time fish spent in the vicinity of the spawning bar was equally divided between diurnal and nocturnal hours. Razorback sucker used various habitats but were often located in depths of less than 1.0 m and velocities between 0.4 and 1.2 m/s. No distinct pattern of either substrate distribution or fish association with a particular substrate size was found. However, locations of fish determined during diel surveys suggest that part of the area used by razorback sucker during the 2000 spawning season was covered with sand during the spawning period. Fish left the spawning area in association with a rapid drop in water temperature but returned within 48 h even though temperature had not increased appreciably suggesting rate of temperature change could influence spawning behavior. Nearly half of the fish collected on the spawning bar with electrofishing gear were hatchery-produced fish, and many were stocked the previous year in various locations in the middle Green River. This finding implicates mechanisms other than natal imprinting in determining spawning site selection.

Fish were observed using the Green River spawning area during very different flow conditions during 2000 and 1984. Based on relations between habitat and flow, conditions in the area where razorback sucker spawn in the Yampa River were also variable from year to year. These results are consistent with other studies showing that razorback sucker have a very flexible spawning behavior including the possible use of multiple spawning areas. Historical flood-flow variation in the Colorado River Basin suggests that razorback sucker behavior in response to changing conditions must be adaptive to allow production of offspring. Conversely, larval razorback sucker survival is dependent on a narrow range of conditions provided in backwater and floodplain habitats. Because razorback sucker larvae are shorter and have smaller yolk sacs than other mainstem catostomids they are susceptible to starvation if they do not have access to food-rich backwaters soon after emergence. These considerations suggest that over long time periods (e.g., 10 years or more), larval access to food-rich backwater habitats is potentially a more restrictive reproductive bottleneck than local conditions at spawning areas.

Future studies should seek to better understand the interrelations between flow, physical processes, floodplain inundation, and bioproduction. Although functions describing area of floodplain inundated versus flow are a good starting point, a more ecosystem-oriented evaluation could provide useful information. For example, it would be beneficial to understand how varying the extent and duration of inundation might affect primary and secondary production in floodplains and influence the effects of competition and predation by exotic fishes. Hydraulic studies of potential floodplain habitats could help determine how floodplain function might change with flow. Such information would be useful to help guide ongoing efforts to acquire land in the river corridor and engineer floodplain habitats. In order to better understand the importance of sedimentation on spawning areas, studies must measure or model sediment transport and deposition over multiple runoff cycles representing different water year types (bearing in mind the importance of antecedent conditions of flow and sediment transport) and reliably document adult use of the spawning area and whether or not larvae are produced. Similarly, studies examining floodplain habitat use should strive for reliable estimates or indicators of recruitment. Owing to the rarity of the razorback sucker in the Green River biological data will probably be the most difficult to obtain.

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