SYNTHESIS OF FLOOD PLAIN WETLAND INFORMATION: TIMING OF RAZORBACK SUCKER REPRODUCTION IN THE GREEN RIVER, UTAH, RELATED TO STREAM FLOW, WATER TEMPERATURE, AND FLOOD PLAIN WETLAND AVAILABILITY

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Final Report

Colorado River Recovery Implementation Program Projects 22F and FR-FP Synthesis

Larval Fish Laboratory Contribution 163

March 2011

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Suggested citation:

Bestgen, K. R., G. B. Haines, and A. A. Hill. 2011. Synthesis of flood plain wetland information: Timing of razorback sucker reproduction in the Green River, Utah, related to stream flow, water temperature, and flood plain wetland availability. Final Report to the Upper Colorado River Endangered Fish Recovery Program, Denver. Larval Fish Laboratory Contribution 163.

EXECUTIVE SUMMARY

Decline of endangered razorback sucker *Xyrauchen texanus* has been attributed to alterations of physical habitat and negative effects of introduced fishes. In the Upper Colorado River Basin, stream flow reduction due to storage of spring runoff in reservoirs, and effects of channelization and levees reduces frequency and duration of flood plain inundation. Flood plain wetlands, particularly in the Green River Basin, are thought to have great value as rearing areas for razorback sucker larvae because they are low-velocity, relatively warm, and food-rich during spring runoff when main channel rearing habitat is minimal. A decrease in warm, food-rich flood plain areas may limit recruitment of razorback sucker and is thought an obstacle to recovery of this endangered species. This report summarizes previous research to: describe the reproductive ecology of razorback sucker in the middle Green River; evaluate uncertainties related to the utility of flood plain wetlands for rearing early life stages of razorback suckers; and understand effects of timing and magnitude of discharge patterns of the Green and Yampa rivers on razorback sucker recruitment. Results will be useful to evaluate effectiveness of existing flow and temperature recommendations, and will identify possible strategies to enhance recommendations for flood plain wetland habitat management and for conservation and recovery of razorback sucker in the middle Green River, Utah.

Based on light trap sampling results, razorback suckers reproduced every year in the middle Green River from 1992-2009 and in the lower Green River from 1993-1999, and 2008-2009, the only years sampling occurred there. Abundance of razorback sucker larvae declined in the middle Green River from 1993-1994, until 1999, concurrent with abundance of wild adult razorback suckers. Abundance of razorback sucker larvae increased in the middle Green River perhaps beginning around 2000 and certainly after 2004, coincident with establishment of larger populations of stocked razorback suckers, indicating successful acclimation and reestablishment of some adults. Timing of spawning, hatching, and emergence of razorback suckers in the lower and middle Green River has close associations with water temperature; timing of first occurrence of razorback sucker larvae captured in light traps in the lower Green River was typically before peak flows because warmer water temperatures there promoted earlier reproduction. Timing of first occurrence of razorback sucker larvae captured in light traps in the middle Green River was typically coincident with peak flows because water temperatures were cooler and promoted later reproduction.

We used recaptures of marked razorback sucker larvae released into the Green River to further evaluate ecology of early life history stages of razorback suckers. Recapture rates of marked razorback sucker larvae were similar across most release occasions and indicated rapid downstream dispersal of larvae. Larvae were able to rapidly colonize quiet, nearshore areas adjacent to flood plain wetlands, many were recaptured well downstream from release locations, and their broad spatial distribution suggested that provision of mosaic of wetland habitat downstream of spawning areas was important.

Surface area of flood plain wetlands increased as flow levels in the middle Green River increased after thresholds of inundation for breaches were reached. Entrainment rates of water (assumed proportional to entrainment rates of razorback sucker larvae for flow-through and single breach wetlands) for four flow-through wetlands increased exponentially at higher Green River flows and entrainment rates of flow-through wetlands were approximately 7x that of single-breach wetlands. Entrainment rates of water for single-breach wetlands increased at higher Green River flows; the nature of the entrainment rate-flow relationship was uncertain but area and volume of entrainment into flood plain wetlands increased substantially at flows > 450 m^3/sec and then again at flows > 625 m^3/sec. Short-term fluctuations (e.g., daily snowmelt pulses) fluctuations were substantial in many years and are important because such events cause water to flow into (and out of) flood plain wetlands and may entrain fish larvae; such fluctuations are responsible for a large proportion of total flow entrainment into single-breach wetlands. Entrainment rates of single-breach wetlands were approximately 12% of that for flow-through wetlands, in spite of much greater wetland numbers and total surface area, because exchange rates were lower. The reduced exchange rates do not diminish their importance because of their large size and enhanced overwintering capacity. Some flood plain wetlands, including single breach and flow through types, may be incapable of supporting longer-term survival of entrained razorback suckers because of low overwinter survival or contaminants; those deficiencies need to be remedied if such wetlands continue to be a central part of the recovery process for razorback suckers. Flows sufficient to connect wetlands to the river to allow escapement of age-1 + razorback suckers that did overwinter are also important. Sedimentation of breaches via bedload transport can be substantial and increase the level of Green River flows required for inundation; effects of suspended sediment were less clear but could be substantial especially in flow-through wetlands.

Middle Green River flow peaks and timing of occurrence of razorback sucker larvae were only partially overlapping. This was, in part, because releases in spring that were designed to enhance flood plain-river connections, and based on snowmelt forecasts, usually occurred before first appearance of the razorback sucker larvae. Thus, first occurrence of razorback sucker larvae may be a better trigger to signal release of Flaming Gorge flows.

Simulations of flow and entrainment rates showed that even at average flow levels, the volume of water entrained into flood plain wetlands when razorback sucker larvae were present was low and constituted only a few hours of Green River flow per year in all wetland types. Simulations also showed that flow regimes since 1992 resulted, on average, in only about 50% of the number of days of flood plain inundation at the two lowest flow levels tested and only 25% of the number of days at the higher flow level tested compared to the unregulated condition; the higher flow was only the equivalent of the Average hydrologic condition called for in the Flow Recommendations for Flaming Gorge Dam. Longer duration and especially, higher magnitude flows, timed to occur when razorback sucker larvae were present, may be minimally sufficient conditions to enhance recruitment of razorback suckers in the middle Green River, Utah.

We make a number of recommendations based on the findings of this study which are listed below:

- Continue to develop information on early life history ecology of razorback sucker in the Green River Basin, consistent with that being collected under Project 22f. A related investigation may be to better understand the role of altered spring thermal ecology of the Green River, induced by Flaming Gorge Dam operations, on timing of spawning, development of embryos, and emergence of razorback sucker larvae, as well as the potential effects on spawning of non-native fishes.
- Expand sampling in the lower Green River, at least consistent with that which occurred in 2009 and 2010. Additional information on timing of spawning, hatching, and emergence of larvae using otolith analyses may be appropriate. A better understanding of habitat use and survival of razorback sucker larvae in the lower Green River may also be useful. This may be especially important if timing of releases from Flaming Gorge Dam, or flow magnitude or duration, is altered.
- Continue studies which evaluate utility of various flood plain wetlands as recruitment habitat for early life history stages of razorback sucker. Important aspects include better understanding of colonization/entrainment rates of larvae into single-breach wetlands, which could be accomplished experimentally using small batches of marked larvae, in conjunction with present sampling. Utility of terrace-type wetlands as temporary habitat for razorback sucker larvae should also be assessed. Breach and wetland monitoring should also be conducted to ascertain whether sedimentation is a substantial problem.
- Continue studies which evaluate utility of various flood plain wetlands as overwinter habitat for young razorback sucker, and develop plans to enhance fish overwintering capability of key wetlands. One specific aspect is to investigate utility of outlet gate(s) to maintain water levels in flow-through wetlands.
- Consider utility and feasibility of scheduling filling of specific gated wetlands of any type to fill with Green River water only when high densities of razorback sucker larvae are present, timing for which could be based on ongoing real-time sampling information.
- Develop a simple population dynamics tool to assist with modeling entrainment and survival rates of early life stages of razorback suckers in various flood plain wetlands. Variables to model could include temporal dynamics of occurrence of larvae (including seasonal density distribution), Green River flow levels, entrainment rates into flood plain wetlands, individual attributes of larvae relative to growth and survival, presence/absence of existing fish communities and predation rates, and attributes of individual flood plain wetlands.
- Implement a schedule of altered timing of flow releases from Flaming Gorge Dam to coincide more closely with presence of razorback sucker larvae, or perhaps, presence of abundant larvae, in the middle Green River. Reliable real-time monitoring is already in place to guide timing of releases. In lieu of that, develop relationships based on physical

attributes, mostly water temperature and time of year, which would predict timing of emergence of razorback sucker larvae.

- Investigate the feasibility of increased magnitude and duration of spring flow releases from Flaming Gorge Dam, after razorback sucker larvae are present, to maintain connections with flood plain wetlands and increase entrainment rates. Corollary to that, it may be possible to save water in Flaming Gorge Reservoir in some lower flow years, to release in other higher flow years to sustain river-wetland connections. Flow releases that simulate unregulated conditions should be used for a realistic test of effectiveness of increased flows to enhance recruitment. Subsequent effects on base flow levels, among other things, will also need to be considered.

Implementation of some or all of these recommendations may assist with recovery of razorback sucker in the Green River.

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Introduction

Endangered razorback sucker *Xyrauchen texanus* was once widespread and abundant throughout the Colorado River Basin but is now rare (McAda and Wydoski 1980; Minckley 1983; Bestgen 1990; Minckley et al. 1991; U. S. Fish and Wildlife Service 2002). Concentrations occur in lakes Mohave and Mead, Arizona and Nevada, and in the upper Colorado and Green rivers, Utah and Colorado, as stocked hatchery fish but elsewhere occur only as scattered wild or hatchery-origin individuals (Minckley 1983; Tyus 1987; Bestgen 1990; Minckley et al. 1991; Modde et al. 1996; Holden et al. 2001; Albrecht et al. 2008; Zelasko 2008; Zelasko et al. 2009; 2010; 2011). Wild fish in Lake Mohave have declined in abundance to about 4,000 individuals in 2001 but has declined to only 24 fish (Minckley et al. 1991; Marsh 1994; Marsh et al. 2003; Kesner et al. 2010). An active population replacement program is ongoing in Lake Mohave with mixed results, as stocked fish have relatively low survival (Marsh et al. 2003; 2005; Kesner et al. 2010). Wild populations of razorback suckers are dominated by large, old individuals, and recruitment rates in most localities are thought low or non-existent; the Lake Mead population apparently has ongoing recruitment (Minckley 1983; Minckley et al. 1991; Tyus 1987; Gutermuth et al. 1994; Modde et al. 1996; Holden et al. 2001; Bestgen et al. 2002; Marsh et al. 2005; Albrecht et al. 2008). In the Upper Colorado River Basin, wild fish were extirpated from the San Juan River but stocked hatchery fish are surviving and reproducing annually (Platania et al. 1991; Brandenburg and Farrington 2009; Bestgen et al. 2009). Wild razorback suckers in the Upper Colorado River were thought extirpated many years ago (Bestgen 1990). Abundance of wild adult Green River razorback suckers was estimated at about 300 to 950 during the 1980 to 1992 period (Lanigan and Tyus 1989; Modde et al. 1996) but declined to less than about 100 fish by 2000 and that population was likely extirpated soon after (Bestgen et al. 2002). Survival of relatively large hatchery-reared razorback suckers released into the Green and Colorado rivers has bolstered populations and some are now reproducing (Zelasko 2008; Osmundson and Seal 2009; Zelasko et al. 2009; Zelasko et al. 2010, this report).

Decline of wild razorback suckers has been attributed to alterations of physical habitat and negative effects of introduced fishes. Mainstem dams alter flow patterns, water temperature, and sediment loads and also serve as barriers to upstream fish movement (Carlson and Muth 1989). In the Upper Colorado River Basin, flow reduction due to storage of spring runoff, and effects of channelization and levees reduce frequency and duration of flood plain inundation. A decrease in warm, food-rich flood plain wetlands, which are likely important as rearing and resting habitat in spring for early life and adult stages of razorback suckers, may limit recruitment (Modde et al. 1996; Wydoski and Wick 1998; Modde et al. 2001; Bestgen 2008). Predation on early life stages of razorback suckers, combined with slow growth, is also thought a primary factor limiting recruitment (Minckley et al. 1991).

Flood plain wetlands are thought to have great value as rearing areas for razorback sucker larvae because they are low-velocity, relatively warm, and food-rich (Modde et al. 2001; Birchell et al 2002; 2004; Christopherson et al. 2004; Brunson and Christopherson 2005; Modde and Haines 2005). This is in contrast to habitat in the mainstem Green River during spring peak or post-peak runoff, which is generally high velocity, cold, and low in food resources for early life stages of fishes. Thus, a main thesis for the flood plain wetland management plan in the Green River is that wetlands are a critical element of rearing habitat for early life stages of razorback sucker and may be limiting recruitment. This thesis was supported by the finding of adult and early life stages of razorback suckers, including juveniles, in flood plain wetlands when few other early life stages were evident at any time in main channels of the Upper Colorado River Basin (Taba et al. 1965; Bestgen 1990; Tyus and Karp 1991; Modde et al. 1996; Modde et al. 2001).

Two main management actions initiated by the Upper Colorado River Basin Endangered Fishes Recovery Program (Program) were responsive to the need to increase flood plain wetland habitat availability for early life stages of razorback sucker. The first was a program to identify key flood plain wetlands of the Upper Colorado River Basin (Irving and Burdick 1995; Valdez and Nelson 2004). High quality wetlands (e.g. depression wetlands) downstream of known or suspected razorback sucker spawning areas in the middle Green River, Razorback Bar (RKM 500.9) and Escalante Spawning Bar (RKM 494.8), were high priority areas for management because those may enhance entrainment of drifting larvae into flood plain wetlands (Modde et al. 1996, 2001; Muth et al. 1998; 2000, Bestgen et al. 2002; Valdez and Nelson 2004). Upon identifying high priority flood plain areas, efforts were made to increase river connection and functioning of flood plain habitats via removal or breaching of levees (Birchell et al. 2002). Eight flood plain levees were breached in 1997 and 1998.

A second main management action to increase flood plain wetland habitat availability for early life stages of razorback sucker was to implement flow recommendations to enhance river-flood plain connections in the Middle Green River, Utah (Muth et al. 2000). This was needed because spring discharge levels of the Green River have been reduced due to storage of flows in Flaming Gorge Reservoir. Specifically, recommendations implemented were designed to match spring peak and immediate post-peak flow of the mostly unregulated Yampa River with releases from Flaming Gorge Dam, to increase the frequency and duration of flood plain wetland connections. Recommendations sought to increase those connections mainly in average, moderately wet, or wet hydrologic conditions (Muth et al. 2000) because flows in moderately dry or dry years were usually insufficient to achieve substantial river-flood plain connections.

Flow recommendations for the Green River downstream of Flaming Gorge Dam listed uncertainties regarding the response of native fishes to certain flow and temperature regimes (Muth et al. 2000). Because provision of flood plain habitat to benefit native fishes was mainly an hypothesis, research and monitoring is ongoing to test that hypothesis. Recommendations in average hydrologic conditions, which occur on average in about 4 of every 10 years (40% of the time), call for flows in Reach 2 of the middle Green River near Jensen, Utah, to reach > 527 m^3/sec (18,600 ft^3/sec) in 1 of 2 average flow years, and that flow should be maintained for at least 2 weeks in 1 of every 4 years. No recommendations were made for the upper limit of any peak flow under any hydrologic condition because a greater extent of flood plain inundation was viewed as beneficial to native fishes. The average hydrologic condition recommendations were questioned mainly because lowering or removal of levees may enhance riverine connections sufficiently without the need for Flaming Gorge Dam flows of the magnitude or duration forwarded in recommendations (Hayse et al. 2005, see Appendix III for an evaluation of those alternative flow patterns).

Information to guide management of Green River flood plain wetlands for razorback sucker recruitment is extensive but a single synthesis of that information does not exist. The following sections of this report present new data and build on a host of previous research, to evaluate uncertainties related to the utility of flood plain wetlands for rearing, timing and magnitude of discharge patterns of the Green and Yampa rivers, and the reproductive ecology of razorback sucker in the middle Green River. A first main source of information was light trap sampling monitoring data collected in the middle Green River since 1992 (Recovery Program

Project 22f), which describes seasonal reproduction patterns and annual reproductive success of razorback sucker. Reporting of those results, which was originally conceived as a separate report, was combined with objectives of the flood plain synthesis project (*Floodplain Inundation and Entrainment Studies*), to aid understanding by the reader and further a true synthesis of available information.

The Funding Opportunity Announcement for this flood plain synthesis study, which was a product of the Green River Study Plan (Green River Study Plan *ad hoc* Committee, 2007), listed eight specific hypotheses or information needs (see also Appendix I), which are summarized below.

Information need 1. Flow and stage at which floodplains with levee breaches become sufficiently inundated to provide nursery habitat for razorback suckers.

Information need 2. Frequency of flood plain inundation relative to the hydrologic cycle.

Information need 3. Area, depth, volume, and persistence of floodplain depression habitat after peak flows recede and relationship with peak flow magnitude.

Information need 4. Rates of sediment deposition and erosion in breaches and floodplains.

Information need 5. Entrainment and retention of larvae in floodplain nursery habitats as a function of physical characteristics and timing of drift.

Information need 6. Temporal relationships between drifting larvae and hydrology during the runoff period with a focus on the peak flow characteristics needed to entrain larvae.

Information need 7. The area of terrace and depression floodplains inundated at different flows.

Information need 8. What is the optimal combination of flow magnitude and duration to maximize entrainment of razorback sucker larvae.

To fill those information needs to the fullest extent possible, we used data gathered and synthesized from available literature and technical reports, and original field sampling data. Report results will be useful to evaluate effectiveness of existing flow and temperature recommendations, and will identify possible strategies to enhance of those recommendations for flood plain wetland habitat management and for conservation and recovery of razorback sucker in the middle Green River, Utah.

STUDY AREA

The main study area was the Green River from the confluence of the Yampa River downstream to the confluence with the Colorado River, with a particular focus on the low-gradient middle Green River section, from just upstream of Jensen, Utah, downstream to near the White River confluence (Figure 1). In valley reaches such as the Study Area, channel gradient was low, substrate was mostly sand, and the flood plain was relatively broad.

METHODS

Fish sampling.—Much of the original fish data used in preparation of this report was derived from sampling early life stages of razorback sucker in the middle Green River. Portions of those data were reported in Muth et al. (1998; 2000) and Bestgen et al. (2002), for data collected through 1999, and since then, in annual project reports for Recovery Program Project 22f. Another main source of fish sampling data for this study was gathered during a flood plain entrainment study (Hedrick et al. 2009). Light traps were used as the primary sampling gear for fish larvae because Muth et al. (1998) demonstrated that gear was the most effective means of sampling early life stages of razorback suckers from low-velocity areas. Since 1996, light-trap sampling for early life stages of razorback suckers occurred mostly in the middle Green River reach, where we will focus our efforts for this report. Sampling for early life stages of razorback suckers also occurred in the lower Green River from 1997-1999, and that sampling resumed with a low level of effort in 2008 and a higher level of effort in 2009 and 2010. Light-trap sampling localities for the middle and lower Green River reaches are presented in Results. Only a few samples were collected in the lower Yampa River (1996 and 1998), with the exception of drift net sampling conducted each year in the Yampa and Green rivers in Echo Park, mostly in late spring and summer with a goal to understand timing and success of reproduction by Colorado pikeminnow *Ptychocheilus lucius*. Sampling in the middle Green River occurred in three main reaches but was concentrated near the Escalante (now Thunder) Ranch spawning area (e.g., Cliff Creek) in most years, and near downstream Old Charlie Wash and Ouray National Wildlife Refuge (e.g., Greasewood Corral). In recent years, additional sampling sites in the middle portion of the reach (e.g., Baser Wash) have also been used. In general, sampling became more focused on areas where suitable low-velocity habitat was available each year and throughout the season regardless of flow level. Because of this need for consistency, sampling with light traps in flood plain wetlands, which are not always available, was not conducted. Instead, sampling in those places was conducted under separate studies (e.g., sampling in Old Charley Wash by Modde 1996; Modde et al. 2001). Light-trap sampling effort at individual sites or reaches varied among seasons and years due to differences in flow level and availability of suitable sampling areas so effort by sites was not reported. Cliff Creek has been sampled in a reasonably consistent manner each year and results from that site, along with patterns from the entire reach, may offer some insights into longer-term trends in reproduction and abundance of razorback sucker larvae.

In each sampling area, 1 to 10 light traps were set at dusk and were emptied prior to dawn each sampling day. Light traps were described by Muth et al. (1998). In the middle Green River, light-traps were usually set twice per week after catostomid larvae were first detected and sampling continued until few or no additional larvae were captured, usually by mid to late June, but sometimes as late as mid-July (e.g., 2009) in years when runoff was relatively late and water was cool. Samples other than those for brood stock collected in 1999 were examined in the laboratory to provide real time information on presence of razorback sucker larvae in the system by one of us (GBH), and specimens were preserved in ethanol for later verification by the LFL.

Recaptures of marked razorback sucker larvae, 2004-2006.—During the flood plain wetland entrainment study (Hedrick et al. 2009), razorback sucker larvae were marked via immersion in a solution of tetracycline hydrochloride (TC, 350 mg/L) for four to five hours, a time sufficient to mark otoliths at those concentrations (Muth and Meismer 1995). A few (about 10) larvae were preserved in 100% ethanol just post-marking and then again two to three days later to ensure that fish were adequately marked. Examination of otoliths of fish immersed in the TC solution showed that 100% of fish were marked and marks were bright yellow and clear (Muth and Bestgen 1991). Marked larvae were released in each of three years, 2004, 2005, and 2006 (Table 1). In 2004, a single relatively small batch of larvae was released on 26 May just downstream of Razorback Bar (RK 500.9). In 2005, three batches of larvae were released, one on 20 May (n = 104,000), one on 24 May (n = 94,500) and the final one on 31 May (n = 395,500), and fish were marked so that individuals from each batch could be identified. The first batch had a single mark following standard immersion procedures just after swimup. The second batch was double-marked by conducting the standard marking at eight days post-hatch, followed by another mark application at 11 days post-hatch. The three-day interval between marking was sufficient to allow for the marks to be spatially well-separated (not overlapping) on the otolith. The third batch was marked with a single mark following standard procedures. The two batches of single-marked fish, one early and one late, could be differentiated after capture in light traps because the most recently hatched and released group had a relatively small otolith with the mark close to the outside of the otolith. Conversely, the earliest batch of fish could be differentiated because the otolith (and fish, in some cases) was relatively large, the mark was well-contained within and nearer the core of the otolith, and in some cases, daily ring counts were greater than the age of fish in the last batch of larvae released. In 2005, larvae were released at each time from each of two locations, Razorback Bar (larvae follow river right, which is north or west bank) and Escalante Bar (river left, larvae follow south or east bank, Hedrick et al. 2009). Three batches of single-marked larvae were released just upstream of the Thunder Ranch wetland in 2006, one on 21 May (n = 175,500), one on 23 May (n = 125,000) and the final one on 24 May (n = 225,000); determining the release batches of recaptured larvae was not possible due to the brief interval between releases. Sucker larvae were preserved in 100% ethanol, otoliths were removed and mounted on microscope slides, observed under a compound microscope equipped with UV illumination, and presence of a mark was noted to differentiate marked hatchery-produced razorback sucker larvae from wild-produced larvae. All fish captured and reported here are from light trap samples collected throughout the middle Green River, Utah. In order to determine if razorback sucker larvae captured in 2005-2006 were wild or hatchery-released fish, we examined all larvae captured for presence of tetracycline marks. For 2004 samples when the number of razorback suckers collected was high, we subsampled a few light trap samples of razorback sucker larvae that were collected after release of marked fish. We found that all but 1 of 47 marked fish captured that year was in samples collected 36 to 44 hr after release on 26 May; the single other larva was captured on 1 June. A total of 218 razorback sucker larvae was captured on 28 May (light traps set on the evening of 27 May), 217 were captured at Wyasket Bottom; 1 was from nearby Leota), and 65 larvae were examined for marks. A total of 49 of 65 larvae (75%) were marked, so up to 114 additional larvae (0.75 x [217-65] = 114) from samples collected on 28 May (traps set on 27 May, pulled on 28 May) may be marked and not wild fish. We did not remove these from total fish numbers captured because the total was large overall (n

= 1,047). Of 165 razorback sucker larvae captured on 27 May (traps set the evening of 26 May) at Wyasket Bottom and Leota in light traps set 10 to 18 hr after release of marked larvae, no marked fish were found among the 29 examined. That gave us confidence that few marked larvae were available for capture other than on 28 May in 2004.

Data analysis, larvae.—We present capture data for all species and also catch per unit effort (CPUE) for three native catostomids, razorback sucker, flannelmouth sucker *Catostomus latipinnis*, and bluehead sucker *Catostomus discobolus*. We also used data from 1992-1996 presented by Muth et al. (1998) to obtain a longer data series so that we could evaluate trends in capture rates. The CPUE analyses were number of fish captured per night of light trapping; average trap sampling time per night was about 8.5 hours. Total annual sampling effort was based on samples collected only after the first sucker larvae was captured each year.

Capture dates of razorback sucker larvae were used to reconstruct timing and duration of hatching of embryos and reproduction by adults in relation to flow and water temperature regimes. This approach follows Muth et al. (1998) for fish captured from 1992-1996, except they used otolith increments to estimate hatching dates and growth rates of some larvae (Bundy and Bestgen 2001). We revised that analysis slightly and used all larvae, including those not aged, and back-calculated hatching dates for fish captured from 1992 to 1999. We subtracted length of larvae at capture from average length at hatching (8.0 mm TL) and divided the difference by 0.3 mm, the average daily growth rate of wild larvae observed by Muth et al. (1998), to obtain days post-hatch for each larva. Subtracting age in days from capture date allowed calculation of hatching date. After 1999, we used year-specific growth rates (0.17 – 0.27 mm TL/day) to estimate timing of hatching and spawning, which were obtained by counting daily increments in otoliths from a sample of the fish captured in any given year. The result of otolith aging was an estimate of the number of days since hatching, which was subtracted from the capture date to obtain hatching date. Time of embryo fertilization (spawning) was estimated by subtracting temperature-dependent times of incubation from hatching dates; incubation times for fertilized embryos reared at water temperatures of 10-20°C were estimated from data presented by Bozek et al. (1990) by the negative exponential function:

$$y = 1440.3e^{-0.109x}$$

where y = incubation time in days and x = water temperature in degrees °C (Figure 2). The equation fit to the data was relatively high at $r^2 = 0.96$. Water temperatures during the presumed period of incubation were estimated from water temperature data gathered at the USGS gauge near Jensen, Utah (09261000), or unpublished Recovery Program data from that same site. Dates of incubation, hatching, and capture were compared to flow and temperature regimes gathered from U.S. Geological Survey gauges or other sources (pers. comm., G. Smith, U.S. Fish and Wildlife Service, Denver, CO). Temperature data were average daily or instantaneous readings. Winter and early spring water temperatures (through mid-April) for the middle Green River gauge at Jensen, Utah, were not available in 1998 and 1999 but were estimated from the average of daily readings collected from 1980 to 1997. The information and discussion provided by the analyses described above will fulfill reporting requirements for project 22f, and also add to information needed to fulfill requests under Floodplain Inundation and Entrainment scope of work (Floodplain Inundation; FR-FP Synthesis).

The information needs identified in the Request for Proposals indentified specific areas of investigation which are summarized below. Some of the techniques and methods used to address questions overlap among the various information needs and we will provide clues about elements that are being addressed as we proceed through Methods.

Flood plain wetland connectivity, area, and entrainment.—This general topic area minimally encompasses information needs 1 and 7.

Information need 1. Flow and stage at which floodplains with levee breaches become sufficiently inundated to provide nursery habitat for razorback suckers; and

Information need 7, The area of terrace and depression floodplains inundated at different flows.

Information to understand flow and river stage needed to inundate levee breaches and their respective flood plain was contained in a number of sources and was based mostly on observations gathered in the field or on measured breach elevations from surveys relative to river elevations at various flow stages (FLO Engineering 1993; 1996; 1997; 1999; Muth et al. 2000; Valdez and Nelson 2004; Tetra Tech 2005; Argonne National Laboratory 2006; Hedrick et al. 2009; observations of investigators). Variation in breach inundation level (e.g., Hedrick et al. 2009) across years was also reported and will be discussed in relation to sedimentation and investigator techniques and potential error. Some wetlands had no specific data regarding flow levels needed for inundation. In that case we sometimes relied on sequential aerial photographs collected at increasing flow levels in 2005, which showed a stable amount of flood plain wetland area for individual habitat areas with increasing flow level followed by a sudden increase in flooded area, indicating breach inundation and wetland filling (Argonne National Laboratory 2006). That information was used to estimate breach inundation level, and wetland area at various flow levels. The unpublished report that made available aerial photographs reported flood plain area for 15 flood plain wetlands at flows levels of 249, 406, 455, 528, and 247 m^3/sec, as measured at the Green River, Jensen, Utah gauge, on 13, 21, 22, and 23 May, and 29

June 2005, respectively. Those wetlands are the main focus of the Green River flood plain management plan and will also be the focus of this report (Valdez and Nelson 2004). Methods for interpolation of aerial photographs are reported in the unpublished report by Nesta (2008, Argonne National Laboratory). For flood plain areas located upstream of Ashley Creek (Thunder Ranch, Stewart Lake), flow levels at inundation were the Jensen gauge flow levels. For flood plain areas located downstream of Ashley Creek (Bonanza Bridge, Horseshoe Bend, The Stirrup, Baeser Bend [we assumed this site was still breached to allow lower river access], Above Brennan, Johnson Bottom, Leota Wetlands, Sheppard Bottom, Old Charley Wash, and Lamb Property), we added the sometimes substantial flows of Ashley Creek in 2005, measured from the prior day to measured Green River flow at Jensen to account for transit time, to yield Green River flow levels in downstream reaches. Wetlands "IMC" and Sportman's Lake were not included in calculations because flow levels to effect inundation were poorly understood and the latter is controlled by mechanical gates. Flow levels and inundation thresholds at other wetlands (e.g., Stewart Lake, Leota, Old Charley) were also under the control of other entities at certain flow levels so we used observations of investigators and landowner contacts to make the best determinations of inundation flow levels. Other wetlands that may be present in the middle Green River were not included in assessments here because they were not among those listed in the Green River flood plain management plan and because there was no information available regarding inundation thresholds and area flooded at various flow levels.

We used data for each flood plain wetland area at various Green River flow levels (adjusted for effects of Ashley Creek) reported in the unpublished aerial photography report to fit regression functions to allow prediction of wetland area at a variety of flow levels within the range of streamflow levels observed (Appendix II). These relationships were used to estimate wetland area as a function of flow stage (e.g., Table 15), using Green River flows at the Jensen USGS gauge if wetlands were upstream of Ashley Creek or the Jensen Gauge flows plus Ashley Creek if the wetlands were downstream of Ashley Creek. For those wetlands downstream of Ashley Creek, flows from the day prior to wetland area observations were used to account for transit time to the Ouray National Wildlife Refuge, where most wetlands in that reach were located. For flows ≤ 623 m^3/sec, surface areas were predictions from regression relationships of area as a function of river stage. Area of flow-through wetlands was assumed to stabilize at flows >623 m^3/sec because no data were available to estimate their area; thus, those high flow estimates are likely conservative. Area of single breach wetlands at higher flows (>623 m^3/sec) were from observations or field measurements. Actual timing of inundation and duration of connections were adjusted based on the streamflow level needed to inundate wetland breaches.

A main goal of these analyses was to estimate the timing of inundation, duration of connections, and the amount of water flow that passed into or through each wetland during each hydrologic year in the period 1992-2008. We used streamflow into wetlands as a surrogate for estimates of entrainment of larvae because there is a strong relationship between amount of water entrained into a wetland, and the number of buoyant beads, and presumably razorback sucker larvae available for entrainment. This was based on Hedrick et al. (2009), who used marked razorback sucker larvae, semi-buoyant beads, and flow measurements to estimate entrainment rates into flood plain wetlands as a function of river flows. Entrainment rates of water into wetlands were also useful as a metric of larvae entrainment because abundance of larvae varied dramatically and unpredictably within and among years over the 1992-2008 study period (data below). Actual entrainment rates of larvae into wetlands could be estimated from entrainment rates of water if reliable and relevant estimates of larvae density on a seasonal and annual basis were available.

We used 1992 as a starting point for our analyses because it was the first year that spring flow recommendations were instituted at Flaming Gorge Dam with the express purpose of providing more extensive flood plain inundation in spring. We recognize that not all wetlands were breached to allow river flow access as far back as 1992, but we used those hydrologic years as if wetlands were breached, to provide a longer historical view of flooding potential and so comparisons across years were for a comparable set of wetlands. Separate analyses were conducted for flow-through wetlands (Thunder Ranch, Stewart Lake in years when the outlet gate was open, Bonanza Bridge in 2005 and 2006; due to different inundation levels in each years, and Above Brennan), those with at least one inflow and outflow breach each, and single breach wetlands (Horseshoe Bend, The Stirrup, Baeser Bend, Johnson Bottom, Leota wetlands complex at each of 494 and 594 m^3/sec Green River flows due to differing information on breach inundation level needed to fill the wetland, and Old Charley Wash, which under present Ouray Refuge practices, fills only from the downstream outlet even though it has an upstream inlet).

Specific details regarding operation of Stewart Lake were received from the Utah Division of Wildlife Resources (pers. comm., Trina Hedrick, 2010) as follows... "Speaking with the Habitat Manager regarding Stewart Lake, his general management at the floodplain is to keep the inlet gate open until water begins moving out of the floodplain through the inlet (after the floodplain is filled, the river has peaked, and the river is coming down). He does raise the outlet gate as flows begin coming up in the river because if he does not, the water will actually push the gate up and the cables are no longer taut. Therefore, in most years, unless otherwise requested, Stewart Lake has only one breach on the upstream end. However, there is a high flow crossing where water flows around the outlet gate. This occurred for about 4 weeks in 2009 and for almost 3 weeks this year (though not likely continuously) from June 1 through June 17. Flows therefore seem to need to be around 19,000 cfs or higher to go over this. The high flow crossing would make Stewart Lake a flow-through site at high enough flows." Operational vagaries were discussed in this report and in Hedrick et al. (2009), but in general, we treated Stewart Lake as a flow through wetland because it has the capability to be operated that way.

For flow-through wetlands, we used breach inflow data measured at a variety of Green River flow levels (Tetra Tech 2005; Hedrick et al. 2009) to estimate total river flow through the wetland. To do this, we fit a regression function that estimated inflow rates for each of the four flow-through flood plain wetlands as a function of various 2005 Green River flow levels (Figure 3). Using those functions and a hypothetical or actual set of Green River flow values, we were then able to estimate flow rate and average daily flow volume that passed into flow-through wetlands, given that the breach inundation threshold had been exceeded. We also assumed those inflow volumes as a function of stage did not change across seasons or years (e.g., assumed breach aggradation or degradation, which would change inflow functions, was not occurring). Using inflow values over an entire spring runoff period when the wetland was connected with the river, we estimated the entire volume of flow that passed through the wetland to understand total entrainment potential for all flow-through wetlands. We then used timing of appearance of razorback sucker larvae from light trap sampling for a given year to constrain total flow-through volumes to only the period when larvae were available for entrainment. This was always a subset of the total entrainment volume because razorback sucker larvae appeared only after wetland breach connections with the Green River were established. Thus, flow volumes were summed for the entire flow-through period, and for the period after larvae appeared until breach connections with the river ceased, the latter of which provided an estimate of total entrainment potential for razorback sucker. The latter scenario also required the assumption that larvae were available for the entire post-connection flow period, which was reasonable given that in most years, larvae were captured on the descending limb of the hydrograph after breach-river connections ceased.

Single-breach wetlands required a different method for estimating annual flow entrainment under different flow regimes. This was because measurements of inflow or outflow rates from the single breach were not feasible, over the wide range of inflow (and outflow) rates that might be possible. Breach elevations and field observations from wetland breach construction survey estimates suggested expected inundation levels at a given Green River water flow level (stage), and these were subsequently used to estimate the annual level of flow needed to achieve river-wetland connection. We again used the aerial photography data to estimate the relationship of wetland area as a function of Green River flow level. A simple estimate of total inflow volume in a year could be achieved by multiplying average wetland area during the period of river connection by the annual increase in river stage during the connection period (average wetland area multiplied by the amount of stage increase from breach inundation to maximum stage of the river = volume). However, that method would discount any fluctuations in stream flow elevation that occurred during the period (see example hydrographs in Results for examples of variation), which is potentially important because of the manner in which these wetlands function. For example, when streamflow and river elevation increases due to changes in snow melt runoff in a day or due to a rain event, a river-connected wetland fills. However, such river-connected wetlands also drain in response to declines in stream flow because river stage and wetland stage (elevation) during connection are closely linked. This is a main difference between flow-through and single-breach wetlands, because flow-through wetlands continuously entrain (and release) water essentially until the upstream breach connections cease, whereas single-breach wetlands fill or drain depending on whether river elevation (flow) is increasing or decreasing. Thus, the simple volume estimation technique would underestimate total flow volume entrained because wetland filling after the sometimes substantial shorter-term drainage events would be largely ignored. To account for the difference caused by short-term flow fluctuations, we obtained estimates of river stage (elevation) at various flows from measurements used to estimate a stage-river flow relationship at the Green River, Jensen gauge (# 09261000, Figure 4). Those 366 stage-flow measurements, which date back to 1958, were available for Green River flows from 22.9 to 861.2 m^3/sec, and thus adequately encompassed the range of flows we investigated. Normally, stage measurements are used to estimate changes in streamflow and are collected at 15' intervals. We used those same data in a reverse fashion and estimated river stage as a function of stream flow with a power function as follows:

$$y = 0.0626x^{0.5113},$$

where y = stage in feet and x = flow in ft^3/sec. Values were then transformed to metric units. The equation had a fit of $r^2 = 0.99$. This allowed us to use the more readily available stream flow data collected at intervals of 15' to predict changes in stream elevation in a manner inverse to the normal stream flow rate estimation procedure. The fit of the equation was quite good but estimation bias was further explored by estimating stream stage (elevation) as a function of stream flow using the equation above and subsequently comparing actual measured 15' stage changes for a small dataset in 2009 (30 March to 4 June, 6375 observations) when the data were readily available and over a period of relatively high flow. Using this proofing procedure, we found our stage estimation technique had a maximum error of about 3.1% (6.7 cm over an average stage height of about 215 cm), and the error percentage declined as streamflow increased above most flow levels that allowed wetland connections (e.g., 5.8 to 3.7 cm bias at streamflow levels of 368.3 m^3/sec and 546.7 m^3/sec, respectively). Thus, we chose to ignore those relatively small and consistent error rates rather than obtain the large and difficult to access historical 15' stage dataset. We then used the historical 15' streamflow data for the Green River and predicted river stage. Summing the minute and sequential positive and negative changes (< 3 cm) in stage elevations at 15' intervals produced very large estimates of total stage change over the annual period. We instead used stage change data averaged at 1 hour intervals to estimate the stage changes over a daily period, which eliminated the large cumulative effect of the many small and sequential changes; we also felt that wetlands would not fill or drain substantially at 15' intervals. We then used the minimum and maximum stage level observed in a day to estimate the total stage change for the day and summed the increases over a season, on both the increasing, and descending limbs of the hydrograph. That total increase in stage elevation in the wetland for the runoff period was then further constrained to the period when the wetland first connected to the river and ended when the wetland last disconnected from the river, periods which are different for each wetland because of differences in breach inundation levels. That total constrained increase in stage elevation in the wetland was again censored for the period when razorback sucker larvae were present in the river, as determined by light trap captures.

Calculation of total inflow volume into a single breach wetland also required understanding wetland area over the period of interest. We estimated the average wetland area over the period when the river-wetland connection was present, by taking the mean of the daily estimates of wetland area predicted by the equation of area as a function of streamflow for the total period of connection, and for the period when razorback sucker larvae were present, and multiplied that area by the stage change. Volume units of entrained water are presented as hectare-meters, the amount of water required to cover one hectare surface area [10,000 m^2] with water 1 meter deep (10,000 m^3), a metric equivalent of acre-feet, because it has some relevance for understanding the height of water inundation in wetlands of various sizes; it also allows for relatively simple volumetric comparisons of annual water entrainment in flow-through wetlands. A main assumption required when considering stage elevation changes in single breach wetlands is that wetlands fill and drain instantaneously at the 1-hr stage-change durations we used. We feel this is reasonable because minor changes that occurred over 15' intervals were eliminated. If anything, the stage rate changes overestimate the total stage change and volume, because single-breach wetlands, especially large ones, likely do not drain (or refill) quickly. We also did not consider the initial filling volume of each single-breach wetland when it first fills after river connection in the total entrainment volume. That is, in part, because some water was likely already present in most wetlands prior to connection. Also, most wetlands filled prior to the period when razorback suckers were present, so those volumes were not considered in total water entrained in a season. Similarly, flow volumes in flow-through wetlands, which typically first fill from the lower elevation outlet rather than the higher elevation inlet(s), were not considered in total volumes entrained either, so total volumes among the two wetland types were estimated comparably.

Flood plain wetland entrainment simulations.—Flow simulations were conducted to understand tradeoffs of total wetland entrainment volume into the four flow-through flood plain wetlands as a function of more days of lesser flow or fewer days of greater flow of the Green

River. To begin, we started with a base flow of 368.2 m^3/sec, since that level represented the flow when some flow-through flood plain wetland breaches were first inundated. We then chose a total water volume of 849.9 m^3/sec (30,000 cfs) water for 24 hr and divided that total amount of flow over increments that were added to scenarios that were 3.3 to 15 days long; a 30 day scenario was eliminated because baseline flows of the magnitude chosen were unlikely to persist for that duration. The additional amount of flow was added for each time interval (15, 10, 7.5, 6, 5, 4.3, 3.75, and 3.3 d) such that the total added flow volume over the baseline amount was equivalent over each time period simulated. For example, at a river flow of 425 m^3/s (56.7 m^3/sec added to baseline of 368.2 m^3/sec), the additional flow volume added would last 15 days, at a river flow of 538 m^3/sec, the additional flow volume would last 5 days, and at a river flow of 623 m^3/sec, the additional flow volume would last 3.3 days. Entrainment flow volumes for each flow-through flood plain wetland at each river stage were then estimated with equations that estimated flow entrainment rate as a function of Green River discharge, which was then multiplied by 86,400 (24 hr/d x 60 min/hr x 60 sec/min = 86,400) to get daily volume (m^3/day). That daily entrainment volume was subsequently multiplied by the number of days in the simulated period (e.g., 3.3 to 15) to obtain total entrainment volume.   Entrainment volumes were then plotted as a function of Green River flow rate to understand how entrainment volumes varied when river flow was delivered over longer periods at lower levels compared to shorter periods at higher levels. A scenario for management may be to consider baseline flows as those from the Yampa River, while simulated additions may be releases from Flaming Gorge Dam.

Operations of Flaming Gorge Dam.—To understand the effects of Flaming Gorge Dam releases on timing and magnitude of downstream middle Green River flows, and the relationship with presence of razorback sucker larvae, it was necessary to review the operational regimes for the dam since spring releases began in 1992. This was mostly accomplished by examining flow records from the Greendale gauge just downstream of Flaming Gorge Dam, to determine the timing, magnitude, and duration of releases. We then matched those records with flow peaks of the Yampa River (Deerlodge gauge, or the sum of the Yampa River, Maybell gauge and Little Snake River, Sunbeam gauge, flows) to understand if the goal of releasing Flaming Gorge Dam flows coincided with the peak and post-peak Yampa River flows, per flow recommendations (Muth et al. 2000). In some years, large volumes of water were apparently being evacuated from the reservoir in early spring in order to accommodate what was forecast to be a large runoff year (e.g., 1996-1999, which are pre-flow recommendations, although years such as 1999 the Dam was operated similar to flow recs). In such years, the prerelease base flow was quite large and started early in the year, and the increase to full runoff release was negligible, except when releases above power plant level were made.

Flaming Gorge Dam release scenarios for flood plain wetland connectivity.—A main goal of this synthesis was to understand how current operational regimes at Flaming Gorge Dam interact with the need to provide habitat for endangered fishes, particularly razorback sucker. Information useful to describe those relationships includes timing of reproduction of razorback sucker and availability of larvae, relationships of hydrology with timing and extent of flood plain wetland habitat, particularly in relation to flow magnitude and timing of Yampa River and Green River, and knowledge of the operation of Flaming Gorge Dam. With this information, we developed six scenarios that described Yampa River-Green River flow relationships with availability of flood plain wetland habitat and their overlap with timing of availability of razorback sucker larvae for entrainment into flood plain wetlands for the period 1992 to 2009 (18 years), with one exception. That was in 1999, a year for which we did not change the flow regime at all because that was when Flaming Gorge Dam was managed for high releases, to benefit razorback sucker as well as to reduce water levels in Flaming Gorge Reservoir. The scenario comparisons also relied on observing flows in a baseline condition, typically powerplant maximum flow levels, with which to compare with other, typically higher magnitude or longer duration flow scenarios. Since 1999 flows were some of the highest recorded in the post-dam era, there was relatively little in the way of comparisons to be made with lower scenarios. We then compared habitat availability created under those scenarios with the expectations under an unregulated scenario, to understand effects of Flaming Gorge Dam. Some scenarios require release of higher flows over longer durations than under present management, which if implemented, would require managers to consider tradeoffs with subsequent base flow levels. That scenario may also be in conflict with recent management actions to release higher base flows in summer to disadvantage non-native fishes.

The first scenario was characterized by the natural flow of the Yampa River and flat flow releases from Flaming Gorge Dam. Flat flows were calculated based on the average flow rate from the dam over the calendar year; no seasonal adjustments were made for power production or other uses as was normally done. We thought the calendar year may also reflect annual flow availability more closely than those in the water year (1 October to the subsequent 30 September) because decisions regarding releases (hydrologic condition) in some years are based on snow pack levels in the early part of the calendar year. Flow regimes for the middle Green River were plotted and the number of days that flows exceeded three threshold levels during the time when razorback sucker larvae were available (based on presence in light trap samples) was the main evaluation metric. The three flow levels chosen were 368 m^3/sec (13,000 cfs), 396 m^3/sec (14,000 cfs), and 527 (18,600 cfs) m^3/sec. The lowest flow level provided connection with Stewart Lake and Above Brennan flow-through wetlands and also connected with single-breach wetland Baeser Bend. The 396 m^3/sec level provided connection with all flow-through flood plain wetlands and several other single-breach wetlands (The Stirrup, Johnson Bottom, Old Charley Wash). The highest but relatively modest flow level scenario, 527 m^3/sec, provided connections with most single-breach flood plain wetlands, supplied relatively high flow levels into flow-through wetlands, and also described the flow level target in average hydrology years in the middle Green River in 1 of 2 years, per the flow recommendations described in Muth et al. (2000). The timing of availability of razorback sucker larvae, as measured by light trap sampling, and the flow connection metrics just described will be the benchmark conditions for all evaluation scenarios. Again, there were no assumptions made regarding abundance patterns of razorback sucker larvae other than that they were available through the entire flow release duration of interest. We used presence of larvae as a metric rather than abundance because timing was a key issue in flow recommendation scenarios and objective metric of abundance was unknown, given wide annual and seasonal fluctuations in numbers captured. The need to develop some sort of density distribution based on limited drift data will be discussed later. Thus, if one assumed that razorback sucker larvae abundance was constant through time, then the volume of water entrained becomes a comparable metric across all flow regimes that were compared. It was also assumed that annual light trap sampling accurately described the timing of appearance of early life stages of razorback sucker, except for 1997 and 1999, when only 3 and 12 larvae were collected, respectively. In those years we used 28 May as the first date of appearance, the average date of first presence of razorback sucker larvae in light traps samples collected in the middle Green River in other years in the period 1992-2009.

The second scenario (historical) examined past management practices at Flaming Gorge Dam (1992-2009) to understand flow levels and duration of habitat availability that was provided in the middle Green River for razorback sucker larvae. As flow recommendations are presently written, timing of flow releases "should coincide with peak and immediate post-peak spring flows in the Yampa River". That scenario required managers to predict the Yampa River maximum flow peak in each year to trigger Flaming Gorge flow releases. This observed or historical regime is the one all others are compared to in order to show differences with what occurred.

The third scenario used timing of appearance of razorback sucker larvae as a trigger for flow releases from Flaming Gorge Dam rather than what actually occurred. Thus, instead of attempting to match timing of Yampa River flow peaks, Scenario 3 used a biological metric, timing of appearance of larvae determined from light trap sampling, as a trigger for Flaming Gorge Dam releases, which may be a benefit since larvae must be present for high flows to inundate flood plain wetlands and presumably benefit them. This scenario was enabled by simply shifting timing of spring releases described in Scenario 2 forward (always forward because Flaming Gorge flow releases always were prior to first capture of larvae) to the first day when larvae appeared and tallying the number of days that flow levels in the middle Green River exceeded the three thresholds; no changes were made to flow durations or magnitudes from those that historically occurred. Identifying the day of spring releases made from Flaming Gorge Dam was typically relatively easy in low flow years, because increases were large and sustained over the period of interest. In higher flow years, especially the period 1996-1999, large volumes of water were being evacuated from Flaming Gorge Reservoir prior to typical spring releases presumably to manage the reservoir for large volumes of incoming flows as a result of large snowpack melt. During those years it was more difficult to identify the peak of releases because flows were already high, so we assumed the onset of the peak was consecutive days at full power plant capacity (e.g., about 127 m^3/sec). In all years, we estimated a pre-release base flow, by taking the mean of flows for 30 days prior to the certain start of flow increases, which usually included a ramping release day(s). That quantity was subtracted from the full release level over the period of spring releases, because the pre-release base was the amount that was assumed would be flowing from the dam irrespective of occurrence of a spring flow release. Thus, only the difference in flows between the peak and pre-release base flow levels was available to reallocate in other scenarios. For example, if the spring pre-release base was 50 m^3/sec, and the maximum release that spring was 127 m^3/sec, only 77 m^3/sec was available for reallocation over the duration of the release. If the pre-release base was high (e.g., 1996-1999, pre-release base each year was > 85 m^3/sec) and maximum spring release did not exceed full power plant capacity of about 127 m^3/sec, then the amount of water available to reallocate was less.

Scenario 4 was the same as Scenario 3, except that the flow volume of the annual releases above the pre-release base level in Scenario 3 was summed, and that water volume was redistributed over a release period that was half as long as was previously used. The main idea was to restrict the volume to the same amount used in scenarios 2 and 3, but attempted to show the effect of obtaining a smaller number of higher flow days that may more effectively support Yampa River flows than lower flow magnitudes over a longer period. Timing of releases, again, was coincident with first appearance of razorback sucker larvae and because releases were compacted in time, Scenario 4 required flow releases above that of power plant capacity in some years because flow magnitudes were higher in the shorter duration release period.

The fifth and sixth scenarios required additional releases of water above that released in scenarios 2-4. Scenario 5 doubled the duration of compacted releases from Scenario 4, which essentially extended the period of the Flaming Gorge Dam spring flow period back to that used in scenarios 2 and 3, but retained the higher magnitudes of flow for the entire period. It should be noted that scenario length was driven primarily by that which was deemed appropriate by managers in the year releases were made. Duration of the flow released was for a maximum of 30 days unless the historical scenario was for longer than that, and was shorter if simulated middle Green River flows declined below 368 m^3/sec.

Scenario 6 was similar to Scenario 5 because it used the same flow duration and same 30 day limit on the flow release period. Scenario 6 differed from 5 because the daily magnitude of releases was increased up to a maximum of 244 m^3/sec (8,600 cfs), which was equal to the combined capacity of the power plant and the bypass tubes. Exceptions were 1997 and 1999, flows for which were held at the release peaks actually made (239 and 309 m^3/sec, respectively). However, unlike Scenario 5, Scenario 6 was implemented only for the wetter 11years (1993, 1995-1999, 2003, 2005, 2006, 2008, and 2009) in the 18 year period. In the remaining seven years, flows remained the same as in Scenario 5. This was done because it seemed unreasonable to have high releases in lower flow years.

The number of days that flows exceeded each of the three categories (368, 396, and 527 m^3/sec) were tallied for each of the six flow scenarios and the unregulated pattern to compare the benefits of each in terms of flood plain wetland access and inundation provided. Finally, the volumes of water required to conduct releases under all scenarios was tallied by summing the amount of water released in excess of the prerelease flow over the duration of the flow release period. This was compared to the total releases made from Flaming Gorge Dam in that calendar year to gain an appreciation of the water required to accomplish various scenarios. Those flow volumes, which should be viewed as approximations, may be useful to managers to evaluate the efficacy of various flow regimes to assist with conservation of razorback sucker in the Green River subbasin.

For all scenarios, flows from Flaming Gorge Dam were routed downstream at a pace similar to that described below, and routing began in relation to the timing of first presence of razorback suckers in light trap samples. In other words, if releases were > 170 m^3/sec, flows arrived in the middle Green River two days after first presence of razorback sucker larvae was noted, while flows equal to or less than that level arrived 4 days later. This procedure was appropriate given that a delay between arrival of flows downstream would be realized if presence of razorback sucker larvae was used as a flow release trigger for Flaming Gorge Dam. Also, the first and last days in the release duration were ramped such that only 50% of the total flow was released, if the increase in flow releases above the base were > 141.6 m^3/sec. Although these were not the ramping rates recommended by the Flow and Temperature Recommendations (Muth et al. 2000), we used these to facilitate the flow routing process. Otherwise, flow increases in simulations that were at or less than 141.6 m^3/sec were instantaneous.

The unregulated flow scenario was not an experimental release pattern but instead recreated to the extent possible, the natural hydrograph, so that the effects of the dam on flow magnitude and timing in the middle Green River were excluded. This required development of a simple flow-routing model using the sum of flows measured at gauges upstream of the Jensen gauge (# 09261000) in the middle Green River, Utah, and subsequently routing flows downstream at various rates. Flows from the Greendale gauge (#09234500) were passed to the Jensen gauge in the following manner: flows less $\leq$ 170 m^3/sec (6,000cfs) traveled to the Jensen gauge in 4 days, flows > 170 m^3/sec but ≤ 283 m^3/sec (10,000 cfs) traveled to Jensen in 2 days; travel time for flows > 283 m^3/sec took a single day. These criteria were based on existing information for some lower flow levels (e.g., Muth et al. 2000, unpublished data) and based on daily flow records that documented the time of passage of flows spikes that were measured between gauges. We routed flows of the Yampa River (Maybell gauge, 09251000) and Little Snake River (Sunbeam gauge, # 09260000) to Jensen in 1 day. We used the sum of those two gauges to estimate Yampa River flow to maintain consistency, rather than the downstream Deerlodge gauge, because records from the two stations were fully available for the period of interest.

To test if the flow routing technique we used was accurate, we routed flows from the pre-dam period 1951-1962 in years when flows of the middle Green River were relatively high (peak flow > 600 m^3/sec; 1951-1953, 1957-1958, and 1962, did not compute 1956) as well as one lower flow year (peak flow < 500 m^3/sec), 1954, and compared those flows to the ones actually measured at Jensen. The traces of routed and gauge-measured flows overlapped relatively well in the single lower flow year as well as all high flow years examined (Figures 5-11). We also tallied the number of flow days in each year on or after 28 May that were above certain threshold levels, which have significance for flood plain wetland inundation with each technique (Table 2). The 28 May threshold was used because that is the mean day of the first presence of razorback sucker larvae in light traps in the middle Green River for the period 1992-2009, which adds relevance to the occurrence of various flow levels for inundation of flood plain wetlands (results below). Those results also showed good agreement between estimated and actual days above certain threshold measured flow levels, and further suggested the flow routing model worked well in those years. That the flow routing model worked well in the lower flow year 1954, with a peak flow of 448 m^3/sec, as well as the higher flow years suggested general utility for years when flood plain inundation may occur.

Flow routing in the post-dam era required a slight modification to the approach described above. This was because gauges used to measure and route flows would be affected by reservoir storage and releases (e.g., the Greendale gauge is downstream of Flaming Gorge Dam). Therefore, to characterize flows upstream of Flaming Gorge Reservoir in the post-dam period, we used all available gauges on the Green River and major tributaries in the upper Green River system upstream of Flaming Gorge and Fontenelle reservoirs to recreate flow regimes from 1992-2009. We then used flow routing times from those gauges to the Greendale gauge location, and then added the Greendale to Jensen gauge routing times developed for pre-dam flows to fully route flows to the middle Green River, near Jensen, Utah. The gauges used are listed below as are routing times, which are based on map distances and observations of flow spike timing between gauges on tributaries (Blacks Fork, WY, gauge # 09224700, 6 days to Jensen, 2 days to Greendale; Fontenelle Creek, WY, # 09210500, 8 days to Jensen, 4 days to Greendale; Henry's Fork, UT, # 09229500, 4 days to Jensen, 2 days to Greendale) and the mainstream Green River (LaBarge, WY, gauge # 09209400, 8 d to Jensen if flow $\leq$ 170 m^3/sec [6,000cfs, 4 days to Greendale]; 4 d to Jensen if flows > 170 m^3/sec but $\leq$ 283 m^3/sec [10,000 cfs, 2 days to Greendale]; 2 d to Jensen if > 283 m^3/sec, 1 day to Greendale), which is upstream of all the tributary gauges. These gauges and streams were used in the post-dam era because they were largely unaffected by impoundments, although total routed flow volumes were likely conservative since not all streams had gauges. The ideal flow routing model scenario and testing would have used the same gauges to predict streamflows downstream in both the pre-dam and post-dam era, but this was not possible because many of the gauges used for flow routing in the post-dam era were not available for pre-dam flow routing. Absence of flow records from some tributaries such as Big Sandy Creek, for example, are not problematic because most flow was stored in Big Sandy Reservoir in both the pre-dam and post-dam era and was not usually released until after spring runoff.

Because of differences in routing times among flow rate categories, it became necessary to back up flow rates in time (mostly on the ascending limb of the hydrograph) when flows increased and passed from one flow and routing time category to the next, in order for flows to arrive at the Jensen, Utah, gauge at the correct time. Similarly, lower flows were moved forward in time as flows passed from a higher flow category with shorter routing times to a lower flow category with longer routing times (mostly descending limb of hydrograph). Flows moved back in time simply replaced days, while days moved forward used average flows for the first and last actual measurements for the days that were fabricated. For example, if flows at LaBarge, WY, were in the intermediate category with flows of 272 m^3/sec and 278 m^3/sec on 29 and 30 May, respectively, but flow then increased to 297 m^3/sec on 1 June thereby exceeding the upper flow category threshold, the 1 June flow was moved back to 29 May (routing time changed from 4 to 2 days with that flow level transition) so that the higher flow was routed in the correct time. Similarly, if flows transitioned from > 170 m^3/sec on 27 June to the lowest flow classification category on 28 June, the average of flows between 28 June and 2 July (transition routing time extended from 4 to 8 days) were the average of the two in the intervening period. Short-term (e.g., 1-2 day) transitions between flow classes were not corrected but instead used the prevailing flow class prior to the short-term increase. The accounting method for transitioning between flow categories sometimes caused sharp increases (or decreases) in flows seen in the simulated hydrographs (see Results).

RESULTS

Distribution of razorback sucker larvae.—Early life stages of razorback sucker have been captured at most locations sampled in the middle Green River since sampling began in 1992, but most fish were captured at relatively few localities (Table 3, see also Table 5). Most razorback sucker larvae captured in the middle Green River from 1992-1999 were from the Escalante reach (e.g., Cliff Creek) and Ouray reach (Greasewood Corral, Old Charley Wash), although large numbers occasionally were captured near the Stewart Lake inlet or outlet. More recent sampling showed that larvae, which were presumptive offspring of hatchery-released razorback suckers, were also relatively abundant in the middle Green River reach in places such as Walker Hollow and Baser (sic, presumably this is "Baeser", but is spelled Baser in the River Guide) Wash.

We also note that a razorback sucker larva was captured on 2 July 2000 in the lower Yampa River, as well as from 28 June to 4 July 2008, when three razorback sucker larvae (and two more razorback sucker of questionable taxonomic identity) were captured during drift net sampling that targeted Colorado pikeminnow larvae. Those small sucker larvae (9-13 mm TL) suggested relatively late spawning in a location where razorback sucker was not common in recent years. Sampling in the lower Green River from 1996-1999 showed a relatively broad distribution of razorback sucker larvae (Table 4). Limited sampling conducted in 2008 showed continued presence of razorback sucker larvae in the lower Green River, findings that were substantiated by more widespread and intensive sampling in 2009 (n = 170 larvae captured in light traps) and 2010 (pers. comm., P. Badame and K. Breidinger, Utah Division of Wildlife Resources, Moab).

Abundance of razorback sucker and other larvae.—During sampling from 1992 to 2008, a total of 221,376 fish in 22 taxa (excludes potential hybrids and unidentifiable fish) was captured in 2,395 samples (mostly light-trap samples) over 332 sampling days in the middle Green River (Table 5). Of those total fish, 82,778 (37.4 %) were native catostomids (included all unidentified fish), and 7,055 (3.2 % of total fish) were razorback sucker larvae. In 1999, the 12 razorback sucker larvae captured were sent to Ouray National Fish Hatchery for possible rearing and use as brood stock. All other specimens were discarded that year so information for other taxa was not available.

We consider only native catostomids in these analyses because abundance of the only other catostomid captured, introduced white sucker *Catostomus commersonii*, was low in most years. However, white sucker has increased in frequency of occurrence and abundance since 2000. Other changes to non-native species composition from light trap samples collected since 2005 included addition of smallmouth bass, Iowa darter, bluegill, and black crappie; they were mostly rare and locally distributed. For example, Iowa darter was captured only at Cliff Creek.

From 1993 to 1998 and 2000 to 2008 when light traps were used consistently and mostly full samples were retained (fish from samples lacking razorback suckers were inadvertently discarded in 2008), the number of catostomid larvae captured varied from 104 in 1997 to 14,833 in 2004. Number of catostomid larvae did not appear related to sampling effort (number of light trap samples) for 1993 to 2008 (excluding 1999, Pearson correlation coefficient $r = 0.19$). Similarly, sampling effort and number of razorback sucker larvae captured was not positively correlated ($r = -0.05$, 1993 to 2008, excluding 1999). In other words, increased numbers of samples were not responsible for increased abundance of catostomid larvae, including razorback sucker. Rather, increased numbers of catostomid larvae were due to increased abundance of larvae per light trap sample. The CPUE for bluehead sucker *Catostomus discobolus* was highest in 1994, followed by 2007, 2005, and 2008 (Table 6). Flannelmouth sucker *Catostomus latipinnis* CPUE was highest in 2004, but was also high in 2006 and 2007.

The number of razorback sucker larvae captured and CPUE was very high in 2007, but also high in 1994, 2004, 2006, and 2008 (number captured was also high in 2009, n = 942). In those five sampling years, a total of 5,981 razorback sucker larvae were captured, representing 85% of all those captured over the study period. The CPUE for razorback sucker was relatively low in 1995 and 1997 to 1999, but has generally increased since 2000. Similarly, the proportion of razorback sucker larvae to all catostomid larvae was relatively high in 1993 and 1994, declined and remained at relatively low levels in the later 1990's, and generally increased after that, particularly in 2007 and 2008 (Figure 12).

Average total length of razorback sucker larvae captured was 11.8 mm for the period since 1997 (Table 7). No lengths were taken on larvae captured in 1999 because those fish were sent to the Ouray National Fish Hatchery. The maximum length of larvae captured since 2004 has increased, as fish larger than 18 mm TL were captured in each year, compared to none that size in samples from 1997 to 2003; larger larvae were captured in 1993 and 1994.

Number of fish of all species captured varied over the years of sampling, and in general, higher numbers of fish captured were in years with lower spring runoff. We note 2004 as a year with especially high fish abundance in samples (n = 73,657), when over 1/3 of all fish taken during the period 1992-2008 were captured. Samples in that low flow year contained very large numbers of red shiner *Cyprinella lutrensis* (n = 47,302), as well as over 11,000 flannelmouth sucker larvae.

Timing of razorback sucker reproduction.—In general, razorback sucker spawning and early life stage developmental rates are positively correlated with water temperature, whereby spawning occurs earlier and development is faster in warmer water and spawning is later and development is slower in colder water. Razorback suckers first spawned in the middle Green River from early-April to early-May (mean = 23 April) when water temperatures averaged about 11.3°C (range 8 to 14°C) and when accumulated degree days ranged from about 250 to 900 (Table 8, Figures 13-28). The Pearson product-moment correlation between first spawning (Julian days) and accumulated degree days was positive (r = 0.84) and indicated spawning occurred as the water warmed but nearly always occurred before mean daily water temperature exceeded 14°C. Spawning generally began 9 to 51 days (mean = 33 d) prior to the day of highest spring runoff flow. The Pearson product-moment correlation between first spawning (Julian days) and days prior to highest spring runoff flow was negative (r = -0.86), and indicated that as peak runoff approached, fish were more likely to spawn.

The mean timing of spawning (average spawning date for all razorback sucker larvae captured in a year) for razorback suckers in the middle Green River ranged from early-May to late-May (average 13 May) when mean water temperatures were about 12.7°C (range 11 to 17°C) and when accumulated degree days ranged from about 500 to 1050 (Table 9). The Pearson product-moment correlation between mean spawning and accumulated degree days was positive (r = 0.62) and indicated mean spawning time occurred as the water warmed and when the mean number of days when mean daily water temperature exceeded 14°C was 5 (0 to 14 days). Mean spawning time generally began 0 to 29 days (mean = 13 days) prior to the day of highest spring runoff flow. The Pearson product-moment correlation between mean spawning time and days prior to highest spring runoff flow was negative (r = -0.60), and indicated that as peak runoff approached, fish were more likely to spawn.

Hatching dates across years were variable and ranged from late April to early July; mean hatching date across years 1993-2008 was 26 May at mean water temperature of 14.3°C (12 to 16°C; Table 10). Mean hatching date generally occurred within 7 days on either side of the peak spring runoff in the middle Green River (mean was < 1 d after the peak); mean hatching date was also nearly coincident with the 28 May mean peak in Yampa River spring runoff in the period 1993-2008.

First capture dates and the midpoint of capture dates each year were useful to understand presence of razorback sucker larvae in the Green River related to stream flows and their availability for entrainment into flood plain wetlands. This was true because razorback sucker larvae remain in spawning gravel generally for 10-14 days after hatching and were not available for entrainment until they emerged; we know this because mean age of razorback sucker larvae captured in light traps each year was about 12 days (larvae first form daily increments at hatching and thus, are 0 days old at that time). First capture dates for razorback sucker ranged from 15 May to 13 June (range excludes 1997 when only 3 larvae were captured) and was typically later in years when stream flows were higher and cooler and earlier when flows were lower and warmer (Table 11). Mean daily water temperature of the main channel Green River at first capture averaged 15°C (13-16°C). First capture dates were typically coincident with onset of peak flows in the middle Green River; the mean first capture date was 28 May and the mean peak flow was on 26 May (1993 to 2008).

Mean capture dates for razorback sucker larvae in the middle Green River in each year ranged from 27 May to 27 June (mean = 9 June, Table 12). Mean daily water temperature at mean capture date averaged 16°C (14-19°C). Mean capture dates were after onset of peak flows in the middle Green River in all years except 2000; average mean capture date was 14 days post peak flow (range 1 day before peak to 22 days post-peak, 1993 to 2008).

Dates of spawning, hatching, and capture showed a bell-shaped distribution in most years, with few occurrences early and late, and most in the middle of each respective season (Figures 13-28). Plots of presence of razorback sucker larvae in the middle Green River related to stream flows showed that in most cases the first availability of larvae, based on first captures in light traps, was after peak flows had occurred. Although some entrainment may occur on the descending limb of the hydrograph, in nearly every case, highest annual abundance of razorback sucker larvae was well after peak flows had passed and Green River connections with the flood plain had ceased. Only in 1995, 1999, 2000, and 2003 were a substantial proportion of larvae available during high flow periods, and only 1995 and 1999 were relatively high flow years. Flows from Flaming Gorge Dam were reduced during the peak of the 1995 runoff season to reduce flooding in downstream reaches. We also note that flows in 1999 were managed specifically to enhance entrainment of razorback sucker larvae into flood plain wetlands (also in part to accommodate high reservoir inflows), by continuing high releases late into the year when larvae were present.

Data that describes abundance and reproductive ecology of razorback sucker in the lower Green River from 1993 to 1999 were presented in Bestgen et al. (2002); a brief discussion of that is included here for completeness. Razorback suckers were similar in abundance or slightly more abundant in the lower Green River (e.g., 1996) than in the middle Green River in the period 1993-1999 (Table 13). Spawning of razorback suckers in the lower Green River occurred at similar temperatures to those in the middle Green River, but because those temperatures occurred earlier in the year, spawning was earlier. The offset and earlier spawning and first appearance information also indicated that razorback suckers had to be spawning in the lower Green River, rather than drifting from the upstream middle Green River. Similarly, the number of days for first spawning prior to highest spring runoff flow were higher, which suggested that water temperature rather than stream flow, had a larger influence on timing of first spawning of razorback sucker in the Green River system.

In the lower Green River from 1993-1999, first capture dates for razorback sucker ranged from early to late May (excluding the late spawning year 1993) and similar to the middle Green River, was typically later in years when stream flows were cooler and earlier when flows were warmer. The mean earliest capture date in the lower Green River was 10 d earlier than in the middle Green River, on 18 May, or 8 days prior to peak flow. Mean water temperature at mean first capture date was similar to that in the middle Green River at 13.7°C.

In the lower Green River, mean capture dates for razorback sucker larvae ranged from mid-May to late June from 1993-1999. The mean of capture dates in the lower Green River was 10 d earlier than in the middle Green River, on 30 May. Mean water temperature at mean capture date was similar to that in the middle Green River at 15.8°C.

Recaptures of marked razorback sucker larvae, 2004-2006.—In 2004, only a single relatively small release (n = 69,688) was made on 26 May, and a total of 47 marked larvae were recaptured (0.067% of those released) among 1,047 razorback sucker larvae captured in light traps that year (Table 1). Although no recaptures of marked larvae were made in samples collected near Wyasket Bottom and Leota wetlands on 27 May, which was about 8 to 20 hr after marked larvae were released, 46 marked larvae were captured from that area on 28 May, about 32-44 hr after release (fish released about 1000 hrs, traps were typically set in the evening before about 1800 hrs and pulled prior to 0600 hrs the following day). This elapsed time reflected dispersal rates of 2.0-2.8 RK/hr from the point of release 89 RK upstream in this relatively low flow year; flows were 161 m^3/sec the day of release.

Of the 47 marked larvae detected from samples taken until mid-June, 46 were captured on 28 May and the other was collected on 1 June, in the outlet of Stewart Lake. None were captured in other Stewart Lake or Cliff Creek samples (upstream sampling localities relatively near the release site) on 1 June or after that year, or in downstream samples in areas such as Wyasket Lake on 3 June or after. Only 4.5% of all larvae captured were marked.

In 2005, three relatively large releases of marked razorback sucker larvae (n = 594,000 total larvae) were made on 20 May (n = 104,000), 24 May (n = 94,500), and 31 May (n = 395,500). A total of 48 (0.046 %), 48 (0.051 %), and 230 (0.058 %) larvae were recaptured from each release, respectively, for an overall mean recapture rate of 0.055%. Fifty of the 326 marked larvae were sampled in upstream locations Cliff Creek and Stewart Lake; the remainder (n = 274) were taken downstream of those places and most (n = 249) were collected at Greasewood Corral and Old Charley Wash. Most of the 498 total razorback sucker larvae captured in light trap samples during the 2005 season were marked; only 172 wild fish were captured (31% of total) and 326 (69%) were marked.

Larvae released on 20 May 2005 were recaptured in the interval 25 May to 27 June, larvae released on 24 May were recaptured in the interval 25 May to 6 June, and larvae released on 31 May were recaptured in the interval 31 May to 30 June (Table 1, Figure 29). The highest number of razorback sucker larvae recaptured occurred relatively soon after release, but some persisted as long as a month after release, apparently in the main channel margins, and essentially until the end of the sampling season.

The 11 day duration of time razorback sucker larvae were recaptured from the second release in 2005, which occurred during the highest flow of the year (538 m^3/sec), was the shortest of all three releases. Comparatively, recapture durations for the first (33 days) and third (31 days) releases, which were released on days when flow was lower (391 and 470 m^3/sec, respectively), were substantially longer. Distribution of recapture locations varied by release occasion as well. Most recaptures of larvae from the second release were at Cliff Creek (29 of 48) and more proximal to the release site and relatively few were made at downstream Greasewood Corral and Old Charley Wash sites (15 of 48). In comparison, recaptures of razorback sucker larvae at Cliff Creek were lower following the first (4 of 48) and third (17 of 230) releases, and higher in first and third releases at downstream sites (33 of 48, and 201 of 230, respectively).

Overall, of 392 marked larvae that were recaptured in the 2004-2006 period, a few sampling localities were responsible for most of those, and most marked larvae (68%) were recaptured near downstream locations such as Wyasket Lake, Leota wetlands, Old Charley Wash, or Greasewood Corral. Only 57 of those larvae (15%) were collected in upstream localities such as Cliff Creek or Stewart Lake sampling areas; other larvae were captured in intervening areas.

Marked razorback sucker larvae from all three releases in 2005 were recaptured in the same samples on 31 May and 1 June in light traps set at Greasewood Corral and Old Charley Wash, areas which were well downstream of release sites. This meant that marked larvae from the third release on 31 May were recaptured only 12-18 hr after release and 89 RK downstream, which equated to dispersal rates of 5 to 7.4 km/hr.

Changes in length of marked razorback sucker larvae in the interval between release and recapture were different for each of the three releases. Fish from the first release had mean TL of 10.7 mm on 25 May (n = 9), but by the period 20-27 June, marked larvae had mean TL of 18 mm, or grew about 0.25 mm TL/d. Fish from the second release grew little over the short recapture period, which occurred during the highest flow during the study. Larvae had mean TL of 11.1 mm on 25 May (n = 27), and 12 d later on 6 June were only 12.2 mm TL, representing a change in length about 0.09 mm TL/d. Fish from the third release also grew relatively slowly over the longer recapture period; larvae had mean TL of 10.4 mm on 31 May (n = 23), and larvae in the interval 21 – 30 June had mean TL of 14.4 mm, and suggested a change in length of about 0.16 mm TL per day.

In 2006, only 19 marked razorback sucker larvae were recaptured out of 525,000 released (0.0036%) from 21 to 24 May, a recapture rate over an order of magnitude lower than that observed in 2004 and 2005. Four of those were recaptured at Cliff Creek and the remaining 15 were recaptured at downstream sites Greasewood Corral and Old Charley Wash. Recapture dates ranged from 25 May to 9 June; larvae had apparently grown little over the recapture interval because they had mean TL of 10.8 mm.

Flood plain connectivity and area.—Sixteen flood plain wetlands were thought the primary ones of management interest in the middle Green River (Table 14), and totaled about 2,968 ha of surface area (Valdez and Nelson 2004). Surface areas reported were the maximum areas that may reasonably exist under a relatively high flow of about 748 m^3/sec. Qualifications were needed because individual wetland size varied substantially with flow and areas would be substantially larger or smaller depending on flow levels and whether certain areas achieved connection with the Green River, which was also flow specific. Wetlands IMC (Intermountain

Concrete Company), RSS (Richens/Slaugh/Slaugh), and the Lamb Property were terrace-type wetlands (ones that fill and drain with river stage with no residual pool after river-flood plain connection has ceased) that have perpetual easements associated with them. Those three terrace-type wetlands consisted of 216 ha of area (7% of total area), most of which (Lamb) first became inundated at flow levels between 453 and 525 m^3/sec based aerial photographs taken in 2005 (Argonne National Laboratory 2006 and Valdez and Nelson (2004).

The area of terrace (and other) wetlands likely expanded greatly as flow levels increased above 527 m^3/sec, the average minimum flow level required in 1 of 2 years to meet the average hydrologic condition in Reach 2 of the middle Green River (Muth et al. 2000). Terrace type wetlands will be considered only minimally in this report because little is known about their flooding characteristics, and because the utility of terraces as habitat for early life stages of native fishes was poorly understood. Similarly, Sportsman's Lake (53 ha, 2% of total wetland area) will not be considered further because it was privately controlled and the filling cycles for it were not well understood.

The remaining 12 flood plain depression wetlands (wetlands that fill when the flood plain connects to the river and retain residual water after the connection has ceased, Valdez and Nelson 2004) were of most management interest (2,705 ha total) were distributed over about 100 km of the middle Green River beginning just a few km downstream of razorback sucker spawning areas, Razorback Bar and Escalante Bar. Four of those were flow-through wetlands, those characterized as having at least one inlet and one outlet, and consisted of about a maximum of 396 ha or 14% of the total area of the 12 wetlands considered here. Three of the four flow-through wetlands were also located relatively far upstream; Above Brennan further downstream. The flow-through wetlands had 1-5 inflow breaches and a single outflow, although when wetlands were initially filling, incoming flow was through the outlet because it was the lowest elevation point.

Flow and stage at which flood plain wetlands with levee breaches become sufficiently inundated to provide nursery habitat for razorback suckers varied with flow level (Information need #1, Table 14). Likewise, area of each flood plain wetland increased with river flow level once inundation was achieved (Information need # 7, Table 15). Note that we used slightly different means to estimate total surface area of flood plain wetlands at some flows, because predictive equations based on data from aerial photographs were available only for Green River flows up to 623 m^3/sec. We used field observations to supplement surface wetland area information at flows > 623 m^3/sec.

Stewart Lake, a flow-through wetland (but see Methods for description of operations), was the first to connect with the Green River, by virtue of its constructed canal that connects with the river at a relatively low stage. Thunder Ranch and Bonanza Bridge were the last flow-through wetlands to connect with the river. Relative to flow levels outlined in flow recommendations for the Green River in Reach 2 (Muth et al. 2000), connection levels of the Green River with flow-through wetlands were relatively low at 227 to 396 m^3/sec, and were well below the flows expected in some years in the average hydrologic condition (> 527 m^3/sec), and all years in the moderately wet ($\geq$ 575 m^3/sec), and wet ($\geq$ 748 m^3/sec), hydrologic conditions. None of these flow-through wetlands except Stewart Lake connected with the Green River during some average or drier flow conditions, and Stewart Lake only minimally, because connection occurred at about 227 m^3/sec.

The eight remaining flood plain wetlands were single-breach types (we include Old Charley Wash [Main and diked since they were connected] in this wetland type because it now will fill only from the downstream outlet), with only a single flow-level-dependent connection point with the river. Those eight wetlands consisted of about 2,385 ha, or 86% of the total flood plain wetland surface area under consideration. Those were scattered throughout the downstream half of the study area, but most were located on Ouray National Wildlife Refuge. Those included Johnson Bottom, the Leota wetlands complex, Wyasket Lake, Sheppard Bottom, and Old Charley Wash (Wood Bottom), and they totaled 2,270 ha, or 82% of all wetland habitat considered here. Those were all considered single-breach flood plain wetlands because Ouray National Wildlife Refuge will no longer operate any wetlands as flow-through types because of sedimentation issues (Heitmeyer and Fredrickson 2005; D. Alonzo, pers. comm., in Hedrick et al. 2009).

Connection levels of the Green River with single breach wetlands were relatively higher than for flow-through wetlands at flows of 337 to 538 m^3/sec. Several wetlands connected with the river at about 368 m^3/sec (13,000 cfs) by virtue of breach elevations set during construction excavation, although those varied due to scour or sedimentation of breaches, or design changes since original construction. That flow level may be achieved in some years in the average hydrologic condition outlined in flow recommendations (Muth et al. 2000), and perhaps in drier conditions as well. However, substantial single-breach flood plain wetland areas were not available until flow levels exceeded 527 m^3/sec (the required flow condition in 1 of 2 years when average hydrologic conditions prevailed [Muth et al. 2000]), mostly because several large wetlands on the Ouray National Wildlife Refuge were not connected until flows exceeded that level. Connection of single-breach wetlands with the Green River will not be achieved in some years with the average hydrologic condition or in drier flow conditions (e.g., 235 m^3/sec peak flow) because many wetlands only first connected at flows of 368 m^3/sec, and then, only minimally.

As expected, total wetland area in the middle Green River Study area increased in a relatively regular fashion with increasing Green River flow (Figure 30), based on the summed totals of predicted areas from 2005 aerial photographs (those ≤ 623 m^3/sec); threshold values for substantially increased area were at about 450 and 625 m^3/sec. Values at the upper end for the predictions (e.g. Stewart Lake at flows > 527 m^3/sec) did not change because that was the limit of our functional relationships so we used the maximum values from estimates that were available. Baeser Bend wetland was originally breached to allow inundation by the Green River at a relatively low flow level, but that breach was filled so the wetland would be separate from the river and exclude access by non-native fishes. Use of additional observations on inundation area suggested a large threshold increase in wetland area at flows between 578 and 643 m^3/sec. This was because breaches of some relatively large wetlands were exceeded at those flows (Wyasket Lake), or area (and likely depth) increased substantially for already connected areas (Leota and Johnson Bottom).

The areas of total inundation reflected at a lower flow of 255 m^3/sec were mostly a result of post-runoff wetland areas estimated from aerial photographs taken a short time (29 June) after the flow peak in 2005 and after the Green River disconnected with the wetlands. This value does not represent the area remaining until the following runoff season because those wetlands may decline substantially after river flows further decline in summer and beyond and due to evaporation and seepage loss. The residual wetland area remaining after runoff for the remainder of the year is also likely higher than the 333 ha value, which was from aerial photographs taken on 13 May 2005, because even though that area was measured prior to establishment of any known springtime 2005 connections of wetlands with the river (in part, Information Need # 3), there were no connecting flows the previous year. Thunder Ranch (12.6 ha), IMC (0.45 ha), Stewart Lake (66.9), Sportsman's Lake (0.93), Bonanza Bridge (3.3), Stirrup (5.5), Baeser Bend (2.4), Johnson Bottom (25), Leota Wetlands (63.9), Wyasket Lake (1.1), Sheppard Bottom (104.4), Old Charley Wash (44.8) and Lamb Property (4.0) wetlands all contained some water, while Horseshoe Bend and Above Brennan wetlands were dry.

Describing the flow levels required to connect the Green River with flood plain wetlands was an important first step to understanding this complex system. However, simply making connections between flood plain wetlands of any type (flow-through, single breach, terrace, e.g., Hayse et al. 2005) with the river will likely be insufficient to effect substantial entrainment of razorback sucker larvae because density of larvae per unit of flow was low. What was required instead, were substantial flow volumes to enhance availability of flood plain wetlands timed with presence of larvae, which in turn would result in entrainment of larvae into wetlands. Below, we detail the importance of flow magnitude, duration, and timing of availability of wetlands and timing of appearance of razorback sucker larvae on potential entrainment.

Flood plain wetland entrainment simulations.—This section of the report addresses, in part, information needs 5, 6, and 8.

Information need 5. Entrainment and retention of larvae in floodplain nursery habitats as a function of physical characteristics and timing of drift.

Information need 6. Temporal relationships between drifting larvae and hydrology during the runoff period with a focus on the peak flow characteristics needed to entrain larvae.

Information need 8. What is the optimal combination of flow magnitude and duration to maximize entrainment of razorback sucker larvae.

Among flow-through wetlands, Thunder Ranch had the highest simulated flow-through volumes across the period of study, and eclipsed second-ranked Stewart Lake by 2x, followed by

Above Brennan, and Bonanza Bridge with 2005 breach elevations and Bonanza Bridge with 2006 breach elevations (Figure 31); Bonanza Bridge totals in the different years are averaged for the summed total, but shown to illustrate effects of breach elevation changes. High Thunder Ranch inflows were partly a function of the relatively large size of the wetland (134 ha) as well as the presence of multiple breaches. Stewart Lake had a larger maximum size (231 ha) than Thunder Ranch, and connected at a much lower level, but had only a single breach that was controlled by an adjustable gate. The Above Brennan wetland had a higher inundation level and was less than 1/10 the size (20 ha) of Stewart Lake, but had similar simulated total inflows over the 1992 to 2009 period of record. Bonanza Bridge simulated inflows were lowest among the flow-through wetlands and the flow-through total declined from 2005 to 2006, because Green River inundation flow level of the breaches increased from 394 m^3/sec to 434 m^3/sec due to sedimentation.

The highest annual simulated entrainment flow volumes for all flood plain wetlands was in 1997, the highest flow volume year in the period 1992 to 2009 (Figure 32, Tables 16 and 17); 1997 was also the year when the second-highest Flaming Gorge Dam flow release (239 m^3/sec) occurred in the 1992-2009 period (highest in 1999). Little or no simulated flow was entrained by any flow-through (1992, 2002, 2004) or single-breach flood plain wetland (1992, 1994, 2002, 2004, and 2007) in several years in the 1992-2009 period. Pearson product-moment correlation of mean daily Green River flow at Jensen, Utah, from 1 May to 30 June per year, a metric of the volume of spring runoff, and the sum of the annual simulated entrainment volumes for all flow-through wetlands across the period 1992-2009, was relatively high ($r = 0.81$).

The mean percent of annual flow entrained into flow-through wetlands when razorback sucker larvae were present was only 33% of the total flow entrained in the 1992 to 2009 period.

Mean flow entrainment when razorback sucker larvae were present was lowest for the Thunder Ranch wetland (24% of the total simulated flow entrained when larvae were present) and highest for Stewart Lake (45%). The relatively high Stewart Lake simulated entrainment volume percentage when razorback sucker larvae were present was likely due to the lower breach elevations that connected with the Green River for a longer time period. Thunder Ranch entrained the most overall simulated flow in the period when razorback suckers were present from 1992 to 2009 and Bonanza Bridge at 2006 breach elevations the least; the rank of other wetlands was the same as for total flow entrained. Correlation of mean daily flow from 1 May to 30 June per year and the sum of the simulated entrainment volumes when razorback sucker larvae were present for all flow-through wetlands across the period 1992-2009 was $r = 0.65$, and was only 0.54 when years with no entrainment were excluded.

Similar to total flow entrainment, the percentage of simulated flow entrained into flow-through wetlands when razorback sucker larvae were present relative to the total entrained in the same year varied substantially across years with different flow volumes in the period 1992 to 2009. In four years (1994, 2000, 2006, and 2007), the percent of flow entrained when razorback sucker larvae were present exceeded 80% of the total entrained for the year. However, all of those years had below average flow so overall flow volumes entrained when larvae were present was low. In the four highest flow volume years (1993, 1997, 1999, 2008), only an average of 28% of the flow entrained into flow-through flood plain wetlands was when razorback sucker larvae were present.

There was no correlation ($r < 0.001$) between the percent of simulated flow entrained when razorback sucker larvae were present and the volume of spring flow in the Green River. Some of the low annual percentages of flow entrained when larvae were available in higher water years (e.g., 1997, 5.1%) may be a function of mis-estimation of the period of availability because few were captured (n = 3). However, even in 2008 and 2009, when larvae were abundant and the timing of their presence in light trap samples was presumably well-estimated, and flows were relatively high, the percentage of flows entrained when razorback sucker larvae were present was only 8-21%.

Similar to flow-through wetlands, entrainment capacity and functioning of single-breach flood plain wetlands varied broadly and was mostly related to Green River flow rate (Table 17, Figure 32). Consideration of other single-breach wetlands not included in the totals described above have limited capacity for recruitment of razorback suckers, based on present configurations and ability to hold water.

It is important to remember that all single-breach wetlands fill but also drain once connected to the river, depending on river flow stage. This is a main difference between flow-through and single-breach wetlands, because flow-through wetlands continuously entrain (and release) water essentially until the upstream breach connections cease, whereas single-breach wetlands fill or drain depending on whether river elevation (flow) is increasing or decreasing. Mainly because of this difference, single breach wetlands entrained only about 12.5% of the volume of water of flow-through wetlands in the period 1992-2009, in spite of being more numerous, and having a much greater surface area (971 ha vs. 396 ha for flow-through types). Old Charley Wash entrained the most simulated flow volume, by merit of its relatively large size and relatively low connection level, followed by Leota (at 494 m^3/sec inundation level), Johnson Bottom, Baeser Bend (assuming connection at low levels), The Stirrup, and Horseshoe Bend. Old Charley Wash and Leota (494 m^3/sec connection level) entrained simulated water volumes over the study period that was similar to the lowest entrainment volume flow-through wetland, Bonanza Bridge, in 2006. However, lower entrainment volumes do not necessarily reduce the utility of single breach wetlands as habitat for early life stages of razorback sucker.

The highest simulated entrainment flow volumes for all single-breach flood plain wetlands was in 1997, the highest flow year in the study period 1992-2009. No flow was entrained by any single breach flood plain wetland in 1992, 1994, 2002, 2004, and nearly none in 2007. Pearson product-moment correlation of mean daily flow for the period from 1 May to 30 June for the year, again, a metric of spring runoff volume, and the sum of the simulated entrainment volumes for all single breach wetlands across the period 1992-2009 was high (r = 0.93).

Simulated flow entrainment in single-breach wetlands was much reduced when flow volume was constrained to the period when razorback sucker larvae were present in the system. The mean percent of annual flow entrained when razorback sucker larvae were present was only 32% of the total flow entrained, in the 1992 to 2009 period, and all wetlands were in a similar range of 29-36% (excluding Leota at 594 m^3/sec connection level). The rank order for water volume entrained when razorback suckers were present was identical to that for total entrainment, with Old Charley Wash the highest, and Horseshoe Bend the lowest. Correlation of mean daily flow from 1 May to 30 June per year and the sum of the simulated entrainment volumes when razorback sucker larvae were present for all single-breach wetlands across the period 1992-2009 declined to r = 0.53.

Similar to total flow entrainment, the percentage of simulated flow entrained in single breach wetlands when razorback sucker larvae were present varied substantially across years with different flow volumes in the period 1992 to 2009. In six years, there was no, or nearly no, flow entrained when razorback sucker larvae were present (1992, 1994, 2001, 2002, 2004, 2007), a third of the years in the study period. In three other years (2000, 2006, 2007), the percent of flow entrained when razorback sucker larvae were present was > 97% of the total flow entrained, but again those were relatively low flow years. In the highest four flow years (1993, 1997, 1999, 2008), the percent of simulated flow entrained when razorback suckers were present was only 31% of the total flow entrained into single-breach flood plain wetlands.

There was no correlation ($r < 0.055$) between the percent of simulated flow entrained into single-breach wetlands when razorback sucker larvae were present and the volume of spring flow. As previously described, the 1997 data may have been affected by limited information regarding availability of larvae (n = 3 larvae captured). However, even in 2008 and 2009, when larvae were abundant and the timing of their presence in light trap samples was presumably well-estimated, and flows were relatively high, the percentage of flows entrained in single breach wetlands was even lower than that for flow-through wetlands at 8%.

Simulations showed that higher, shorter duration flows entrained substantially more water than lower, longer duration flows (Figure 33). At the lowest flow level of 425 m^3/sec over a 15-day period, flow-through wetlands entrained only about 45% of the water that the same wetlands did in 3.3 days at the highest flow level of 623.2 m^3/sec. Thunder Ranch wetland entrainment dominated the total flow entrainment relationship, but all flow through wetlands increased in flow volume entrained as Green River flows increased, except for Stewart Lake. Stewart Lake declined slightly as flows increased until the highest level simulated, 623.2 m^3/sec, was reached, when flow entrainment volume increased slightly. We did not simulate higher flow levels because we did not want to exceed the flow levels upon which the relationships of flow entrainment as a function of Green River flow were based. However, entrainment likely increased at higher Green River flow levels along a trajectory similar to that for lower flow levels.

We also evaluated entrainment rates of water entrainment and connection days (see Appendix III) for various simulated hydrographs (modified peaks of 368, 396, and 425 m^3/sec, 13,00, 14,000, and 15,000 cfs, respectively) presented in Hayse et al. (2005) compared to the average flow recommendation (527 m^3/sec, 18,600 cfs) presented by Muth et al. (2000). Similar to the results above, flow connection days were slightly higher (20%) at lower peak flow levels but the amount of flow entrained at the 527 m^3/sec level was 2.5X as high and 2X as high for flow through and single breach wetlands, respectively, compared to entrainment volumes at the 368 m^3/sec level.

We did not model the inflows of single breach wetlands in the same fashion as for flow-through wetland relationships, because the effects of short-term fluctuations on flow entrainment would have been difficult to simulate. However, the relationship of total entrainment volume for all single-breach flood plain wetlands was positively related to Green River flow for the period 1992-2009 (r = 0.82) when flows were sufficient to inundate breaches.

Breach elevation makes a large difference in the amount of water entrained into flood plain wetlands, for both flow-through and single breach types. Differences in Bonanza Bridge simulated entrainment volumes when razorback sucker larvae were present for 2005 and 2006 breach levels, were about 30% lower for the 2006 scenario when breach elevation was higher (inundation at 434 m^3/sec compared to 394 m3/sec); differences for total flow volume were even larger. Leota wetland entrainment levels were even more markedly different, due to the difference in breach inundation level (494 vs 594 m^3/sec). The highest flow level entrained only a small volume of water and none when razorback sucker larvae were present. The entrainment level at the lower 494 m^3/sec flow was the second-highest among the single-breach wetlands, but the amount of flow entrainment was relatively low given the large size of the Leota wetland complex.

Operations of Flaming Gorge Dam.—Flaming Gorge Dam spring release flow peaks in the 1992-2009 period ranged from 112.5 to 308.8 m^3/sec; most spring peak releases were about 130 m^3/sec, the capacity of power plant flows (Table 18). Comparatively, Yampa River peak flows from 1992-2009 ranged from 98.3-617.6 m^3/sec, with a mean of 361.4 m^3/sec; mean date of the Yampa River peak was 26 May.

On average over the 1992-2009 period, onset of Flaming Gorge Dam spring releases occurred 15 days prior to the peak of Yampa River flows; flows were released an average of 11 days prior to the Yampa River peak if the years when high pre-runoff flows were excluded (1996-1999). The mean duration of Flaming Gorge Dam releases was 36 days, but was 24 days when high release years 1995-1997, and 1999, were excluded. In those four years, higher releases began early and extended for a relatively long time, presumably to reduce Flaming Gorge Reservoir elevation in anticipation of high inflows.

First capture dates for razorback sucker larvae in middle Green River light traps were typically near or shortly after Yampa River peaks (mean peak date = 26 May); mean first capture date was 28 May. Spring high flow releases were ramped down, on average, 10 days after the first razorback sucker larvae were detected, when high release years 1995-1997 and 1999 were excluded. In some years (e.g., 2009) when presence of larvae was later in the year, releases were declining before razorback sucker larvae were first captured.

Flaming Gorge Dam release scenarios for flood plain wetland connectivity.— Based on the potential number of days that flood plain wetlands may be inundated in the middle Green

River when razorback sucker larvae were present, relative to that available under an unregulated regime, Scenario 1, the constant release regime, had the fewest inundation days for each of the three flood plain wetland inundation flow levels; the mean number of inundation days was also only about a third or less of the number available in the unregulated flow scenario (Table 19, Figures 34-39). Constant flow release performance was best in high flow years when water volumes from the Yampa River were high (1993, 1995, 1997, and 1999; for example, compare scenarios 1 and 2 for Figure 36, 38, or 39 [lower flow years] to those in Figures 34, 35, or 37 [higher flow years]). Performance of Scenario 1 in 1995 at the two lowest flood plain inundation flow levels was higher relative to scenarios 2 and 3 for unusual reasons. In 1995, Flaming Gorge flow releases (the actual flows, which were used in scenarios 2 and 3) were at power plant maximum relatively early, but were then turned down to near or below pre-release levels about the time razorback sucker larvae were available, and then turned back up, mostly after flood plain wetlands had disconnected (Figure 35). Thus, flow conditions in the flat release Scenario 1 were higher when razorback sucker larvae were present than in either scenarios 2 or 3, accounting for the greater number of inundation days in Scenario 1.

The mean number of flood plain wetland inundation days in Scenario 2 was about twice that realized in Scenario 1, for the lower two flow inundation levels and added several days at the higher flow level in some years (e.g. 1999, Figure 37) but none in others. It is important to remember that the higher flow level simulated in this exercise represents only the average condition of 527 m^3/sec as recommended in the flow recommendations. The mean number of wetland inundation days in Scenario 2 was less than half that predicted under an unregulated scenario, and was especially low in the higher flow inundation condition, reflecting flows lower than the unregulated condition. Only in years when Flaming Gorge Dam releases were for extended duration and well above maximum power plant level (maximum of 239 and 309 m^3/sec, for 1997 and 1999, respectively) were the number of inundation days at the higher flow level substantial and more similar to unregulated regimes.

In Scenario 3 where simulated flow patterns were identical to that in Scenario 2 but release date was timed with first presence of razorback sucker larvae in light traps, the mean number of inundation days at the various flow levels was similar to Scenario 2, with some year to year variation. Performance of both scenarios 2 and 3 was best, again, in high flow years when water volumes from the Yampa River were high (1993, 1996, 1997, 1999, 2005, 2006) and when flows higher than power plant capacity were released from Flaming Gorge Dam (1997, 1999, 2005, 2006). Performance declined particularly dramatically in the higher flow inundation condition tested, 527 m^3/sec, in most years presumably because flow releases from Flaming Gorge Reservoir that were higher than that of power plant level were rare. Relatively good performance in 1997 and 1999 at all inundation levels was due, again, to high flow releases from Flaming Gorge Dam as well as high Yampa River flows, which provided water needed to inundate flood plain wetlands for substantial periods even at the higher inundation level. Even in those years, however, flows were not sufficient to match the number of inundation days realized under the unregulated condition. In 2005 and 2006, the only other years when flows in excess of power plant capacity were delivered from Flaming Gorge Dam, releases were relatively low (195 and 173 m^3/sec, respectively) and for short durations. Poor performance in 1995 was again, due to a relatively late first hatching date for razorback suckers of 13 June, after highest flows had passed, and because releases were turned down about the time of first occurrence of razorback sucker larvae. Only 32 razorback sucker larvae were captured in light trap samples that year, so conservative (late) first hatching date estimation may have also played a role in poor performance of those flow regimes in that year in particular. Performance improvement was especially substantial in 2009 at the intermediate inundation level because flows in the actual scenario were reduced especially early (Figure 39, Table 19).

Scenario 4, which used presence of razorback sucker as a trigger, but had a higher and shorter duration peak, increased the number of flood plain wetland inundation days only marginally by an average of 1 day under each flow level. The apparently large increase in 1995 at the lowest flood plain inundation level was due mostly to the higher magnitude release that better-supported declining Yampa River flows, and particularly, because most of the effect of the unusual decline in Flaming Gorge flows when razorback sucker larvae were available, was removed. Essentially what occurred in Scenario 4 was to offset the longer duration flow with a higher shorter duration flow, but which made little difference in the total inundation days because the water volume was the same.

Scenario 5 flows, which essentially doubled the duration of Scenario 4 flows, had a more notable effect on the number of flood plain wetland inundation days in the two lower flow levels, but made little difference at the higher level of flood plain inundation. Increased number of days of flood plain wetland inundation was greatest in 1993, 2003, and 2005-2009 (exclusive of 2007) at the lowest two wetland inundation levels, when inundation days doubled or nearly so in some cases. The mean flow magnitude in years when releases above power plant level was required was 190 m^3/sec (excludes 1997 and 1999). That flow level was insufficient to provide flows needed to increase flood plain wetland inundation at the 527 m^3/sec level.

Scenario 6 flows retained the duration of flows used in Scenario 5, but in wetter years (1993, 1995-1999, 2003, and 2005-2009 exclusive of 2007) increased maximum release level to 244 m^3/sec for up to a maximum of 30 days, unless previous flow durations were greater. Flows during 1999 were unchanged. Scenario 6 increased the mean number of days of flood plain wetland inundation over that in Scenario 5 and also increased inundation days to about the mean number realized under the unregulated scenario, except for the higher flow level, which was lower. Increases were particularly large in 1993, 1995, 1996, 1998, 2003, 2006, and 2008 for one or both of the lowest two flow inundation levels, and were also substantial in 1993, 1997, and 2008 at the higher flood plain inundation flow level. The number of inundation days for flood plain wetlands in 1995 in Scenario 6 increased for all flow levels because the unusual flow patterns that occurred at Flaming Gorge Dam, and propagated through scenarios 2-5, were partially mitigated.

Scenario 6 flow patterns created numbers of inundation days for flood plain wetlands in the lower two flow scenarios that matched reasonably well with those predicted from unregulated hydrographs. Exceptions were 1995 and 2009, when simulated flows created fewer days of flood plain wetland inundation, and 2003, 2005, 2006, and 2008, when more days were created. The low number of days estimated in 1995 was likely due to the relatively late date of presence of razorback sucker larvae; in 2009 it was due to the reduction in flows at Flaming Gorge Dam that occurred prior to the date of first presence of razorback sucker larvae. In the higher flow level scenario, days of flood plain wetland inundation were generally fewer in Scenario 6 than in the unregulated condition, especially for years 1995-1997; an exception was in 2008 when 8 inundation days were simulated in Scenario 6 and none existed in the unregulated scenario.

The volumes of water released during spring flows from 1992-2009 varied mostly depending on the flow year, with more released in wet years and less in dry years (Table 20). The mean annual volume actually released in the period was about 17,400 ha-m (multiply ha-m

X 8.09 to get acre-ft); the smallest releases were in 2004, 1998, and 1992, and the largest were in 1999 and 1997. By plan, scenarios 2-4 used the same volumes of water. However, Scenario 4 required release of flows above power plant level in all cases because flow volumes were bundled into a release period that was only half as long as that required for scenarios 2 and 3.

Releases conducted under Scenario 5 required an average of 54% more water than those in scenarios 2-4, while Scenario 6 required about twice the volume of water required for scenarios 2-4 (100% more). Recall that Scenario 6 flow volumes were increased over those for Scenario 5 only in 11 of 18 of the wetter years. Simulated flow volumes were highest in 1997, 1993, and 2008; recall that 1999 flows remained constant throughout these simulations.

Flow volumes for spring releases from Flaming Gorge Dam were about 11% of the mean annual release volumes in scenarios 2-4, 1992-2008 (8.3% is average under steady flows). The lowest percentage (3.3%) occurred in 1997, and was partially an artifact of the relatively high pre-release flow level and the resulting relatively lower spring release volume. The highest percentage of flow releases under scenarios 2-4 occurred in 2005 (19.7%). The mean percentage flow volume for spring releases from Flaming Gorge Dam increased to nearly 26% under the assumptions of Scenario 6, 1992-2008, and was nearly 31% for just the 11 wetter years in the same period.

DISCUSSION

Reproductive ecology of razorback sucker was examined in light of present management efforts to bolster populations and enhance habitat in the regulated middle Green River, Utah. A main part of the existing management scheme was to schedule flow releases from Flaming Gorge

Dam coincident with peak flows of the mostly unregulated Yampa River to provide overbank flows and access to relatively warm and food rich flood plain wetlands for rearing of razorback sucker larvae (Muth et al. 2000). We found that reproduction by razorback sucker, which has increased since 2004, was driven mainly by onset of warmer water temperatures but occurred relatively late, such that most larvae were available only after peak flows in the middle Green River had declined to levels that provided minimal or no connection between the river and flood plain wetlands. This occurred because peak flow releases from Flaming Gorge Dam, which historically (pre-dam) occurred after the Yampa River, were not of sufficient magnitude or duration to sustain such habitat. We also found positive relationships between flow levels of the Green River and the effectiveness of both flow-through and single breach flood plain wetlands to entrain water, and presumably, razorback sucker larvae when they were available. We then explored alternative flow release scenarios for Flaming Gorge Dam that may better link the reproductive ecology of razorback sucker with availability of flood plain wetland habitat. The most effective patterns required higher and longer duration releases that overlapped more fully with presence of razorback sucker larvae. Higher and longer spring flow durations have implications for summer base flow levels, and may conflict with recent trends for higher summer base flows in the Green River. Below, we discuss the multiple lines of evidence that support these ideas and discuss possible options for future management of razorback sucker in the middle Green River.

Razorback sucker distribution.—Sampling since 1992 indicated that razorback suckers remained in a large portion of the Green River, but that most individuals still occurred in the middle Green River from near Jensen, Utah, downstream to Ouray National Wildlife Refuge. Reproduction was documented in summer 2000 and 2008 in the Yampa River in Echo Park, and one adult fish was captured upstream of Yampa Canyon in the Yampa River in spring 2009 (pers. comm., J. Hawkins, Colorado State University), so a small population of adults must exist upstream of Echo Park. Given capture of ripe razorback suckers in a cobble side channel at river mile 103.7 in 2008, capture of three age-1 juveniles (119-120 mm TL) between river miles 18 and 44 in 2008 in the lower Green River, and ongoing captures of larvae in the lower Green River in 2008 and 2009 (pers. comm., P. Badame, Utah Division of Wildlife Resources, Moab), which were typically present earlier in the season than those in the middle Green River, a reproducing population of adults must also occur in that area (Muth et al. 1998; Chart et al. 1999; Bestgen et al. 2002). That area deserves additional attention in the form of increased sampling, so managers can better assess the importance of the lower Green River to razorback sucker recovery.

Abundance of razorback sucker and other larvae.—Reproduction by razorback suckers was documented each year from 1992-2009 in the middle Green River based on captures of early life stages of razorback sucker. Reproduction also occurred in seven consecutive years in the lower Green River since sampling began in 1993 and was also documented in 2008 and 2009; no sampling occurred from 2000 to 2007. Documenting consistent annual reproduction in the 1990's might be considered something of a surprise given the apparent rarity and decline of wild adult razorback suckers during that time (Bestgen et al. 2002). Since then, large numbers of razorback sucker have been stocked and some have survived to reproduce (Zelasko 2008, Zelasko et al. 2010, Zelasko et al. 2011; this report).

Abundance of razorback sucker larvae in light trap samples collected in the middle Green River, Utah, has increased, perhaps since about 2000, but certainly since 2004. Larvae were very abundant in samples collected in 2004, 2007-2009. This trend reversed a decline noted in the

1990's when razorback sucker larvae were relatively abundant in 1993 and 1994 but declined dramatically by 1999 (Bestgen et al. 2002). Light trap sampling in the period 2005-2009 also documented recent high abundance of other native suckers in the middle Green River. We found no correlation between sampling effort and abundance trends for catostomid larvae, including razorback suckers, which suggested that increasing trends in abundance over time were not an artifact of increased sampling effort. The recent increased proportion of razorback sucker larvae in light trap samples compared to all native catostomids, and increased catch per unit effort, is further evidence that increased abundance of razorback sucker larvae was not an artifact.

We also documented increased frequency of occurrence and abundance of white sucker in light trap samples since about 2000. This suggested white sucker was reproducing in the area, perhaps near primary spawning areas for razorback sucker. These data also confirmed continued expansion of white sucker downstream, a trend noted in sampling conducted upstream in the Green River in Lodore and Whirlpool canyons (Bestgen et al. 2006). Expansion of white suckers in the middle Green River and increased abundance of razorback suckers increases the possibility for hybridization, since each species appears to spawn at relatively cool water temperatures early in spring. Although hybridization between white sucker and razorback sucker has not yet been verified, it has been suspected in at least one instance in the Green River in upstream Lodore Canyon (Bestgen et al. 2006). Because monitoring identity of hybrids of larvae with morphological techniques is difficult, managers may wish to begin monitoring identity of suspected hybrid larvae with genetic techniques as well. Combined with diligent efforts to identify hybrids of adult catostomids, monitoring identity of larvae with genetic techniques may yield additional information about the frequency of hybridization of razorback sucker with invasive white sucker.

Increased maximum length of razorback sucker larvae captured in light trap sampling in recent years may indicate some are surviving longer. We cannot exclude more effective late-season sampling as a plausible reason for presence of larger razorback suckers in samples, but regardless of the cause, larger fish present later in the season may enhance chances for recruitment to the adult life stage.

Timing of razorback sucker reproduction.— Our analyses with up to 18 years of data suggested that razorback sucker spawning began each year in the middle Green River from early April to early May when flow levels were relatively low or increasing and when water temperatures were 8 to 14°C (Muth et al. 1998; Bestgen et al. 2002; this report); spawning is earlier when the Green River warms earlier and later when water warms later. Mean spawning time was several weeks later from early May to late May when mean water temperature was about 13°C. Spawning was earlier in the lower Green River, from late March to early June, and over a longer period, than in the middle Green River perhaps because the river warms earlier at that lower elevation and lower latitude. Flow levels during razorback sucker spawning in the lower Green River were relatively low compared to the middle Green River because of earlier reproduction, but occurred at a similar 6 to 15°C temperature range. This suggested rising water temperature or absolute temperature level may be a more important environmental cue for spawning than flow level, a situation true in lentic settings (Bestgen 1990, Bozek et al. 1990).

Given the importance of water temperature on initiating reproduction in razorback sucker, and that timing of reproduction and ultimately, presence of larvae, plays a role in determining the effectiveness of flow releases to enhance flood plain wetland habitat, it is reasonable to consider whether reservoir releases plays a role in delaying spawning by razorback suckers in the middle Green River. For example, in some years, higher flows are released from

Flaming Gorge Dam in early spring to evacuate water and make space in the reservoir for incoming flows. If those flows are abnormally cold or cold because the abnormally high volume does not allow for warming as it proceeds downstream, development of gametes by razorback suckers could be delayed. This situation is exacerbated by reduced availability of warm flood plain wetlands present at lower flows that could assist with gamete development. This issue was alluded to indirectly in the development of the flow and temperature recommendations, because razorback sucker use of off-channel tributaries such as Ashley Creek, which are warm and food-rich, was documented (Tyus and Karp 1990; Muth et al. 2000). However, direct effects of Flaming Gorge Dam operations in spring on water temperatures, and subsequent timing of spawning, development of embryos, and emergence/occurrence of razorback sucker larvae should also be considered, as should the potential concurrent effects on timing of reproduction by non-native fishes. Similarly, most global climate change models generally predict warmer air temperatures and potentially warmer water and lower flows. Climate change may affect reproduction patterns of razorback suckers and flow levels of the Green River, and efforts to manage the system for conservation of razorback suckers should consider this potentially important effect. The importance of timing of presence of razorback sucker larvae to availability of flood plain wetlands will be discussed in detail below.

Following spawning in the middle Green River, timing to hatching and first presence of larvae in light trap sampling gear also proceeded at temperature-mediated rates (Bozek et al. 1990; Haines 1995; Muth et al. 1998; Bundy and Bestgen 2001; Bestgen et al. 2002). In general, mean timing of hatching occurred about 2 weeks (13 days) after mean timing of spawning. After hatching, larvae apparently remained in the spawning gravel for an extended duration as the mean time to first capture was again about two weeks (14 days) after mean time of hatching;

mean capture date (peak of captures) was about two weeks after that. This pattern was supported by aging of larvae, as nearly all individuals captured in light trap samples were at least 10 days old; most were a minimum of 12-14 days old and generally 11 mm TL or more. Importantly, mean time to *mean hatching* (May 26), and the mean *first* date of occurrence in light trap samples (28 May), and the mean date for the spring peak of the Yampa River (26 May) all occurred at about the same time during the study period 1993-2008.

Based on extensive capture data across many years of variable environmental conditions from 1992-2009, it appeared that overlap of presence of razorback sucker larvae in the middle Green River and flow regimes is offset, which is inconsistent with the intent of flow recommendations (Muth et al. 2000). This was true because in most years, the mean time of hatching (not occurrence) and the first presence of larvae, which are relatively rare early in the season, coincided with the latter part of spring peak flows, and even that was inconsistent. This inconsistency was not noted when Flaming Gorge Dam flow recommendations were crafted because only a few years of light trap sampling data were available to match with flows (Muth et al. 1998; Muth et al. 2000).

A more consistent overlap of Green River peak flows with higher abundance of larvae is a more desired condition. An exception occurred in 1999, when presence of larvae coincided with high flows for a longer period because Green River discharge was maintained at a relatively high level by relatively high and extended releases from Flaming Gorge Dam. However, in most years, highest abundance of larvae in light trap samples was only well after spring peak flows had passed. That temporal abundance pattern also had implications for timing of connections between flood plain wetlands and the Green River, which are described below.

Timing of presence of razorback sucker larvae in the lower Green River was prior to, or during, most of the high flow periods from 1993 to 1999 (Muth et al. 1998; Bestgen et al. 2002) and more closely followed the intent of flow recommendations than for the middle Green River. This was presumably due to warmer water temperatures earlier in the year and earlier hatching and presence of larvae. Relatively early spawning in that area would allow larvae to incubate and emerge about the time that flows were peaking. However, lack of flood plain wetland habitat in the lower Green River precludes larvae from being entrained into such places, where they rely instead on the relatively few and small-scale in channel features such as flooded washes for rearing habitat.

Recaptures of marked razorback sucker larvae, 2004-2006.—Recaptures of marked razorback sucker larvae released in the middle Green River during spring runoff periods offered a unique opportunity to examine patterns of dispersal, distribution relative to time of release, and proportions of recaptured fish to the total captured, among other things. Recaptures in 2004 from a relatively small number of released larvae revealed rapid downstream dispersal and colonization of nearshore areas where larvae were available for capture in light traps. Larvae apparently did not persist in 2004 as only one was recaptured after the first day following release, again, perhaps due to the relatively small number released. Presence of only one larva in Stewart Lake samples and none in Cliff Creek samples (upstream sampling localities relatively near the release site) collected on 1 June or after in that year was surprising, given the relatively low flow levels during that release. Their absence in Cliff Creek samples may have been due to their right bank or mid-channel release location, as larvae and beads released there during entrainment studies, tended to remain on the right bank well downstream of the left bank location of Cliff Creek (Hedrick et al. 2009).

In 2005, the three relatively large releases of marked razorback sucker larvae had capture rates (proportion of marked fish recaptured) that were strikingly similar to that observed with the smaller release in 2004, in spite of being released under very different flow levels. This suggested some consistency in efficiency light traps to sample razorback sucker larvae, even though numbers released were quite different. Most larvae captured in light traps in 2005 were marked, a pattern opposite to that observed in 2004 and 2006. This is doubtless due, in part, to the much larger number of fish released in 2005. However, the relatively small number of unmarked larvae in samples also pointed to relatively low reproductive effort of wild fish in 2005 compared to 2004, or perhaps, 2006-2009, when naturally-produced larvae were much more abundant.

Similar to 2004, downstream dispersal rates of larvae in 2005 were rapid and larvae were typically captured soon after the release date in nearshore areas well downstream of release locations. Larvae in 2005 also persisted for a longer time than in 2004, perhaps again reflecting the relatively larger number of them available for recapture, but those patterns also varied by release. The shortest duration recapture period in 2005 was for the second release and was associated with the highest flow at release and most larvae were captured upstream at Cliff Creek. In comparison, duration of recaptures of larvae in the first and third releases was substantially longer and more fish were captured at downstream Greasewood Corral and Old Charley Wash localities. It was also informative to note the presence of larvae from all three releases in the same light trap samples. This suggested razorback sucker larvae were able to find and persist in some localities in spite of the variable hydrologic conditions present during each release.

In both 2004 and 2005, most marked larvae were captured well downstream of release locations, in spite of consistent sampling in upstream locations such as Cliff Creek and Stewart Lake. This pattern was opposite the one postulated by Valdez and Nelson (2004), who predicted that razorback sucker larvae would be most abundant and available for entrainment into flood plain wetlands that were nearest to spawning sites (same as release sites), and that few larvae (< 1%) would be available for entrainment in downstream wetland areas such as those in the Ouray National Wildlife Refuge. Our finding of broadly dispersed larvae, suggested instead that a mosaic of habitat areas should be made available for razorback sucker larvae close to, as well as far downstream, of spawning areas. Further, the merits of individual flood plain wetlands as nursery habitat for razorback sucker larvae should be evaluated with several other criteria (e.g., accessibility as a function of breach type and inundation level, entrainment rates, overwintering capacity, abundance non-natives fishes) in addition to distance from spawning areas, a view supported by Hedrick et al. (2009).

Changes in length of marked razorback sucker larvae in the interval between release and recapture in 2005, which were different for larvae in each of the three releases, suggested that conditions for growth and perhaps survival may have differed over the brief 20-31 May interval. This was in spite of relatively similar proportions of larvae from each release that were recaptured in light trap samples. We assumed no differences in quality or condition of larvae released, since they were from brood stock that were treated similarly, and were produced and marked using similar procedures. Although these data were based on relatively small samples, variable growth and perhaps survival of larvae released over a short time period suggested that provision of a wide variety of habitat types, in a wide variety of locations, and for extended durations, may be needed to benefit some portion of the razorback sucker larvae produced in the wild.

In 2006, the only marked larvae released in the middle Green River were placed a short distance upstream (a few hundred meters) of the inflowing breaches of the Thunder Ranch wetland and nearshore, in order to measure entrainment rates into wetland breaches. The low number of recaptured larvae in downstream light trap samples subsequent to releases may be partly due to high levels of entrainment into, and retention in, the Thunder Ranch wetland. As was discussed in Hedrick et al. (2009), inspection and sampling of the Thunder Ranch wetland in autumn 2006, did not reveal the presence of razorback suckers, in spite of the large number released, so apparently few survived.

Flood plain wetland connectivity, area, and potential entrainment.—Of the 16 flood plain wetlands that were the focus of the Green River Floodplain Management Plan (Valdez and Nelson 2004), we focused on a subset of 12 depression-type wetlands because they were the ones of primary management interest. The area of terrace (and other) wetlands not considered here likely expanded greatly as flow levels increased above 527 m^3/sec, the minimum flow level required in 1 of 2 years to meet the average hydrologic condition in Reach 2 of the middle Green River (Muth et al. 2000). Further, terrace-type wetlands may be of ecological value and several have associated easements, but lacked information with which to characterize their area and utility as temporary rearing areas for razorback sucker larvae. Further investigation of terrace-type wetlands is suggested, given they are widespread and common in some flow regimes. Thus, the relationships we report were for a subset of available flood plain wetlands. Those relationships for wetlands that were better understood likely acted as surrogates for other wetlands not specifically reported on here. Further, inferences regarding all wetlands discussed and relationships with flow should be restricted to the flow levels at which measurements were taken.

The 12 flood plain wetlands of most management interest (2,781 ha total) varied widely in their function, size, placement relative to spawning areas, permanence, and inundation levels, and hence have a widely varying potential as nurseries for razorback sucker larvae. Although flow-through wetlands were fewer in number (4) than single-breach wetlands and had a much smaller total area, they connected with the Green River at relatively lower flows. The eight remaining flood plain wetlands of main management interest were single-breach types and even though they connected with the Green River at higher flow levels than flow-through wetlands, often greater than the average hydrologic condition flow level of 527 m^3/sec (Muth et al. 2000), they constituted the great majority of the surface area of flood plain wetlands. However, a large surface area or volume of habitat was an insufficient metric of the value of various flood plain wetland types for potential entrainment and recruitment of razorback sucker. This was because razorback sucker larvae must first be transported to the flood plain wetland, be entrained or swim into it after access is possible, and then occupy it for some useful duration. In other words, a flood plain wetland must be accessible to larvae and provide overwintering habitat, regardless of size, in order for it to be useful and the largest wetlands are not always the most accessible.

Entrainment capacity and efficiency of single-breach and flow-through flood plain wetlands varied dramatically and was generally positively related to flow volume in the river in any given year. In spite of fewer numbers and smaller total size, the mean annual total amount of water entrained into flow-through wetlands exceeded that of all single-breach wetlands by a margin of about 7 to 1. The large difference in entrainment volumes for Thunder Ranch compared to Stewart Lake was also surprising, given their comparable and large sizes. Higher

Thunder Ranch inflows were partly a function of the relatively large size of the wetland (134 ha) as well as the presence of multiple breaches. Stewart Lake had a larger maximum size (231 ha) than Thunder Ranch, and connected at a much lower level, but had only a single breach. It was also possible that inflows predicted for Stewart Lake were affected by gate structures and that if gates had been operated differently (e.g., perhaps opened fully?), higher inflows may have been achieved. This was postulated because Above Brennan, which had a higher inundation level and was less than 1/10 the size (20 ha) of Stewart Lake, had similar total simulated inflows over the 1992 to 2009 period of record. Bonanza Bridge simulated inflows were lowest among the flow-through wetlands and the total flow through declined from 2005 to 2006. This was because Green River flow level for breach inundation, due to sedimentation, increased from 394 m^3/sec to 434 m^3/sec (Hedrick et al. 2009), the only location where this was measured.

Our calculations supported the intuitive view that entrainment volumes for flow-through wetlands should increase as Green River flow volume increased. The key was the exponential nature of most breach inflow-river flow relationships, because for every unit increase in river flow, breach inflow increased at a greater rate. There was of course, an upper limit to the relationships portrayed. That occurred either when the breach inflow-river flow relationships that we described were exceeded by flows used in calculations, or when very high flows overtopped all levees and water filled the flood plain from multiple sources other than constructed breaches, a condition not observed recently.

Similar to flow-through wetlands, entrainment capacity and functioning of single-breach flood plain wetlands varied broadly and was mostly related to Green River flow rate. However, in spite of being more numerous, and having a much greater surface area, single breach wetlands entrained a much smaller proportion of water than did flow-through wetlands. This was due to the water entrainment process, because single-breach wetlands entrained water only when stage elevation in the river exceeded that in the wetland (i.e., river stage was increasing). When flows and river stage were declining, single breach wetlands were draining even though they were connected to the river Because single-breach wetlands filled only when Green River flows were increasing, and because we assumed complete transfer of water from the river into the wetland (or vice versa when the wetland is draining) even for flow stage increases that were as short in duration as one hour, the amounts of entrained water may be overstated. Although we do not know if the correct transfer time is 1 hour, it was easy to imagine that the process was complex, and may minimally include the stage increase and rate of change in stage height, the duration of the change, the structural complexity (e.g., # dikes), number of breaches and their width (s), and size of the wetland.

The method used to estimate stage changes, tracking short-term fluctuations in stage as flows changed through the day, resulted in a much greater total change in river stage over the season than if stage change had been simply calculated as the difference between maximum stage height for the flow season and stage height when breaches become inundated. Those changes likely varied by year, based on the number of flow fluctuations that occurred on a daily and a more seasonal basis. For example, the late-season increase in flow that occurred in mid-June 2008 (Fig. 28) while flood plain wetlands were still connected to the river added a considerable amount of water back into flood plain wetlands.

Similar to flow-through wetlands, highest simulated entrainment flow volumes for all single-breach flood plain wetlands were in 1997, the highest flow year in the study period. Also, the relationship between spring runoff volume (mean daily flow from 1 May to 30 June) and the sum of the simulated entrainment volumes for all single breach wetlands across the study period was positive and high. Compared to flow-through wetlands, there were many more years when spring flows failed to inundate single-breach wetlands, primarily because of higher breach inundation levels.

Higher inundation levels for single-breach wetlands may not necessarily be a negative effect on entrainment, if larvae are present at the breach mouth when wetlands are first flooded. For many single-breach wetlands, the initial filling event may represent a substantial volume of water entrainment relative to the total volume entrained in a year. This is true because wetland volumes decline after connections with the river cease beginning in early summer and the refill, sometimes substantially again when connected to the river in spring. We did not consider those initial filling volumes in entrainment totals of any flood plain wetlands, and instead considered that the base water level, onto which additional post-breach inundation flows would add. However, if the timing of initial breach inundation was coincident with presence of larvae, then the entrainment volumes with larvae would be greatly enhanced, as would the benefit of single-breach wetlands.

High inundation levels in consecutive years would also assist with connecting all wetland types to the river and allow for escapement of razorback suckers that reared in the wetland in the previous year(s). Such connections are important because they potentially complete the recruitment cycle for razorback suckers from larvae to adult life stage.

The efficiency of flow through and single breach flood plain wetlands to entrain water varied by flow year and was often related to timing of both flow releases and timing of presence of razorback sucker larvae. However, flows were always entrained into flood plain wetlands before razorback sucker larvae were available, which meant entrainment efficiency was always < 100%, and on average, substantially so, at just 33% for flow-through wetlands, and 22% for single-breach wetlands. This was true even in the highest flow volume years. Thus, the main obstacle for realizing higher entrainment efficiency of razorback sucker larvae into flood plain wetlands was one of timing of availability of flows (habitat) relative to availability of larvae. Improving the level of overlap of timing of flows and availability of larvae should be a main focus of future management efforts.

The degree of precision needed to match timing of fish presence and flows was high and is illustrated by data gathered in 1993, a relatively high flow year. In that year, moving the date of presence of larvae 7 days earlier in 1993, increased the total amount of simulated flow entrained when razorback sucker larvae were available from 58% to 88%. There was also no doubt some error in the detection of larvae by light trapping early in the season that negatively influenced the amount of flow entrainment that occurred when larvae were present. However, marked larvae from relatively small release batches were detected within a day or two of release and well downstream of release locations, which suggested that light trapping to detect even relatively small batches of razorback sucker larvae in the river was effective. Further, based on hatching date distributions of larvae captured in light traps, and the mean time of captures, larvae were typically not most abundant early in the year, which decreased the importance of detection of the very first larvae available.

Flow simulations conducted to understand tradeoffs of total entrainment volume into the flow-through as well as single-breach flood plain wetlands as a function of more days of lesser flow and fewer days of greater flow showed that entrainment volumes increased at a faster rate as river flow increased. Thus, relatively lower river flows for longer durations would produce lower entrainment volumes and a higher volume shorter duration scenario, given an equal amount of water released. These scenarios make no assumptions about presence or density of razorback sucker larvae when flows were entrained; actual quantities of larvae entrained would depend on their presence and abundance and places a premium on correct timing. Similar to flow entrainment scenarios described above, these relationships become invalid when Green River flows either exceed the flows for which the inflow relationships were calculated, or when river flow was high enough to inundate wetlands from other, overbank sources. However, our expectation for flows that exceeded those used in our estimation procedure would be that entrainment flows would continue to rise faster than river flows.

Operations of Flaming Gorge Dam.—The goal of Flaming Gorge Dam spring releases was to enhance the Yampa River flow, by releasing water at the peak, or just post-peak. This was historically accomplished by predicting when the Yampa River snowmelt would peak, a forecast based on snowpack monitors, prevailing weather patterns, and predictions from national forecasting centers, and then releasing water based on that information. The main important piece of information from this analysis was that Flaming Gorge Dam releases, based on forecasts for Yampa River peaks, often began before the actual peak and presence of razorback sucker larvae in the Green River and may suggest a need for a different flow release trigger, perhaps one based on biological information.

A higher level of overlap between releases and presence of larvae is a critical need to enhance recruitment of razorback suckers. Better timing would increase overlap of larvae and flood plain wetland availability and reduce the incidence of years when numbers of larvae were high but overlap was low (e.g., 2008-2010). If we assume that annual spring releases from Flaming Gorge Dam involve a finite volume of water, then those early releases would not be expected to perform their main function of creating connections between the Green River and flood plain wetlands at a time when razorback sucker larvae were available. Wick (1997) also supported the notion of later releases from Flaming Gorge Dam. He postulated that later flows would help remove sediment from spawning areas when embryos were developing and would increase reproductive success.

There may be some merit to earlier connections, if such flows stimulate production of food resources for early life stages of fish, but presumably some of that is already happening because most wetlands remained wet before spring flooding begins. Thus, it seems evident that better forecasting is needed, or a different trigger for flow releases should be used. The one trigger that we have used most in this report was presence of razorback sucker larvae in light trap samples, a real-time cue that is expected to be available into the future.

We realize there were and are certain constraints on managers when constructing flow release schedules. One was the limitation of forecasting accuracy, which can change quickly due to changes in weather patterns or snowpack conditions. It would be useful to actually estimate accuracy of various forecasting tools at intervals prior to peak runoff and determine if certain methods or techniques were more useful than others. Another limitation was likely the need managers have to meet the commitments of flow recommendations, and, because of the need to not miss Yampa River peak flows, early flow releases enabled that scenario. Compliance with this commitment should be relaxed to some extent so that managers instead feel the burden is to match Flaming Gorge spring releases with presence of larvae, rather than just with the peak flows of the Yampa River. This commitment would be more easily accomplished if a different trigger were used to release Flaming Gorge Dam flows. If a biological indicator such as presence of larvae does not allow sufficient lead-time for scheduling spring releases, perhaps we should then develop other predictors for presence of larvae that were based on water temperatures or other easily measured environmental variables, which may produce fewer instances of early-release bias and more biologically beneficial flows.

Flaming Gorge Dam release scenarios for flood plain wetland connectivity.—The wide variety of flow scenarios simulated, including flat flows from Flaming Gorge Dam, represented a spectrum of historical and potential flow regimes and their outcomes relative to flood plain wetland inundation. The performance of various scenarios, as measured by the number of days that flood plain wetland breaches were able to entrain water at the various flow levels, improved through the progression of scenarios 1 through 6. Flow performance increased substantially between scenarios 1 (flat flows) and 2 (flow recommendations present at that time), especially at the lower inundation levels. The difference in release performance between Scenario 1 and 2 could be viewed as a general measure of the differences in flow regimes after dam closure and normal operations began (1967-1991) compared to implementation of the first set of flow recommendations beginning in 1992. Exceptions of course, would be high flow years such as 1983, 1984, and 1986, when flow releases from Flaming Gorge Dam were made because of very high runoff in spring due to high snowpack.

The expectation of a higher number of wetland inundation days in Scenario 3 than in Scenario 2 was not met primarily because Flaming Gorge Dam releases were insufficient to support declining flow levels of the Yampa River in the post-peak period (also the period when razorback suckers were available) and maintain flood plain connection and inundation. Thus, use of first presence of razorback sucker larvae as a flow release trigger rather than a forecasted Yampa River peak, while beneficial, was offset by insufficient water volumes to maintain flood plain wetland connections. The lack of performance difference among scenarios 3 and 4 (release volume similar to Scenario 3 but higher and for a shorter duration) demonstrated the nearly-equivalent tradeoff between longer duration, lower magnitude releases, and higher magnitude, shorter-term releases; entrainment volumes into flow-through wetlands would be higher at higher flows (page 80). The apparently large increase in performance for Scenario 4 in 1995 at the lowest flood plain inundation level was due mostly to the higher magnitude release that better-supported declining Yampa River flows, and particularly, because most of the effect of the unusual decline in Flaming Gorge flows when razorback sucker larvae were available, was removed. These simulations were average representations of performance and in some cases, one or the other scenario performed substantially better in some hydrologic settings. The challenge of implementing various scenarios under certain flow conditions would again, in part, be challenged by forecasting uncertainty.

Only in scenarios 5 and 6 did flow release performance, measured in the form of days of flood plain wetland inundation in the middle Green River, increase substantively, but again, usually only for the two lower breach inundation flow levels of 368 and 396 m^3/sec. Scenario 5 flows, which essentially doubled the duration of those in Scenario 4, had a higher mean flow magnitude than present-day Scenario 2 releases. However, those levels were insufficient to provide flows needed to increase flood plain wetland inundation at the 527 m^3/sec level. Scenario 6 flows, which retained the duration of flows used in Scenario 5, but in wetter years (1993, 1995-1999, 2003, and 2005-2009 exclusive of 2007) increased maximum release levels to 244 m^3/sec for up to a maximum of 30 days, increased the mean number of days of flood plain wetland inundation to about the mean number of days realized under the unregulated scenario, except for the higher flow level (527 m^3/sec). Flow releases < 244 m^3/sec were insufficient in most years to provide flows needed for inundation of flood plain wetlands at the Green River flow level of 527 m^3/sec, the average hydrologic condition for flow recommendations in the middle Green River.

Release volumes estimated under scenarios 2-6 give managers some notion of what historically occurred and what expectations may be for flow modifications, should any be considered. A clear conclusion from this analysis was that environmental conditions in the middle Green River remain dissimilar to that evident under unregulated conditions when razorback suckers presumably thrived. Relatively higher flows present in the 1990's (1993, 1995, 1997, 1999) promoted some recruitment of razorback suckers in flood plain wetlands in the middle Green River (e.g., 1995 and 1996: Modde 1996; Modde et al. 2001), in spite of evidence to suggest that abundance of adults was low and declining (Bestgen et al. 2002). Thus, increased reproduction evidenced in recent years, combined with enhanced flow management to provide flood plain wetland access, should promote increased recruitment of razorback suckers in the middle Green River. Spring 1999 provided a good example of how releases from Flaming Gorge Dam could be better used to accomplish the goal of flow recommendations, and that was accomplished with flow magnitudes higher than those used in Scenario 6. However, abundance of larvae in 1999 was very low and recruitment was unlikely. High flows that reconnect the river and flood plain will always be useful to allow rearing fish in wetlands to colonize the river, e.g., 1998 year class fish return to the river in summer 1999. Only with a more sophisticated flow release timing trigger, and increased flow magnitude and duration of releases from Flaming Gorge Dam, can substantial improvements in flood plain wetland inundation, and razorback sucker recruitment, be expected.

Creating the unregulated flow scenarios suggested once more, the multi-peak nature of Green River flows in the pre-impoundment era (e.g., Figures 5, 6 and 8), where the Green River sometimes peaked 2-3 weeks after the Yampa River to provide a larger and more sustained flow at Jensen, Utah. This spatial pattern of runoff has implications for how the unregulated system worked and was the likely reason that the unregulated hydrograph provided the most days of inundation of flood plain wetlands. This was particularly evident in the number of inundation days in the higher flow scenario, which were few in our simulated flow regimes. Also evident from the few years of flow data in the pre-regulation period 1951-1962 were very large peaks in spring and early summer, which have been few since 1992.

In some years, little or no flow was entrained into any flood plain wetlands, even though releases were made from Flaming Gorge Dam. Those flows serve other purposes under the flow recommendations, including channel maintenance and sediment transport processes. Relatively low connecting flows may also provide access to the river for fish that have reared in the wetland from previous years. But from a perspective of flood plain entrainment of razorback sucker larvae, that water volume could, perhaps, be used more effectively in other years, when the positive benefits of additional releases may be more substantive. The concept of water banking was discussed when flow and temperature recommendations for Flaming Gorge Dam were formulated (Muth et al. 2000), and perhaps the potential for that should be discussed again.

Lack of a correlation between % flow entrainment (a measure of fish entrainment) when razorback sucker larvae were available and volume of spring flow, for either flow-through or single-breach wetlands, was not expected. Granted, higher flow volumes were entrained in higher flow volume years, but it appears that the percentage of water entrained will not increase until high flows are more concurrent with presence of razorback sucker larvae. A portion of this lack of overlap may also be caused by environmental conditions, because higher flow years are usually correlated with cooler water, which delays spawning and timing of presence of razorback sucker larvae until later in the year.

The volumes of water that pass into flood plain wetlands when razorback sucker larvae were available in an average or even a high flow year (about 2% in 2008) were surprisingly low. One means to increase the water and larvae entrainment into flood plain wetlands is to alter timing of high flows in the Green River to when larvae are present. Another means to enhance the number of larvae entrained into flood plain wetlands could be attained by targeting flows and entrainment when larvae were most abundant (not just present). This would certainly add another layer of complexity to management of flow releases, and because peak abundance of larvae typically occurs several weeks after their first appearance and the Yampa River spring peak, flow releases would need to be quite high in order to maintain flood plain wetland connections.

Flow simulations conducted to understand tradeoffs of total entrainment volume into the four flow through flood plain wetlands as a function of more days of lesser flow and fewer days of greater flow showed that the latter, higher flow scenario, entrained substantially more water. At the lowest flow level of 368.3 m^3/sec over a 15 day period, flow through wetlands entrained only about 40% of the water that the same wetlands did in 3.3 days at the highest flow level of 623.2 m^3/sec. Thunder Ranch wetland entrainment dominated the total flow entrainment relationship, but all flow-through wetlands increased in flow volume entrained as Green River flows increased, except for Stewart Lake. Stewart Lake declined slightly as flows increased until the highest level simulated flow of 623.2 m^3/sec was reached, when flow entrainment increased slightly, a pattern that may be due to how the inflow gate was operated. We did not simulate higher flow levels because we did not want to exceed the flow levels upon which the relationships of flow entrainment as a function of Green River flow were based.

A corollary concept to targeting entrainment when larvae were most abundant may be attainable for wetlands that have mechanical gates. Such wetlands may include Stewart Lake and Old Charley Wash, which have relatively low inundation levels during spring runoff, and in the case of Stewart Lake, typically fill well before presence of first razorback sucker larvae. If those wetlands were filled only after light trapping information suggested razorback sucker larvae were most abundant, then entrainment of larvae may be greatly enhanced. This is especially true because those wetlands were large and capable of entraining substantial Green River flow volumes. For example, if the 231 ha surface area Stewart Lake was filled with 1 m of water at a time when razorback sucker larvae were as abundant as they were during drift net sampling on 28 May 2004 (0.054 wild larvae/m^3), nearly 125,000 larvae would be entrained (231 ha * 10,000 m^2/ha * 1 m depth * 0.054 larvae/m^3 = 124,700 larvae) during the filling process alone; number of larvae entrained would be higher if the system was operated as a flow through wetland (e.g., keep outlet gate open longer) for longer time durations. We understand that managers of wetlands such as Stewart Lake may have other management responsibilities, including selenium remediation that may require maximizing wetland elevation when flows are highest (and when abundance of larvae may be low), but these options may be worth exploring.

A question that should be asked, but is one that we cannot answer, is what level of entrainment of larvae is enough and into how many flood plain wetlands? Certainly increased numbers of adults that produce larger numbers of larvae would certainly enhance entrainment rates into flood plain wetlands, but what level is sufficient to finally produce enough recruits to sustain the population is uncertain. We suggest development of a small population dynamics model to explore success of various scenarios to provide recruit-sized razorback suckers. Some data is already in place, and a model would be useful to explore consequences of flow timing, timing of razorback sucker reproduction, and the implementation of various flow scenarios (or others) to enhance recovery of razorback suckers. One piece of information that is lacking is a realistic representation of density of larvae available for entrainment during the reproductive season, but we are working on that issue using 2004 drift net sampling data.

Another question to consider is what type(s) of flood plain wetlands should be emphasized for recruitment of razorback suckers. Means to maximize entrainment of razorback sucker larvae, a primary focus of this report, is for naught if larvae grow and survive but do not recruit to the river. One important component of an ideal flood plain not mentioned in The Levee Removal Program evaluation is the need for razorback suckers to over-winter (Birchell et al. 2002). This is important because young-of-year razorback sucker in a flood plain wetland in spring would theoretically not be ready or even able to move into the river in autumn because there is no connection with the river. This life cycle places high importance on connecting flows with wetlands in consecutive years to allow escapement of flood-plain-bound fish back to the river.

We have good evidence to suggest that entrainment rates were highest in flow-through wetlands such as Thunder Ranch. However, the capacity of flow-through wetlands, including Thunder Ranch, to overwinter fish may be suspect. For example, in 2006 nearly 600,000 razorback sucker larvae were released just upstream of the Thunder Ranch wetland breaches, and we know that large numbers, perhaps most, were entrained. However, inspection of the Thunder Ranch wetland in autumn 2006 did not reveal presence of razorback suckers (Hedrick et al. 2009). Further, the topography of the Thunder Ranch wetland is such that few deep spots (> 1

m) were present at base flow levels (Tetra Tech 2005), and those may be insufficient to overwinter fish, particularly when ice and snow cover (affects oxygen production and winterkill) are heavy. Water depth concerns in flow-through wetlands may be exacerbated by relatively low elevations of outlet breaches, which will ultimately control the depth of water retained in those wetlands. Management actions to enhance overwinter survival in flow-through wetlands, such as installation of an outlet control structure, should be evaluated.

Remaining flow-through sites (Stewart Lake, Bonanza Bridge, and Above Brennan) may also have issues that reduce their utility. Therefore, while flow-through sites will entrain more razorback sucker larvae, if the flood plain cannot sustain those fish over-winter, the flood plain wetland will not contribute to recovery of the species. Depth of ice over the Stirrup flood plain wetland was about 0.28 meters in both 2006 and 2007 (deepest point in the Stirrup was 0.76 m in 2006 and 1.2 m in 2007), and suggested that shallow flood plain wetlands may freeze to the bottom. Single breach wetlands entrain less water and fewer particles, but several (Stirrup, Leota) are deep enough to successfully overwinter fish. This suggested that certain trade-offs or combinations of strategies may be necessary to achieve recovery of razorback sucker through use of flood plain wetlands with different breach configurations.

Single-breach wetlands offer a different set of constraints and advantages. First and foremost, entrainment rates of water, and presumably larvae, into those wetlands may be very low. However, substantial numbers of razorback sucker larvae may colonize flood plain wetlands if they are simply placed in the vicinity of single-breach wetlands and are allowed to swim into wetland breaches and the main body of the wetland. This was evidenced in spring 2009 when larvae were captured in light traps more than 100 m from the river at the warm and most upstream end of the inlets to wetlands on Ouray National Wildlife Refuge (pers. obs., G. B.

Haines). Colonization of wetland breaches may also ultimately result in being swept into the wetland when flows rise. Colonization of terrace-type wetlands may also occur in a similar manner, if larvae congregate and maintain nearshore and such wetlands may offer benefits, even though the availability of habitat is temporary. A certainty is that flooded areas of any type are of little consequence when no razorback sucker larvae are available to use them.

Wetland sedimentation issues.— Filling of wetlands with sediment in the flood plain is a natural process of the riverine ecosystem; the question to consider is whether managed Green River wetlands are filling at rates that are unacceptable. A negative aspect of flow-through wetlands is that all suspended particles, including sediment and fish larvae, are entrained with river water (Heitmeyer and Fredrickson 2005). Therefore, over time, breaches as well as the associated wetland will fill and ultimately, these types of wetlands will not be sustainable without active management such as dredging. For example, the natural levee at Bonanza Bridge was originally breached at a river stage of 368 m^3/sec. Entrainment studies in 2006 showed that connection now occurs at a higher river stage (minimal connection at 434 m^3/sec), likely because of sand moving as bedload and subsequent deposition, which increases breach height. From the high amount of scouring of sediment observed in Breach 2 in 2006, it is not difficult to hypothesize the pattern: entrainment of flows and sediment, deposition of sediment as flows recede, and scouring of breach sediment occurring the following year that would then move into the flood plain itself as bedload. This does not consider the suspended sediment that occurs in relatively high concentrations as water is entrained into wetlands through breaches. Even single downstream breaches have been shown to accumulate sediment over time (Birchell et al. 2002; LaGory et al. 2003).

Managers at Ouray National Wildlife Refuge considered wetland sedimentation a serious enough issue that they will no longer allow wetlands to fill in a flow-through fashion. Instead, flood plain wetlands will backfill via a downstream breach(es) as they naturally do, albeit aided in some situations by reduced heights of levee breaches (Heitmeyer and Fredrickson, 2005). Those practices should reduce sedimentation in flood plain wetlands by reducing volume of sediment-laden water (but also larvae) entering wetlands and because much sediment deposition may occur outside of the wetland.

There are perhaps additional data that could be brought to bear on the issue of sedimentation rates in flow-through as well as single-breach wetlands issue. Suspended sediment data are available for the Green River during flood flows. Assuming that the amount of sediment in water is known, and that the volume of water moving through the wetland is also known, it may be reasonable to predict in a gross fashion, how much suspended sediment might be deposited in a relatively low-velocity environment such as a flood plain wetland. This is doubtless a dynamic process dependent upon the timing of high flows and entrainment (early and ascending flows have higher sediment concentrations than post-peak flows), the velocity distribution of flows across the flood plain wetland, export rates of suspended particles, structural complexity of the flood plain wetland, and doubtless many other factors. Flood plain wetland type also may also play a large role because flow-through types entrained so much more water volume and sediment than single-breach wetlands. However, it is likely that all sediment transported into single-breach wetlands is deposited, because of relatively low current velocities. However, since few data exist to model such processes, we do not address this further in this report and instead chose to focus on issues where more data were available to address the problem.

Retention of larvae in flood plain wetlands.—We also present the issue of retention of larvae in flood plain wetlands as an item in Discussion, because we have little or no empirical data to address this issue. It is possible that larvae, once entrained into a flow-through wetland, could be transported through it and back to the river, thereby resulting in reduced net entrainment rates. No data were available to estimate export rates because no sampling of outflows of flow-through wetlands was conducted. Thus, we cannot directly estimate exit rates of beads or larvae. However, we think loss of larvae to the flood plain outflow following entrainment is low because flood plain wetlands likely act as a filter and depositional area for particles (flood plain is by definition a depositional environment), including beads and larvae (Hedrick et al. 2009). This is because breach sites are long distances from outflows, and the intervening area, the main body of the wetland, is typically large, structurally complex with vegetation and other velocity breaks, and has very low current velocity. In the main wetland area, fish larvae are likely capable of finding low velocity refuges and are able to remain there even during higher flows, because the wetland area and low velocity channel margin and benthic areas also expand. Velocity chamber swimming experiments have shown that razorback sucker larvae the size of individuals that are typically available for entrainment into flood plain wetlands (9-12 mm TL) are capable of swimming up to 15 cm/sec for 5-15 sec, and are capable and persistent swimmers at lower water velocities as well (unpublished data, KRB). Current velocity is increased in the immediate vicinity of the outflow, but those areas are small and are unlikely to harbor an important percentage of entrained larvae. Even if small numbers of larvae are transported through the wetland, flow-through wetlands still offer the greatest opportunity for entrainment, retention, and survival of razorback sucker larvae under the flow conditions we tested.

We have discussed in detail, the functioning of different types of flood plain wetlands and their interactions with flow and the reproductive ecology of razorback sucker, with the assumption that maximizing entrainment of flows and fish into wetlands is beneficial to the species. This is, of course, the basic premise upon which the flood plain management plan and activities surrounding it are based. And certainly there is evidence that some of the basic underpinnings of the program have some support. Some of this is intuitive and based on studies of factors that we know promote fast growth and higher survival of early life stages of razorback sucker (Bestgen 2008). Other evidence comes from documenting survival of razorback suckers in flood plain wetlands on some occasions (Modde 1996; Modde et al. 2001). The abundance of those fish documented on those occasions, and whether those are substantive recruitment events that could sustain a species or were merely anomalies that happened to be detected and that have distracted attention from other issues, is unknown.

The basis for flood plain management and the advantages and drawbacks regarding certain wetland types was discussed in Hedrick et al. (2009) and some of that bears repeating or expansion here. A large amount of resources has been invested into flood plain management, from a standpoint of easements, research expenditures, and flow management activities and monitoring, all of which may benefit only a small portion of fish available in a small portion of years. A natural question is whether flood plain management activities as they are presently conducted, have the potential to work sufficiently well to promote recruitment of razorback sucker and recovery of the species. To date, substantive evidence of natural recruitment emanating from any source is not available. Because the little evidence for natural recruitment that does exist comes from flood plain wetlands, this management approach seems like the most logical course of action.

Some perspective is needed to understand flow volumes entrained into flow-through and single-breach flood plain wetlands relative to the total flow volume that passed through the middle Green River during the spring runoff period. In the period 1992-2009, the average amount of water that was entrained into all hypothetical flow-through wetlands when razorback sucker larvae were present was equal to about 3.9 hr per year of Green River flow at 527 m^3/sec. Recall that recommendations for Flaming Gorge Dam, call for Green River flows in 1 of 2 years in the average hydrologic condition to exceed 527 m^3/sec for up to two weeks, and flow recommendations are much higher in wetter hydrologic scenarios. In the highest entrainment year (1993), the hypothetical amount of water flowing into all flow-through wetlands when razorback sucker larvae were present was equal to about 13.1 hr of Green River flow at 527 m^3/sec in the entire season. In 1993, the various flow-through flood plain wetlands as they presently operate were hypothetically connected to the river from 22 to 31 days, and during that time at average Green River flows, those wetlands entrained only 2.4% of total river flows. It should be recognized that 1993 was quite exceptional; it accounted for nearly 20% of entrainment flows in flow-through wetlands after razorback suckers were present in the entire 1992-2009 period so flows in other years were substantially lower. In single-breach wetlands, the hypothetical amount of water entrained relative to Green River flows was much lower; the average and highest (1993 again) amounts of flow entrained represented 32 min and 2.7 hr of Green River flow at 527 m^3/sec, respectively.

The relatively small water volumes entrained in either type of wetland in most years places a premium on maximizing water entrainment, and more importantly, entraining the most water when the most razorback sucker larvae are available. Those relatively low entrainment rates may also be the most important reason that management efforts conducted to date have not enhanced recruitment of razorback suckers. Only recently has abundance of larvae produced by adult fish in the Green River increased to a substantial level, and in most of those years the duration of connection between river and the flood plain were short or non-existent. This suggests a continued need to maintain and enhance populations of adult razorback suckers in the Green River to produce large cohorts of larvae. Perhaps recruitment events, which require timing of larvae availability with that of habitat, are simply dependent on a return to wetter hydrology. Enhancement of such by well-timed flow releases would certainly enhance the recovery process.

Another main obstacle to increasing recruitment of razorback suckers, particularly in flood plain wetlands, is presence of non-native fishes. Presence of established communities of fishes almost certainly limits survival of early life history stages of razorback sucker larvae, and likely in a density independent manner. This is true because regardless of how many razorback sucker larvae are available, it seems likely that recruitment will be negligible in the face of established and abundant communities of introduced fishes. Entrainment of razorback sucker larvae into fishless areas offers more optimism, and is the premise of the flood plain reset process, whereby it was recognized that severe reduction or elimination of existing fish communities was needed for recruitment of razorback suckers to occur (Birchell and Christopherson 2004; Christopherson et al. 2004; Brunson and Christopherson 2005; Modde and Haines 2005). Recruitment may even be possible when razorback sucker larvae and non-native fishes simultaneously colonized flood plain wetlands. The challenge is to simultaneously make habitat available that is recruitment-friendly at a time when razorback sucker larvae are available in sufficient quantities to effect substantial recruitment and ultimately, recovery of the species in the middle Green River.

CONCLUSIONS

- Razorback suckers reproduced every year in the middle Green River from 1992-2009 and in the lower Green River from 1993-1999, and 2008-2009, the only years sampling occurred there.
- Abundance of razorback sucker larvae declined in the middle Green River from 1993-1994, until 1999, concurrent with decline in abundance of wild adult razorback suckers.
- Abundance of razorback sucker larvae increased in the middle Green River perhaps beginning around 2000, and certainly after 2004, coincident with establishment of larger populations of stocked razorback suckers, indicating successful acclimation and reestablishment of some adults.
- Timing of spawning, hatching, and emergence of razorback suckers in the lower and middle Green River was dependent mostly on exceeding reasonably consistent thresholds of water temperature (Mean and range of mean daily water temperature at: mean spawning date was 11.3°C (range 8-14°C), at mean hatching date was 14.3°C (12-16°C), at mean date of first appearance of larvae was at 15°C (13-16°C), and mean capture date was 16°C (14-19°C).
- Otolith analysis was essential to deriving accurate estimates of spawning, hatching, and emergence times for razorback sucker larvae in the lower and middle Green River reaches, because ages and growth rates of larvae were variable among years and reaches.
- Timing of first occurrence of razorback sucker larvae captured in light traps in the middle Green River was at or typically after peak flows had passed; peak abundance of larvae was well after flows declined.

- Timing of first occurrence of razorback sucker larvae captured in light traps in the lower Green River was typically before peak flows because warmer water temperatures there promoted earlier reproduction.
- Recaptures rates of marked razorback sucker larvae released in 2004-2005 were very similar for all four releases and over a range of flow rates; recaptures in 2006 were much lower and may have been an artifact of entrainment of most larvae into Thunder Ranch wetland.
- Recaptures of marked larvae soon after release indicated rapid downstream dispersal.
- Recapture of marked razorback sucker larvae soon after release, at varying distances downstream from release sites, indicated ability of larvae to rapidly colonize quiet, nearshore areas adjacent to flood plain wetlands.
- Recapture of marked larvae from all three releases in 2005 in the same light trap samples, releases made as many as 11 days apart and 98 km upstream of capture sites, indicated persistence at sites.
- Most marked razorback sucker larvae were recaptured in downstream reaches far removed from spawning areas, in contrast to hypotheses that suggested an exponential decline of survival and availability of larvae for entrainment into flood plain wetlands downstream of spawning areas.
- Distribution of marked larvae was uneven over releases made at different flow levels; presence of flood plain wetlands over a wide area downstream of spawning areas is important to provide a mosaic of habitat under different flow conditions.
- Growth rates and time of persistence of recaptured marked larvae in 2005 differed among releases and were higher for those released during lower flows.

- Surface area of flood plain wetlands increased as flow levels in the middle Green River increased when thresholds of inundation for breaches were reached.
- Post-breach inundation, higher Green River flows resulted in greater areas of flood plain wetland availability and greater entrainment rates.
- Flow-through flood plain wetlands achieved breach inundation at lower flows than most single-breach flood plain wetlands because breaches were at lower elevations.
- Entrainment rates of water (assumed proportional to entrainment rates of razorback sucker larvae) for four flow-through wetlands increased exponentially at higher Green River flows; more water was entrained per unit increase of the Green River at higher flows than at lower flows, given inundation had occurred.
- Entrainment rates of flow-through wetlands in the middle Green River collectively were approximately seven times that of single-breach wetlands because water was entrained whenever breaches were inundated.
- Entrainment rates of water (assumed proportional to entrainment rates of razorback sucker larvae) for single-breach wetlands increased at higher Green River flows; the nature of the entrainment rate-flow relationship was uncertain (proportional or increasing as flows increased?) but short-term (e.g., daily snowmelt fluctuations) fluctuations were substantial and responsible for a large proportion of total flow entrainment.
- Annual entrainment rates of single-breach wetlands were approximately 12% of that for flow-through wetlands, in spite of much greater surface area and number, because inflows were static or declining unless Green River flows were increasing.
- Some flow-through and single-breach flood plain wetlands may be incapable of supporting longer-term survival of entrained razorback suckers because of low

overwinter survival or contaminants; those deficiencies need to be remedied if such wetlands continue to be a central part of the recovery process for razorback suckers.

- Sedimentation of breaches via bedload transport can be substantial and increase the level of Green River flows required for inundation.
- Suspended sediment entrainment levels may be substantial and influence long-term viability of flood plain wetlands, particularly those operated in a flow-through fashion.
- A flow release trigger that more consistently matches flows from Flaming Gorge Dam with those of the Yampa River, as well as with occurrence of razorback sucker larvae, is needed.
- First captures of larvae may be a better trigger to signal release of Flaming Gorge flows.
- Duration and volume of flow releases from Flaming Gorge Dam since 1992 may be inadequate to recover razorback sucker, based on continued absence of significant recruitment of razorback suckers in that time period, understanding that other significant factors such as low recent flow volumes from drought and negative effects of non-native fishes may also play a substantial and often interacting role.
- Simulations of flow and entrainment rates showed that even at average Green River flow levels, the total volume of water entrained into flood plain wetlands as a proportion of Green River flow, was low.
- Simulations of flow and entrainment rates showed that even at average flow levels, the volume of water entrained into flood plain wetlands when razorback sucker larvae were present was very low and constituted only a few hours of Green River flow per year in all wetland types.

- Simulations showed that flat flow levels from Flaming Gorge Dam resulted in the fewest days of flood plain inundation during the period when razorback sucker larvae were present and at three different flow levels in the middle Green River 1992-2009, and unregulated flows resulted in the greatest number.
- Simulations showed that flow regimes since 1992 resulted, on average, in only about 50% of the number of days of flood plain inundation at the two lowest flow levels tested and only 25% of the number of days at the higher flow level tested compared to the unregulated condition; the highest flow was only the equivalent of the level in the Average hydrologic condition called for in the Flow Recommendations for Flaming Gorge Dam.
- Simulations showed that flow regimes at the two lowest flow levels tested required longer duration and especially, higher magnitude, when timed to occur when razorback sucker larvae were present, to achieve the number of days of flood plain inundation observed in the unregulated flow condition. Flows at the higher level tested, timed to occur when razorback sucker larvae were present, were inadequate to achieve the number of days of flood plain inundation observed in the unregulated flow condition.
- Increasing the magnitude and duration of spring flow releases and delaying their onset to coincide with presence of razorback sucker larvae may be minimally sufficient conditions to enhance recruitment of razorback suckers in the middle Green River, Utah. Increased recruitment is required to achieve recovery of the species in the Upper Colorado River Basin.

RECOMMENDATIONS

- Continue to develop information on early life history ecology of razorback sucker in the Green River Basin, consistent with that being collected under Project 22f. A related investigation may be to better understand the role of altered spring thermal ecology of the Green River, induced by Flaming Gorge Dam operations, on timing of spawning, development of embryos, and emergence of razorback sucker larvae, as well as the potential effects on spawning of non-native fishes.
- Expand sampling in the lower Green River, at least consistent with that which occurred in 2009 and 2010. Additional information on timing of spawning, hatching, and emergence of larvae using otolith analyses may be appropriate. A better understanding of habitat use and survival of razorback sucker larvae in the lower Green River may also be useful. This may be especially important if timing of releases from Flaming Gorge Dam, or flow magnitude or duration, is altered.
- Continue studies which evaluate utility of various flood plain wetlands as recruitment habitat for early life history stages of razorback sucker. Important aspects include better understanding of colonization/entrainment rates of larvae into single-breach wetlands, which could be accomplished experimentally using small batches of marked larvae, in conjunction with present sampling. Utility of terrace-type wetlands as temporary habitat for razorback sucker larvae should also be assessed. Breach and wetland monitoring should also be conducted to ascertain whether sedimentation is a substantial problem.
- Continue studies which evaluate utility of various flood plain wetlands as overwinter habitat for young razorback sucker, and develop plans to enhance fish overwintering

capability of key wetlands. One specific aspect is to investigate utility of outlet gate(s) to maintain water levels in flow-through wetlands.

- Consider utility and feasibility of scheduling filling of specific gated wetlands of any type to fill with Green River water only when high densities of razorback sucker larvae are present, timing for which could be based on ongoing real-time sampling information.
- Develop a simple population dynamics tool to assist with modeling entrainment and survival rates of early life stages of razorback suckers in various flood plain wetlands. Variables to model could include temporal dynamics of occurrence of larvae (including seasonal density distribution), Green River flow levels, entrainment rates into flood plain wetlands, individual attributes of larvae relative to growth and survival, presence/absence of existing fish communities and predation rates, and attributes of individual flood plain wetlands.
- Implement a schedule of altered timing of flow releases from Flaming Gorge Dam to coincide more closely with presence of razorback sucker larvae, or perhaps, presence of abundant larvae, in the middle Green River. Reliable real-time monitoring is already in place to guide timing of releases. In lieu of that, develop relationships based on physical attributes, mostly water temperature and time of year, which would predict timing of emergence of razorback sucker larvae.
- Investigate the feasibility of increased magnitude and duration of spring flow releases from Flaming Gorge Dam, after razorback sucker larvae are present, to maintain connections with flood plain wetlands and increase entrainment rates. Corollary to that, it may be possible to save water in Flaming Gorge Reservoir in some lower flow years, to release in other higher flow years to sustain river-wetland connections. Flow releases

that simulate unregulated conditions should be used for a realistic test of effectiveness of increased flows to enhance recruitment. Subsequent effects on base flow levels, among other things, will also need to be considered.

ACKNOWLEDGMENTS

This study was funded by the Recovery Implementation Program for Endangered Fish Species in the Upper Colorado River Basin. The Recovery Program is a joint effort of the U. S. Fish and Wildlife Service (USFWS), U. S. Bureau of Reclamation (USBR), Western Area Power Administration, states of Colorado, Utah, and Wyoming, Upper Basin water users, environmental organizations, and the Colorado River Energy Distributors Association, and the National Park Service. Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the authors, the U. S. Fish and Wildlife Service, U. S. Department of Interior, or members of the Recovery Implementation Program. Funding for this research was administered by the Bureau of Reclamation and Colorado State University, the Department of Fish, Wildlife, and Conservation Biology, and the Larval Fish Laboratory (LFL). Project administration was facilitated by V. Romero, M. Olivas, R. Muth, D. Speas, T. Chart, C. Morales, and T. Castaneda. We thank the many seasonal and other employees who participated in field sampling. D. Snyder, S. Seal, and D. Miller of the Larval Fish Laboratory expertly assisted with specimen identification. Reviews by D. Speas, T. Chart, T. Hedrick, and M Trammell were appreciated. This is Larval Fish Laboratory Contribution 163.

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Table 1.—Number of marked razorback sucker larvae released in the middle Green River, 2004-2006, and the number, total length, and dates of recaptures, made downstream of release sites with light traps (mostly Hedrick et al. 2009). Release locations were Razorback Bar (RZB Bar, RK 500.9; 2004, 2005), Escalante Bar (RK 493.7; 2005), and just upstream of Thunder Ranch wetland breaches (RK 492.1; 2006); recapture sites were up to 90 river km downstream. Total length of larvae at release in all years was about 10.1 mm (7.6-15.6 mm); age was 8 – 18 days post-hatch. Batches of larvae released in 2005 were uniquely marked; those released in 2006 were not so it was not possible to identify recaptures made by release date. The larvae in 2006 were released just upstream of Thunder Ranch wetland breaches, which may have prevented larvae from being available for capture downstream; releases in other years were well upstream of breaches. Number of wild larvae is the total captured in all light trap sampling conducted that year and the total is all marked and wild fish captured; all fish were examined for marks except in 2004 but the number and percent marked is deemed accurate (see text).

			Larvae release/recapture data				
Year	Release date	Flow (m^3/sec)	No. released	# recap (%)	Recapture date (range)	Recapture TL mm (range)	# wild larvae (% mark/total)
2004	(RZB Bar)						
	26-May	161	69,688	47 (0.067)	5/27 (5/27-6/1)	10.8 (8.9-12.6)	1000 (4.5)
2005	(RZB & Esc. Bar)						
	20-May	391	104,000	48 (0.046)	6/8 (5/25-6/27)	14.6 (9.4-21.9)	
	24-May	538	94,500	48 (0.051)	5/27 (5/25-6/6)	11.1 (10.1-13.6)	
	31-May	470	395,500	230 (0.058)	6/8 (5/31-6/30)	11.2 (8.0-16.8)	
			594,000	326 (0.055)			147 (68.9)
2006	(TR breach)						
	21-May	420	175,500				
	23-May	470	125,000				
	24-May	510	225,000				
			525,500	19 (0.0036)	5/30 (5/25-6/9)	10.8 (9.7-11.8)	524 (3.5)

Table 2.—Estimated (Sim; Simulated) number of days of middle Green River flows that exceeded five threshold values (368, 396, 529, 575, and 748 m^3/sec) compared to those observed (Meas.; Measured) for the Green River, Jensen, Utah (U. S. Geological Survey gauge #09261000) for six years (six higher flow years with peak > 600 m^3/sec; one lower flow year with peak < 500 m^3/sec, 1954) in the pre-Flaming Gorge Dam flow period of record (1951-1962). Estimated number of days that exceeded thresholds come from a flow routing model that that places flows at the Jensen gauge by moving water downstream at flow dependent rates (see Methods) from three upstream gauges on the Little Snake River near Lily, Colorado (gauge # 09260000), the Yampa River near Maybell, Colorado (gauge # 09251000), and the Green River near Greendale, Utah (gauge # 09234500). Flow regimes for the various gauges and routed and actual flow regime patterns are presented in figures 5-11.

Green River flow	1951		1952		1953		1954		1957		1958		1962	
(m^3/sec)	Sim.	Meas.	Sim.	Meas.	Sim.	Meas.	Sim.	Meas.	Sim.	Meas.	Sim.	Meas.	Sim.	Meas.
>368	28	28	26	25	17	22	2	1	51	50	18	18	24	23
>396	26	24	25	24	15	15	1	0	44	49	17	17	20	18
>529	15	16	18	17	9	9	0	0	34	36	12	12	0	0
>575	13	10	15	15	7	7	0	0	30	31	10	10	0	0
>748	2	0	9	9	0	0	0	0	13	13	6	5	0	0
peak	739		929		623		448		1023		824		711	

Table 3.—Number of razorback sucker larvae captured per year at sampling localities in the middle Green River, Utah, 1993-2008 (RK = river kilometer, RM = river mile). Parenthetical numbers below Cliff Creek and Greasewood (Corral) are catch per unit effort data (number per light trap sample), where a unit of effort is one 8.5 hr overnight light trap sample set at dusk and retrieved at dawn. Blanks represent no sampling.

Locality (RK, RM)	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Below Yampa River (555, 345)	4															
Green River (494.8, 307.5)	12															
Cliff Creek (487.3, 302.8)	88	390	17	137	2	27		65	85	44	47	262	68	410	549	308
								(1.67)	(1.31)	(0.8)	(0.64)	(7.94)	(1.19)	(5.69)	(11.93)	(10.62)
Escalante (493.7, 306.8)	23															
Stewart Lake (482.5, 299.8)								1				7				
Stewart Lake Outlet (481.5, 299.2)	17	537		30								179	10			84
Above Boat Launch												21				
Above Ashley Creek (481.4, 299.1)												1				
Red Wash Launch	35		4													
Sportsman Lake (477.3, 296.6)		39										5				
Walker Hollow (473.3, 294.1)												25	35		400	175
Baser (cf. Baeser) Wash (452.8, 281.4)															1327	300
New Hatchery,Isolated Pool												2				
Leota Bottom (416, 258.5)												5				
Above Wyasket												41				
Wyasket Bottom (412, 256)												378				
Wyasket (412, 256)												69				
Lower Old Fish Hatchery												2				
Sheppard (407, 253)					1					4						
Old Charley Wash inlet (405.5, 251.9)	3	31	2	6								50	20	40	12	21
Greasewood (405.4, 251.8)	25	220	9	1		27		15	4	40			29	83	5	1
								(1.36)	(0.33)	(1.54)			(0.94)	(3.46)	(0.56)	(0.63)
Old Charley Wash Outlet (401.5, 249.5)	21					4				5			10	2		
Below Bonanza Bridge								1								
Little Grand Wash																14
Total	228	1217	32	174	3	58	12	82	89	93	47	1047	172	535	2293	903

TABLE 4.—RAZORBACK sucker light-trap sampling localities, lower Green River, 1996 to 1999. Sample number in the "near Green River" localities represents the number of distinct sample locations in each reach; not every site was sampled in each year. At each other Green River locality, one to several samples was collected per year. Samples at the San Rafael River locality represented collections made at or near the mouth in the Green River and just upstream in the San Rafael itself.

Locality (RK, RM, fish #)	1996	1997	1998	1999
Green River valley				
Near Green River				
(209.2, 130, N = 6)	X	X	X	
(202.8-206, 126-128, N = 8)	X	X	X	
(196.3-201.2, 122-125, N = 12)	X	X	X	
(181.9-191.5, 113-119, N = 3)	X			
(177-181.9, 110-113, N = 5)	X		X	X
(161-175.4, 100-109, N = 6)	X		X	X
San Rafael confluence (156.1, 97)	X	X	X	X
White Wash (153.7, 95.5)	X	X	X	X
Red Wash (152.9, 95)	X	X	X	X
Blue Wash (152.1, 94.5)	X	X	X	X
Millard Canyon (54.2, 33.7)	X	X	X	X
Anderson Bottom (50.7, 31.5)	X	X	X	
Anderson Bottom (49.9, 31)			X	X
Bonita Bend (49.9, 31)	X			
Below Bonita Bend (49.1, 30.5)	X			
Holeman Canyon (45.1, 28)	X	X	X	X

Table 5.—Species composition and gear types for samples collected in the middle Green River, Utah, 1992-2008. Light trap (LT) samples consist of about 8.5 hr of dusk-to-dawn sampling time. Razorback sucker larvae reported here were produced from wild fish and were not the results of hatchery-released fish (2004-2006), with the exception of 47 fish captured in 2004.

	1992	1992	1993	1993	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008*
Gear:	Drift net	Seine	Drift net	Seine	LT	LT	LT	LT	LT	LT	LT	LT	LT	LT	LT	LT	LT	LT	LT	LT
Native taxa																				
Cyprinidae																				
Gila sp.	2	7	-	-	1	-	-	-	2	-	-	-	-	-	-	-	-	1	1	-
Ptychocheilus lucius	-	-	-	-	1	-	1	-	-	-	-	-	-	-	-	-	-	-		-
Rhinichthys osculus	119	85	15	-	4	-	58	23	2	3	-	2	3	1	32	2	13	-	1	1
Catostomidae																				
Catostomus discobolus	1516	583	69	58	100	6455	2088	3277	39	256	-	124	800	799	646	2411	3062	963	2431	1402
C. latipinnis	579	612	140	760	938	5252	634	5142	62	1005	-	1751	1516	605	508	11375	4445	5828	5764	1728
Xyrauchen texanus	3	17	9	55	228	1217	32	174	3	58	12	82	89	93	47	1047	172	537	2293	889
					1266	12924	2754	8593	104	1319	12	1957	2405	1497	1201	14833	7679	7328	10488	4019
Cottidae																				
Cottus bairdi	-	3	-	-	-	-	-	2	2	-	-	-	-	-	-	1	-	-	-	-
Nonative taxa																				
Cyprinidae																				
Cyprinella lutrensis	5	167	12	65	5859	-	1655	281	305	558	-	550	673	2577	111	47302	4273	5928	3903	11
Cyprinus carpio	1	3	2	-	1360	-	3	230	103	8	-	36	9	-	3	1	407	3	1	-
Notropis stramineus	3	25	60	12	1584	-	-	129	239	116	-	105	101	356	36	925	285	896	174	-
Pimephales promelas	-	38	29	1	1239	-	-	3678	1461	2372	-	164	510	1714	881	23	8	285	297	157
Richardsonius balteatus	-	-	-	-	3	-	-	12	128	23	-	11	-	-	-	18	-	-	1	1
Unidentified Cyprinidae	7	-	-	221	94	430	4955	623	60	228	-	1	81	380	407	10385	8827	3457	10664	462
Esocidae																				
Esox lucius	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 5. cont.

Gear:	1992 Drift net	1992 Seine	1993 Drift net	1993 Seine	1993 LT	1994 LT	1995 LT	1996 LT	1997 LT	1998 LT	1999 LT	2000 LT	2001 LT	2002 LT	2003 LT	2004 LT	2005 LT	2006 LT	2007 LT	2008* LT
Catostomidae																				
Catostomus commersonii	2	1	2	1	4	-	3	5	3	2	-	9	26	10	85	145	209	50	87	130
Catosomus ardens	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	7	-	-	
Catostomus hybrid	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	6	-	-	3	-
Xyrauchen hybrid	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11	1	15	23	3
Unidentified Catostomus	7	1	12	79	32	462	13	14	-	4	-	11	13	10	5	4	13	5	3	3
Gasterosteidae																				
Culaea inconstans	-	-	-	-	-	-	-	8	2	-	-	-	-	1	-	-	97	279	1	1
Centrarchidae																				
Lepomis cyanellus	-	-	-	-	17	-	22	1	86	6	-	1	-	-	-	1	21	-	-	-
Lepomis macrochirus	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	18	-
Unidentified Lepomis	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	4	-	7	-
Pomoxis nigromaculatus	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5	-	-	-
Unidentified Pomoxis	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10	-	-	-
Micropterus dolomieu	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	4
Percidae																				
Etheostoma exile	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11	42	214	24
Perca flavescens	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5	-	-	-
Total number of fish	2244	1542	350	1253	11464	13816	9464	13599	2497	4639	12	2847	3821	6546	2761	73657	21875	18287	25886	4816
Number of Collections	50	30	60	52	210	196	298	174	190	127		89	80	86	73	173	177	118	123	89
Days of sampling	6	5	20	7	23	16	30	19	20	18		15	18	17	15	19	23	17	22	22

*2008 only species collected in samples with razorback suckers are shown.

Table 6.—Mean catch per unit effort (CPUE) for larval catostomids captured during light trapping in the middle Green River, Utah, 1993-2008. CPUE is number of fish per night per collection of light trapping (mean effort = 8.5 hours per overnight light trap sample). Effort was based on collections made on and following the date of first capture of sucker larvae in each year.

Reach	Species	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Middle Green River	Bluehead sucker	0.58	41.65	8.77	2.97	0.21	2.02	-	1.39	10.00	9.29	9.10	13.94	17.30	8.16	19.76	15.75
	Flannelmouth sucker	5.39	33.88	2.66	40.49	0.33	7.91	-	19.67	18.95	7.04	7.16	65.75	25.11	49.39	46.86	19.42
	Razorback sucker	1.31	7.85	0.13	1.37	0.02	0.46	-	0.92	1.11	1.08	0.66	6.05	0.97	4.53	18.64	9.99
Lower Green River	Bluehead sucker	-	2.76	0.20	0.40	0.00	0.51	0.15									
	Flannelmouth sucker	0.07	5.15	0.93	6.00	0.54	6.01	4.70									
	Razorback sucker	4.00	1.85	0.02	0.62	0.01	0.14	0.10									

Table 7.—Mean total length (TL) and standard deviation (SD) of wild razorback sucker larvae collected in the middle and lower Green River, Utah.

Reach	Year	n	Mean TL (mm)	SD	Range (mm TL)
Middle Green					
	1993	228	12.9	1.88	10.0-24.0
	1994	1217	11.7	0.84	9.0-18.0
	1995	32	11.9	1.13	10.0-16.0
	1996	174	11.8	1.09	10.2-16.5
	1997	3	11.6	0.40	11.2-12
	1998	58	12.5	1.31	10.7-16.3
	1999	12	-	-	-
	2000	82	11.5	0.98	9.8-16.2
	2001	89	12.1	1.38	11.0-16.0
	2002	93	12.6	1.33	10.0-16.0
	2003	47	10.8	0.82	10.0-13.5
	2004	1047	11.1	1.12	7.1-18.4
	2005	172	12.9	2.42	9.8-21.0
	2006	535	11.3	0.90	9.2-18.0
	2007	2293	11.3	1.41	7.0-19.0
	2008	889	11.9	1.41	10.0-19.0
Lower Green					
	1993	120	12.7	0.90	11.0-16.0
	1994	76	11.9	1.03	10.0-15.3
	1995	5	12.2	0.58	11.3-12.8
	1996	214	11.9	1.40	9.8-18.2
	1997	3	12.9	0.70	12.2-13.6
	1998	57	13.2	2.28	10.8-19.7
	1999	30	12.4	1.55	10.5-15.5

Table 8.—Selected mainstem water temperature and discharge parameters associated with the earliest estimated date of spawning by razorback suckers in the middle or lower Green River, Utah, from 1993-2008. Degree days are the sum of mean daily water temperatures between 1 January and the earliest date of spawning. Days > 10^{o}C or > 14^{o}C are the number of days between1 January and the earliest date of spawning that recorded mean daily water temperatures equaled or exceeded each respective threshold. Days before peak discharge are the number of days between the earliest date of spawning and the highest recorded mean daily river discharge for that spring. Date of spawning for 1993-1996, 2004-2006 based on otolith analysis, spawning dates for 1997-2003, 2007-2008 was back calculated using year specific average daily growth rates and a hatch size of 8.0 mm TL. Lower Green River 1993 data based on sampling conducted only from 17-19, June. Sample size is five fish or less for lower Green River in 1995 and 1997, and for Middle Green River 1997. Data for 1993-1996 were from Muth et al. (1998).

River section and Year	Earliest date of spawning	Water temperature (^{o}C) on earliest spawning date	Degree days	Days > 10^{o}C	Days> 14^{o}C	Days before peak discharge
Middle Green						
1993	30-Apr	12.4	318	13	3	28
1994	13-Apr	10.0	498	10	0	37
1995	15-May	12.1	895	40	0	24
1996	7-May	13.9	698	16	0	13
1997	27-May	11.1	881	32	0	9
1998	30-Apr	11.2	569	13	0	23
1999	NA					
2000	21-Apr	10.4	589	23	0	41
2001	18-Apr	13.3	417	10	2	30
2002	18-Apr	9.8	362	20	0	35
2003	25-Apr	11.4	498	19	1	39
2004	6-Apr	13.8	382	21	6	37
2005	10-Apr	8.3	361	7	0	46
2006	4-Apr	9.7	268	2	0	51
2007	4-Apr	11.2	264	13	0	43
2008	29-Apr	10.8	359	13	0	38
Lower Green						
1993	22-May	19	1090	58	36	9
1994	24-Apr	16	798	47	14	28
1995	6-May	14	1016	61	25	44
1996	2-Apr	12	357	12	0	50
1997	11-Apr	7	353	12	0	60
1998	22-Mar	10	338	4	0	65
1999	7-Apr	11	545	22	0	78

Table 9.—Selected mainstem water temperature and discharge parameters associated with the mean estimated date of spawning by razorback suckers in the middle or lower Green River, Utah, from 1993-2008. Degree days are the sum of mean daily water temperatures between 1 January and the mean date of spawning. Days > 10°C or > 14°C are the number of days between1 January and the mean date of spawning that recorded mean daily water temperatures equaled or exceeded each respective threshold. Days before peak discharge are the number of days between the mean date of spawning and the highest recorded mean daily river discharge for that spring. Date of spawning for 1993-1996, 2004-2006 based on otolith analysis, spawning dates for 1997-2003, 2007-2008 was back calculated using year specific average daily growth rates and a hatch size of 8.0 mm TL. Lower Green River 1993 data based on sampling conducted only from 17-19, June. Sample size is five fish or less for lower Green River in 1995 and 1997, and for Middle Green River 1997. Data for 1993-1996 were from Muth et al. (1998).

River section and Year	Mean date of spawning	Water temperature (°C) on mean spawning date	Degree days	Days > 10°C	Days> 14°C	Days before peak discharge
Middle Green						
1993	17-May	12.9	532	28	8	11
1994	3-May	11.5	732	25	4	17
1995	29-May	11	1065	54	0	10
1996	20-May	12.4	867	29	2	0
1997	31-May	13.8	931	36	0	5
1998	16-May	11.5	752	31	0	7
1999						
2000	3-May	14.3	742	35	7	29
2001	1-May	13.7	587	23	10	17
2002	11-May	12.9	658	42	14	12
2003	11-May	10.9	681	35	1	23
2004	2-May	12.1	687	47	12	10
2005	9-May	12.6	680	36	2	16
2006	5-May	11.4	601	28	0	20
2007	11-May	17.4	733	50	13	5
2008	27-May	11.7	676	39	8	10
Lower Green						
1993	25-May	19.0		61	39	6
1994	10-May	17.0		63	28	12
1995	16-May	17.0		71	35	34
1996	26-Apr	16.0		34	11	26
1997	21-Apr	16.0		20	1	50
1998	19-Apr	9.0		16	0	37
1999	26-Apr	14.0		41	10	59

Table 10.—Selected mainstem water temperature and discharge parameters associated with the mean and range of estimated date of hatching by razorback suckers in the middle or lower Green River, Utah, from 1993-2008. Date of hatching for 1993-1996, 2004-2006 based on otolith analysis, hatching dates for 1997-2003, 2007-2008 was back calculated using year specific average daily growth rates and a hatch size of 8.0 mm TL. Lower Green River 1993 data based on sampling conducted only from 17-19, June. Sample size is five fish or less for lower Green River in 1995 and 1997, and for Middle Green River 1997. Data for 1993-1996 were from Muth et al. (1998). The discharge and water temperature ranges represent those on the first and last days of the hatch date range. The Q mean (discharge at the mean hatch date) and the °C is the flow and water temperature at the mean hatch date (which is the average value of all hatching dates).

Year	Hatch date range	Mean hatch date	Q range, m^3/sec	Q mean, m^3/sec	°C range, hatching	°C mean, hatching	Date, peak Q	Q peak, m^3/sec
1993	15 May-12 Jun	31-May	365.3-359.6	540.9	15.1-15.4	15.0	28-May	566.3
1994	3 May-3 Jun	17-May	135.4-305.8	311.5	11.5-16.3	12.8	20-May	331.3
1995	1 Jun-6 Jul	13-Jun	481.4-351.1	382.3	13.1-16.4	15.8	8-Jun	526.7
1996	21 May-16 Jun	2-Jun	577.7-371.0	371.0	12.3-16.3	14.7	20-May	623.0
1997	8 Jun-14 Jun	11-Jun	631.5-509.7	583.3	16-14.8	14.5	5-Jun	705.1
1998	18 May-14 Jun	31-May	337.0-297.3	421.9	12.6-14.5	14.3	23-May	484.2
1999	NA						2-Jun	583.3
2000	5 May-28 May	18-May	297.3-441.7	237.6	15.2-14.8	11.8	1-Jun	458.7
2001	2 May-28 May	14-May	234.2-268.2	294.5	9-15.7	15.8	18-May	407.8
2002	3 May-6 Jun	22-May	100.0-114.4	189.2	13.6-19.4	12.5	23-May	201.6
2003	13 May-3 Jun	24-May	124.3-538.0	402.1	13.4-15.9	14.9	3-Jun	538.0
2004	23 Apr-1 Jun	15-May	106.8-146.4	265.6	9.5-15.5	12.4	13-May	322.8
2005	28 Apr-10 Jun	23-May	205.0-382.3	506.9	11.1-14.6	15.7	26-May	552.2
2006	24 Apr-4 Jun	18-May	226.5-272.1	342.6	12.1-16.9	15.5	25-May	521.0
2007	22 Apr-21 Jun	23-May	130.8-96.0	303.0	11.6-21.1	13	17-May	354.0
2008	17 May-29 Jun	10-Jun	250.0-294.5	475.7	13.5-19.5	13.2	6-Jun	665.4

Table 11.—Selected mainstem water temperature and discharge parameters associated with the first capture date for razorback sucker larvae in the middle or lower Green River, Utah, from 1993-2008. Degree days are the sum of mean daily water temperatures between 1 January and the earliest date of capture. Days > 10°C or > 14°C are the number of days between1 January and the earliest date of capture recorded mean daily water temperatures equaled or exceeded each respective threshold. Days before peak discharge are the number of days between the earliest date of capture and the highest recorded mean daily river discharge for that spring. Lower Green River 1993 data based on sampling conducted only from 17-19, June. Sample size is five fish or less for lower Green River in 1995 and 1997, and for Middle Green River 1997. Data for 1993-1996 were from Muth et al. (1998).

River section and Year	Earliest date of capture	Water temperature (°C) on earliest capture date	Degree days	Days > 10°C	Days> 14°C	Days before peak discharge
Middle Green						
1993	26-May	14.7	656.7	37	12	2
1994	16-May	13.7	920.1	38	13	4
1995	13-Jun	15.8	1265.9	69	3	-5
1996	4-Jun	16.1	1058.6	44	6	-15
1997	19-Jun	14.6	1219.6	55	19	-14
1998	2-Jun	15.1	979.4	46	7	-10
1999	9-Jun	13.5	1069.7	47	15	-7
2000	23-May	16.4	1002.2	55	17	9
2001	24-May	14.9	890.2	45	24	-6
2002	21-May	15.5	818.7	52	24	2
2003	29-May	16.4	944.1	53	16	5
2004	18-May	15-1	920.9	63	24	-5
2005	26-May	14.9	916.9	53	15	0
2006	20-May	15-1	806.9	43	9	5
2007	15-May	15.4	802.4	54	17	2
2008	10-Jun	13.2	856.1	53	14	-4
Lower Green						
1993	18-Jun	16.7		85	60	-18
1994	17-May	14.1		71	36	5
1995	31-May	12.7		87	37	19
1996	7-May	12.7		45	11	15
1997	13-May	13.8		38	4	28
1998	5-May	13.0		32	0	21
1999	6-May	12.9		52	10	49

Table. 12.—Selected mainstem water temperature (°C) and days before peak discharge associated with the mean capture date for razorback sucker larvae in the middle or lower Green River, Utah, from 1993-2008. Degree days are the sum of mean daily water temperatures between 1 January and the mean capture date. Days > 10°C or > 14°C are the number of days between1 January and the mean date of capture recorded mean daily water temperatures equaled or exceeded each respective threshold. Days before peak discharge is the number of days between the mean capture date and the highest recorded mean daily river discharge for that spring; a negative number indicates that mean capture date was after the flow peak. Lower Green River 1993 data based on sampling conducted only from 17-19, June. Sample size is five fish or less for lower Green River in 1995 and 1997, and for Middle Green River 1997. Data for 1993-1996 were from Muth et al. (1998).

River section and Year	Mean date of capture	Mean temperature (°C)	Degree days	Days > 10°C	Days> 14°C	Days before peak discharge
Middle Green						
1993	14-Jun	16.7	923	56	21	-17
1994	29-May	15.3	1104	51	20	-9
1995	24-Jun	16.5	1436	80	12	-16
1996	13-Jun	16.2	1204	53	15	-24
1997	23-Jun	17.1	1285	59	23	-18
1998	14-Jun	14.5	1149	58	13	-22
1999	13-Jun	14.3	1125	51	19	-11
2000	31-May	16.4	1126	63	25	1
2001	31-May	16.4	1000	52	31	-13
2002	10-Jun	17.6	1153	72	41	-18
2003	5-Jun	15.6	1057	60	23	-2
2004	27-May	15.4	1106	72	36	-14
2005	14-Jun	15.1	1176	72	28	-19
2006	1-Jun	14.3	974	55	19	-7
2007	5-Jun	19.1	1136	75	37	-19
2008	27-Jun	18.9	1136	70	28	-21
Lower Green						
1993	18-Jun	16.7		85	60	-18
1994	4-Jun	17.9		89	54	-14
1995	16-Jun			102	41	3
1996	15-May	14.9		53	14	7
1997	18-May	14.8		43	7	23
1998	19-May	14.2		46	1	7
1999	25-May	16.1		70	19	30

Table 13.—Species composition and gear types for samples collected in the lower Green River, Utah, 1993-1999. Light trap (LT) samples consist of about 8.5 hr of dusk-to-dawn sampling time.

Gear:	1993 Seine	1993 LT	1994 Seine	1994 LT	1995 Seine	1995 LT	1996 Seine	1996 LT	1997 LT	1998 LT	1999 LT	Total
Native taxa												
Cyprinidae												
Gila sp.	-	-	1	19	-	-	3	47	-	3	1	74
Ptychocheilus lucius	1	-	36	-	82	11	42	12	-	1	1	186
Rhinichthys osculus	-	1	-	36	-	6	8	388	-	29	4	472
Catostomidae												
Catostomus discobolus	-	-	49	113	7	47	17	140	1	200	48	622
C. latipinnis	1	2	-	211	91	216	529	2083	142	2373	1465	7113
Xyrauchen texanus	2	120	15	76	-	5	8	214	3	57	30	530
Nonative taxa												
Cyprinidae												
Cyprinella lutrensis	804	273	206	9118	1617	1658	4037	19769	2539	223	4547	44791
Cyprinus carpio	3	7	-	19	1	1	22	-	-	7	13	73
Notropis stramineus	1	3	-	78	220	126	376	265	329	131	626	2155
Pimephales promelas	2	32	-	708	73	1	332	133	5	639	55	1980

Table 13 cont.

	Gear:	1993 Seine	1993 LT	1994 Seine	1994 LT	1995 Seine	1995 LT	1996 Seine	1996 LT	1997 LT	1998 LT	1999 LT	Total
Nonative taxa (cont.)													
Richardsonius balteatus		-	-	-	-	-	-	1	6	-	-	-	7
Unidentified Cyprinidae		-	82	-	8	42	9331	65	5083	-	92	44	14747
Catostomidae													
Catostomus commersonii		1	-	-	-	-	-	2	-	-	13	-	16
Unidentified Catostomidae		1	-	3	-	1	1	4	27	-	36	5	78
Ictaluridae													
Ameiurus melas		-	-	-	-	-	-	1	-	-	-	-	1
Ictalurus punctatus		-	-	-	-	11	-	7	-	-	-	-	18
Centrarchidae													
Lepomis cyanellus		-	-	-	-	-	-	1	-	-	-	-	1
Total number of fish		816	520	310	10386	2145	11403	5455	28167	3019	3804	6839	72864
Number of Collections		2	30	2	41	34	232	186	347	263	395	312	
Hours of sampling; total (collection mean)			154.9 (5.2)		352.8 (8.8)		2082 (9.0)		3206.9 (9.2)	2480 (9.4)	3644.3 (9.2)	2934.1 (9.4)	

Table 14.—Terrace (IMC, RSS, and Lamb) and depression (remainder) flood plain wetlands in the middle Green River, Utah. Location (RK = river kilometer), inlet and outlet number, area flooded at high flow, and Green River flow levels required to inundate breaches (Breach) comes from a variety of sources (FLO 1996 reports, Valdez and Nelson 2004, Heitmeyer and Fredrickson 2005, Hedrick et al. 2009). Baeser Bend was assumed to still connect to the Green River at this lower level.

Wetland	RK	Bank	Flow through	Inlets	Outlets	Area (ha)	Breach (m^3/sec)
Thunder Ranch	491.5	left	yes	5	1	134	340
Stewart Lake	482.8	right	yes	1	1	231	227
Bonanza Bridge	465	left	yes	3	1	11	396
Above Brennan	432	left	yes	3	1	20	334
IMC	487	right	no	1		5	NA
Sportsman's Lake	478.2	right	no	1		53	NA
RSS	463.7	right	no			18	527
Horseshoe Bend	458.9	left	no	1		9	404
The Stirrup	443.7	left	no	1		11	368
Baeser Bend	438.9	left	no	1		19	337
Johnson Bottom	422.9	left	no	1		170	368
Leota wetlands complex	414.9	right	no	1		526	431
Wyasket Lake	410	left	no	1		761	538
Sheppard Bottom	407.3	right	no	1		577	525
Old Charley Wash (Woods Bottom)	402	left	no	1		236	368
Lamb Property	392.8	right	no	1		187	525
total						2968	

Table 15.— Surface area (ha) of flood plain wetlands various flow levels of the middle Green River, Utah, near Jensen, for flow-through and single-breach depressions; Breach flow is the flow level of the Green River when wetlands begin filling. For flows ≤ 623 m^3/sec, surface areas were predictions from regression relationships of area as a function of river stage. Wetland areas were from aerial photographs interpolated from the Argonne National Laboratory unpublished report; river stages were either those from the Jensen USGS gauge if the wetland was upstream of Ashley Creek, or represented the sum of the Ashley Creek and Green River at Jensen flows for those wetlands downstream of Ashley Creek, which were offset one day to account for transit time to downstream areas in the vicinity of Ouray National Wildlife Refuge. Area of flow-through wetlands was assumed to stabilize at flows >623 m^3/sec because no data were available to estimate their area. Area of single breach wetlands at those higher flows were from observations or field measurements. Data derive from various sources (Argonne unpublished rpt., FLO1996, Valdez and Nelson 2004, Heitmeyer and Fredrickson 2005, Hedrick et al. 2009).

	Breach	Green River flow level (m^3/sec)									
Wetland	flow (m^3/s)	235	283	340	397	453	527	575	623	643	748
Flow-through											
Thunder Ranch	340	0	0	0	69	86	106	117	126	134	134
Stewart Lake	227	56	90	130	170	210	231	231	231	231	231
Bonanza Bridge	396	0	0	0	6	7	9	10	11	11	11
Above Brennan	334	0	0	8	12	15	16	20	20	20	20
totals		56	90	138	257	318	362	378	388	396	396
Single-breach											
Horseshoe Bend	404	0	0	0	0	6	8	9	9	9	9
The Stirrup	368	0	0	0	6	7	9	10	11	11	11
Baeser Bend	337	0	0	6	9	11	15	17	19	19	19
Johnson Bottom	368	0	0	0	23	42	66	82	97	162	170
Leota wetlands complex	431	0	0	0	0	0	95	175	255	314	526
Wyasket Lake	538						202	214	214	751	761
Sheppard Bottom	525							99	99	567	577
Old Charley Wash	368	0	0	0	73	86	102	113	123	231	236
totals		0	0	6	112	152	496	718	827	2064	2309

Table 16.—Estimated annual volume of water entrained (hectare/meters, the volume required to cover 1 hectare in 1 m of water) into flow-through wetlands (Bonanza Bridge in 2005 used in totals, 2006 for comparison) in the middle Green River, Utah, 1992-2009. The upper (*All flow*) portion of the table reflects all water entrainment after wetlands connect with the Green River, and the lower portion (*Post-RZB*) reflects totals only after razorback sucker larvae were detected in annual light trap samples. The *% flow post-RZB* is the percentage of flow entrainment after larvae were detected relative to the annual total, and the *% diff* is the percentage of flow entrainment after larvae were detected relative to the total by individual floodplain wetland.

Year	Thunder Ranch	Stewart Lake	Bonanza Bridge, 05	Bonanza Bridge, 06	Above Brennan	total	% flow post-RZB
All flow							
1992	0	13	0	0	0	13	
1993	2049	982	293	222	960	4283	
1994	0	106	0	0	36	142	
1995	1494	1008	206	200	862	3571	
1996	1771	924	195	123	747	3636	
1997	8140	2189	1023	516	2437	13790	
1998	626	632	67	33	458	1784	
1999	2801	1309	362	296	1191	5663	
2000	201	253	20	11	150	625	
2001	53	114	6	0	76	249	
2002	0	0	0	0	0	0	
2003	760	424	97	87	365	1646	
2004	0	23	0	0	8	31	
2005	1029	627	156	134	571	2383	
2006	391	376	42	39	201	1010	
2007	0	66	0	0	37	103	
2008	3881	1203	455	243	1222	6761	
2009	722	621	62	52	388	1794	
total	23920	10869	2984	1955	9710	47482	
Post-RZB							
1992	0	0	0	0	0	0	0
1993	1188	610	151	111	536	2485	58.0
1994	0	89	0	0	28	118	82.7
1995	590	436	86	77	371	1482	41.5
1996	187	219	15	1	145	566	15.6
1997	347	211	29	25	122	709	5.1
1998	108	180	9	0	105	402	22.5
1999	1182	552	133	121	452	2319	41.0
2000	201	190	20	11	128	539	86.3
2001	0	22	0	0	0	22	8.9
2002	0	0	0	0	0	0	0
2003	561	273	65	59	218	1117	67.9
2004	0	0	0	0	0	0	0
2005	690	448	79	78	332	1549	65.0
2006	391	280	40	39	178	889	88.0
2007	0	53	0	0	33	86	83.9
2008	219	216	11	7	122	567	8.4
2009	106	175	5	0	88	374	20.8
total	5769	3954	643	528	2860	13226	38.6
% diff	24.1	36.4	21.5	27.0	29.5	27.9	

Table 17.—Estimated annual volume of water entrained (hectare/meters, the volume required to cover 1 hectare in 1 m of water) into single-breach wetlands (Leota Wetlands complex @494 m^3/sec used in totals, other for comparison) in the middle Green River, Utah, 1992-2009. The upper (*All flow*) portion of the table reflects all water entrainment after wetlands connect with the Green River, and the lower portion (*Post-RZB*) reflects totals only after razorback sucker larvae were detected in annual light trap samples. The *single % post-RZB vs. all* is the percentage of flow entrainment after larvae were detected relative to the annual total, and the *% diff* is the percentage of flow entrainment after larvae were detected relative to the total by wetland. The *% single breach vs flowthru* number is the percent of flow entrained by single breach wetlands in each year compared to flow-through wetlands in the *All flow* and *Post-RZB* periods.

Year	Horseshoe Bend 404 (m^3/s)	Stirrup 368 (m^3/s)	Baeser Bend 337 (m^3/s)	Johnson Bottom 368 (m^3/s)	Leota wetlands 594 (m^3/s)	Leota wetlands 494 (m^3/s)	Old Charley 368 (m^3/s)	total	single % post-RZB vs. all	% single breach vs flowthru
All flow										
1992	0	0	0	0	0	0	0	0		0
1993	18	21	35	138	0	179	250	641		15.0
1994	0	0	0	0	0	0	0	0		0
1995	16	20	34	106	0	134	237	547		15.3
1996	13	19	30	106	28	127	228	524		14.4
1997	27	31	49	232	28	424	348	1111		8.1
1998	12	16	24	69	0	2	191	314		17.6
1999	15	20	34	141	0	175	229	614		10.8
2000	3	5	9	24	0	0	60	100		16.0
2001	0	2	4	7	0	0	22	35		14.0
2002	0	0	0	0	0	0	0	0		0
2003	7	8	15	51	0	46	99	226		13.7
2004	0	0	0	0	0	0	0	0		0
2005	8	11	18	66	0	100	129	332		13.9
2006	5	6	11	36	0	24	75	157		15.6
2007	0	0	1	0	0	0	0	1		0.6
2008	17	19	32	130	55	272	226	698		10.3
2009	11	20	29	105	0	52	229	447		24.9
total	152	200	323	1210	111	1537	2323	5745		
Post-RZB										
1992	0	0	0	0	0	0	0	0	0	0
1993	14	16	26	105	0	158	191	510	79.6	20.5
1994	0	0	0	0	0	0	0	0	0	0
1995	7	9	15	51	0	48	104	233	42.7	15.8
1996	3	7	9	27	0	-80	82	47	9.1	8.4
1997	2	3	4	16	0	21	30	76	6.8	10.7
1998	3	5	6	17	0	0	52	83	26.4	20.7
1999	6	7	11	47	0	74	77	222	36.2	9.6
2000	3	5	8	24	0	0	60	100	99.7	18.5
2001	0	0	0	0	0	0	0	0	0	0
2002	0	0	0	0	0	0	0	0	0	0
2003	3	4	6	24	0	40	41	118	52.3	10.6
2004	0	0	0	0	0	0	0	0	0	0
2005	5	5	8	32	0	72	64	186	56.1	12.0
2006	5	6	10	35	0	24	73	153	97.2	17.2
2007	0	0	1	0	0	0	0	1	100.0	0.7
2008	1	1	2	5	0	0	13	21	3.1	3.8
2009	2	3	4	12	0	0	38	59	13.2	15.8
total	54	71	109	395	0	358	823	1810	34.6	9.1
% diff	35.6	35.3	33.8	32.6	0.0	23.3	35.4	31.5		

Table. 18.—Green and Yampa River stream flow characteristics, 1992-2009, and their relationship with timing of razorback sucker reproduction in the middle Green River, Utah. Flow data (m^3/sec) are from the Yampa River Basin (Little Snake River, near Lily, Colorado, U. S. Geological Survey gauge # 09260000 and the Yampa River, near Maybell, Colorado, gauge # 09251000), and the Green River upstream of the Yampa River near Greendale, Utah (gauge # 09234500) in 1951 (upper panel). Peak flow release date was when a sustained increase in flows occurred in late spring; Release end was the day flows tapered to post-release base flow. Days prior is the number of days that Green River releases started before the peak of the Yampa River was achieved. Mean Q release was mean release rate over the release period (Duration days), having subtracted the Pre-release base flow. The First RZB capture date was date of first capture of a razorback sucker larva from light trap sampling conducted in the middle Green River, Utah; First RZB post-peak was the number of days the first larva was captured after the peak of Yampa River flows; a negative number indicates the capture was before the peak. Means are the last row.

	Peak Yampa R.	Yampa Max Q	Release, Green R	Days prior	Green R. Max. Q	Mean Q release	Duration days	Pre-release base	Release end	First RZB capture	First RZB post-peak
1992	29-May	196.0	4-May	-25	122.1	94.3	18	44.4	22-May	20-May	-9
1993	24-May	450.4	15-May	-9	130.9	97.7	40	36.2	24-Jun	26-May	2
1994	19-May	205.9	10-May	-9	132.6	112.9	37	49.2	16-Jun	16-May	-3
1995	24-May	462.6	17-May	-7	131.7	85.2	75	46.4	31-Jul	13-Jun	20
1996	24-May	411.3	1-May	-23	135.1	126.9	62	84.6	1-Jul	4-Jun	11
1997	5-Jun	572.2	22-Mar	-74	238.5	129.8	118	80.6	18-Jul	19-Jun	14
1998	23-May	393.8	21-May	-2	128.0	118.0	29	88.2	19-Jun	2-Jun	10
1999	1-Jun	388.1	10-May	-22	308.8	173.5	69	96.7	18-Jul	9-Jun	8
2000	31-May	308.8	16-May	-15	130.6	107.2	28	52.7	13-Jun	23-May	-8
2001	18-May	268.8	11-May	-7	127.2	88.4	21	32.4	1-Jun	24-May	6
2002	2-Jun	98.3	18-May	-15	112.5	86.8	16	23.9	3-Jun	21-May	-12
2003	3-Jun	444.8	19-May	-15	130.0	101.1	19	23.4	7-Jun	29-May	-5
2004	9-May	197.7	8-May	-1	128.9	81.9	13	27.5	21-May	18-May	9
2005	24-May	430.6	16-May	-8	195.2	127.9	34	31.2	19-Jun	26-May	2
2006	25-May	388.1	16-May	-9	173.1	108.5	23	42.3	8-Jun	20-May	-5
2007	16-May	230.9	12-May	-4	125.8	91.9	18	23.8	30-May	15-May	-1
2008	23-May	617.6	23-May	0	125.5	110.9	28	24.5	20-Jun	10-Jun	18
2009	27-May	439.1	11-May	-16	127.2	111.0	15	24.1	26-May	29-May	2
	25-May	361	10-May	-15	150.2	108.6	37	46.2	16-Jun	28-May	3

Table 19.—Number of days of flood plain wetland inundation when razorback suckers were present in the middle Green River, Utah, for flows that exceeded threshold levels of 368 m^3/sec, 396 m^3/sec, and 527 m^3/sec for the period 1992-2009 under six different scenarios and an unregulated condition (7). Flow scenarios for Flaming Gorge Dam included; (1) a steady annual flow; (2) conditions as they existed under prevailing flow releases with release timing attempting to match Yampa River flow peaks; (3) conditions as they existed under prevailing flow releases with release timing matched to first appearance of razorback sucker larvae; (4) conditions as they existed under prevailing flow releases except that total release volume was compacted into a time period half as short as under prevailing conditions with release timing matched to first appearance of razorback sucker larvae; (5) conditions as in Scenario 4 except duration extended twice as long as in scenario 4 (up to 30 days maximum, back to the duration used in scenarios 2 and 3); and (6) conditions as in Scenario 5 except flow magnitude in 11 of 18 wet years (1993, 1995-1999, 2003, 2005, 2006, 2008, and 2009) was increased to 244 m^3/sec (8,600 cfs). Exceptions were 1997 and 1999, flows for which were held at the release peaks actually made (239 and 309 m^3/sec, respectively).

	Flow scenarios, 368 m^3/sec							Flow scenarios, 396 m^3/sec							Flow scenarios, 527 m^3/sec						
Year	1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7
1992	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1993	11	24	21	24	30	33	35	10	21	17	22	26	33	28	0	6	4	9	9	15	12
1994	0	0	0	4	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1995	13	5	6	12	12	16	38	12	2	3	5	5	15	38	4	0	0	0	0	4	23
1996	8	13	10	15	15	22	26	1	8	7	11	11	21	23	0	0	0	0	0	1	15
1997	28	29	29	29	29	31	35	24	28	28	28	28	31	34	14	15	15	15	15	22	30
1998	1	7	9	8	11	31	28	0	5	2	2	6	25	23	0	0	0	0	0	2	4
1999	9	28	26	26	26	26	36	8	27	26	26	26	26	36	0	15	19	19	19	19	24
2000	4	10	7	10	10	10	11	1	9	5	9	9	9	8	0	0	0	0	0	0	0
2001	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2002	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2003	7	8	9	11	14	25	13	7	8	8	9	9	20	11	0	3	2	3	3	6	4
2004	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2005	7	17	19	21	32	32	26	3	15	13	19	28	30	25	0	2	0	7	7	10	12
2006	6	11	11	11	18	28	16	3	11	8	8	8	24	10	0	0	0	2	2	6	4
2007	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2008	4	13	16	16	25	30	23	0	5	9	15	20	28	19	0	0	0	0	0	8	0
2009	4	6	8	9	16	17	36	2	5	12	8	15	15	35	0	0	0	0	0	3	8
mean	6	10	10	11	13	17	18	4	8	8	9	11	15	16	1	2	2	3	3	5	8

Table 20.—Volume of flow releases from Flaming Gorge Dam, Utah, from 1992-2009 under various release scenarios (see Tables 18 and 19). Flow scenarios for Flaming Gorge Dam included; (2) conditions as they existed under prevailing flow releases with release timing attempting to match Yampa River flow peaks; (3) conditions as they existed under prevailing flow releases with release timing matched to first appearance of razorback sucker larvae; (4) conditions as they existed under prevailing flow releases except that total release volume was compacted into a time period half as short as under prevailing conditions with release timing matched to first appearance of razorback sucker larvae; (5) conditions as in Scenario 4 except duration extended twice as long as in scenario 4 (up to 30 days maximum, back to the duration used in scenarios 2 and 3); and (6) conditions as in Scenario 5 except flow magnitude in 11 of 18 wet years (1993, 1995-1999, 2003, 2005, 2006, 2008, and 2009) was increased to 244 m^3/sec (8,600 cfs). Exceptions were 1997 and 1999, flows for which were held at the release peaks actually made (239 and 309 m^3/sec, respectively) and were for periods longer than 30 days. Annual release volume is the total water volume released from Flaming Gorge Dam, and the % annual volumes under scenarios 2 and 6 represents the release volume as a percentage of the total annual volume. As a point of reference, the high flow year 1983 release volume was 374,163 ha/m; the mean for the post-dam period 1964-2009 was 177,683 ha/m. The Scenario 6 base flow is the mean daily flow rate for the remainder of the year ("year" starts with the date of spring release) following the spring release, estimated by subtracting spring release volume from the total released and dividing by the number of days remaining in the 365 d period.

Year	Scenarios 2	3	4	5	6	Scen. 6 release period (d)	Annual release (ha/m)	Scen. 2 % annual (ha/m)	Scen. 6 % annual (ha/m)	Scen. 6 baseflow (m^3/sec)
1992	7,879	7,879	7,879	15,759	15,759	16	123,107	6.4	12.8	36
1993*	21,606	21,606	21,606	31,881	55,243	30	144,011	15.0	38.4	31
1994	20,534	20,534	20,534	35,201	35,201	30	151,426	13.6	23.2	40
1995*	9,103	9,103	9,103	14,373	49,409	30	169,741	5.4	29.1	42
1996*	22,121	22,121	22,121	23,625	30,235	23	222,717	9.9	13.6	65
1997*	42,162	42,162	42,162	42,162	64,337	30+	282,752	14.9	22.8	75
1998*	7,783	7,783	7,783	15,567	38,933	30	237,547	3.3	16.4	69
1999*	46,151	46,151	46,151	46,151	46,151	30+	285,075	16.2	16.2	83
2000	13,186	13,186	13,186	26,371	26,371	28	147,674	8.9	17.9	42
2001	10,158	10,158	10,158	20,315	20,315	22	93,804	10.8	21.7	25
2002	8,711	8,711	8,711	17,423	17,423	17	84,718	10.3	20.6	22
2003*	12,754	12,754	12,754	24,165	43,758	24	90,945	14.0	48.1	16
2004	6,585	6,585	6,585	13,171	13,171	12	97,020	6.8	13.6	27
2005*	28,642	28,642	28,642	47,463	53,235	30	145,173	19.7	36.7	32
2006*	13,158	13,158	13,158	26,316	48,699	29	117,568	11.2	41.4	24
2007	10,662	10,662	10,662	21,324	21,324	19	94,519	11.3	22.6	24
2008*	21,055	21,055	21,055	40,658	54,910	30	129,181	16.3	42.5	26
2009*	11,464	11,464	11,464	21,495	28,446	16	144,137	8.0	19.7	38
	17429	17429	17429	26857	36829	25		11.2	25.4	40
								(3-20%)	(13-48%)	(16-83)

* simulated wetter year

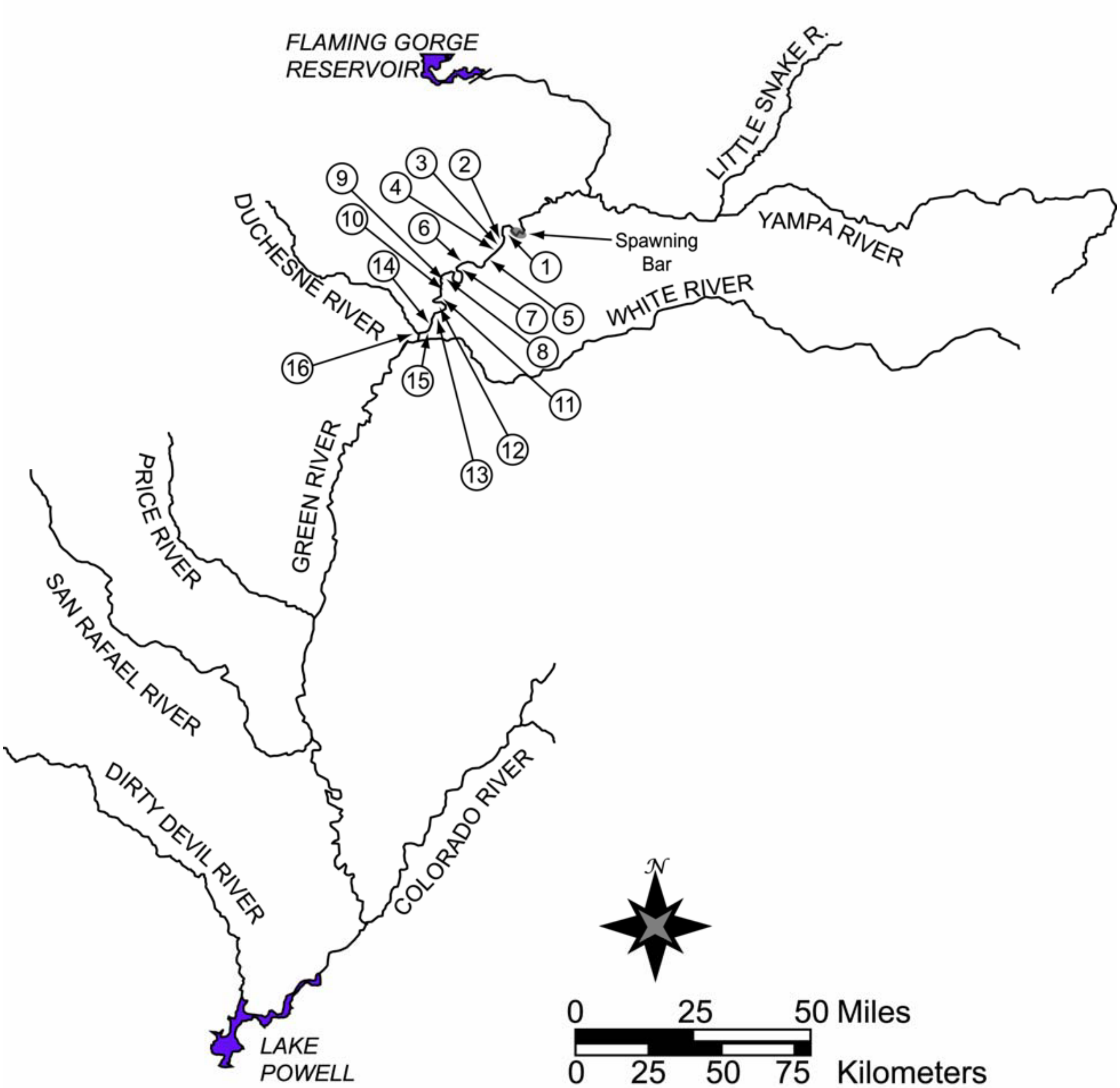


Figure 1. Green River study area showing locations of 16 priority flood plain wetlands (from Hayse et al. 2005, and Valdez and Nelson 2004). Location 1= Thunder Ranch, 2 = IMC, 3 = Stewart Lake, 4 = Sportsman's Lake, 5 = Bonanza Bridge, 6 = Richens, Slaugh, 7 = Horseshoe Bend, 8 = The Stirrup, 9 = Baser Bend, 10 = Above Brennan, 11 = Johnson Bottom, 12 = Leota ponds, 13 = Wyasket Lake, 14 = Sheppard Bottom, 15 = Old Charley Wash, 16 = Lamb Property. From Hayse et al. (2005) with permission.

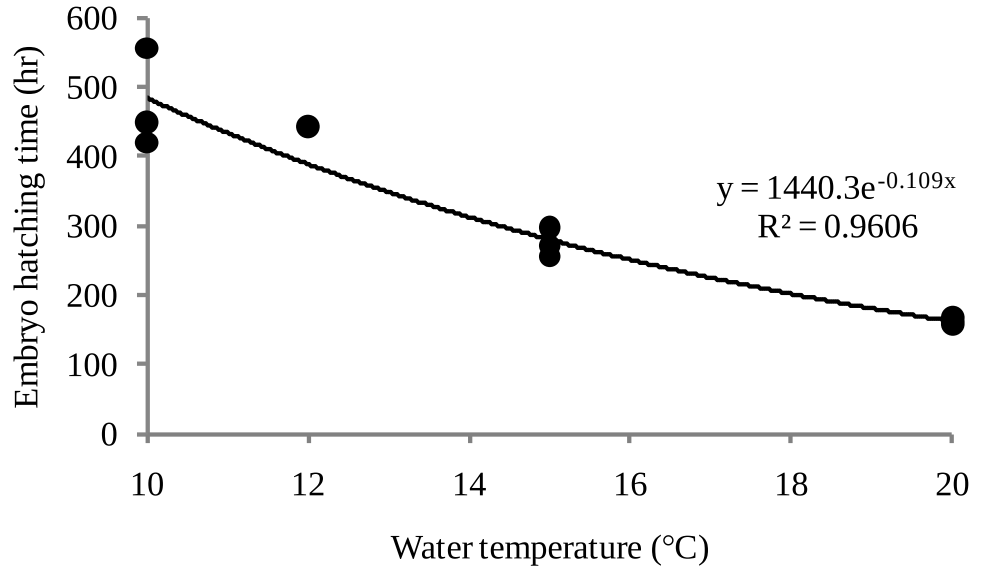


Figure 2. Relationship of time to 50% hatching of batches of razorback sucker embryos as a function of water temperature (°C); data from Bozek et al. (1990).

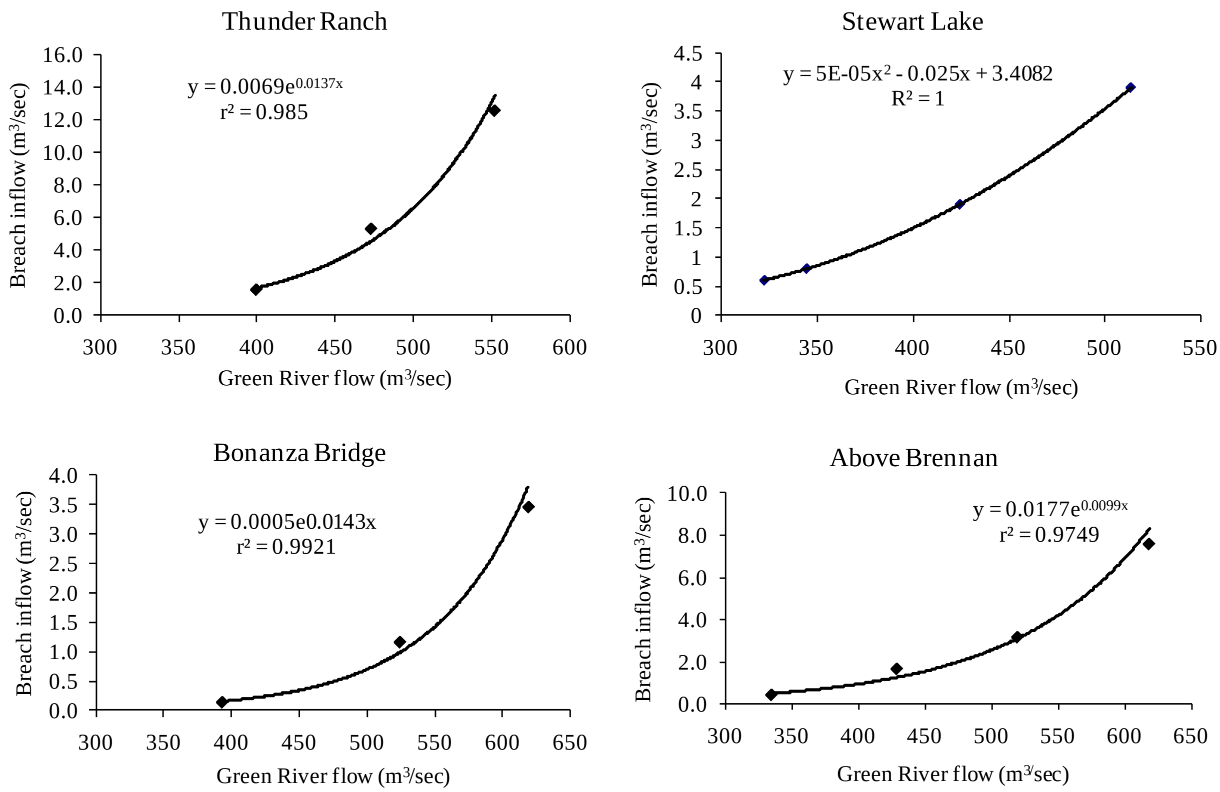


Figure 3. Inflow into Thunder Ranch, Stewart Lake, Bonanza Bridge, and Above Brennan flow-through flood plain wetlands, as a function of Green River flow rate in the middle Green River, Utah. Wetland breach inflows were measured at breach cross-sections for each wetland in 2005 at a variety of Green River flow levels once inundation was achieved (Hedrick et al. 2009) and were summed for various inflow breaches for each wetland (except Stewart Lake, which had only one breach). Green River flow was measured at the U.S. Geological Survey Jensen gauge (#09261000); river flows for wetlands Bonanza Bridge and Above Brennan, which were downstream, were Green River flows at Jensen plus upstream tributary Ashley Creek offset by one day to account for downstream travel time.

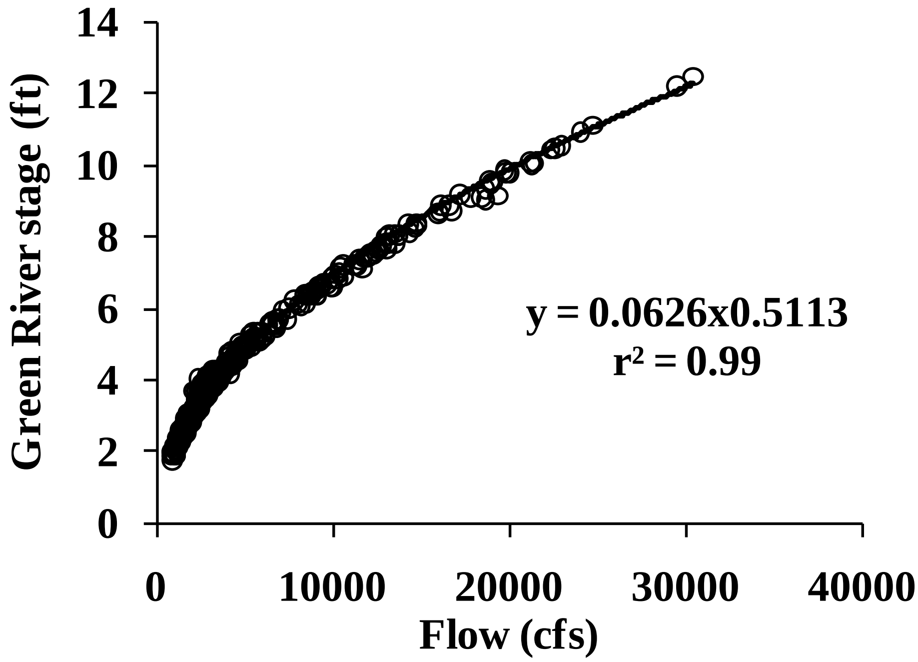
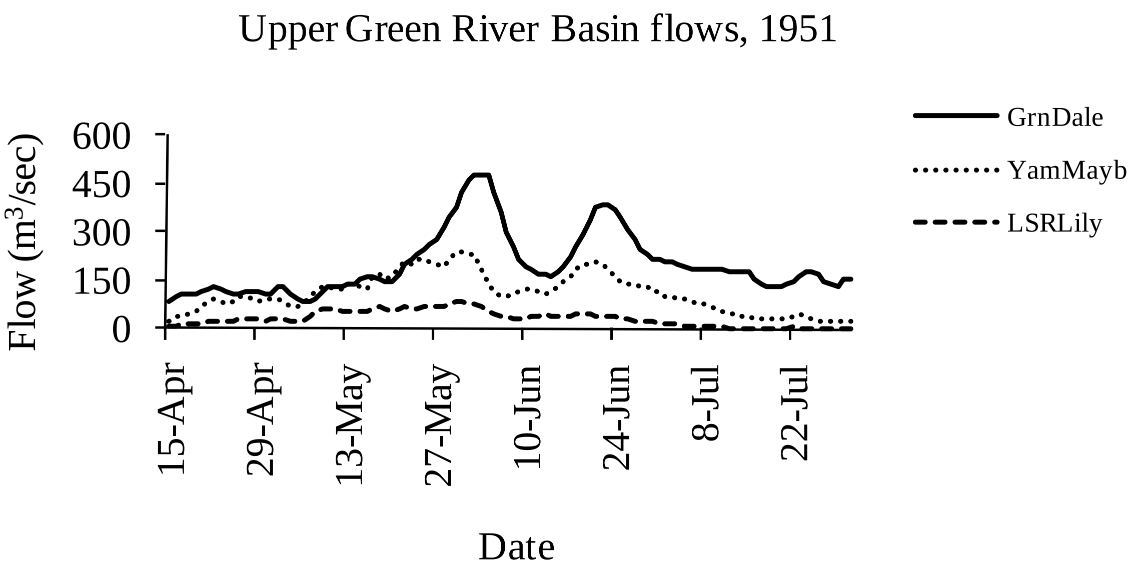


Figure 4. Green River stage as a function of discharge (Jensen, Utah, U. S. Geological Survey gauge, # 09261000). Data were collected from 1958 to 2009 (n = 366).



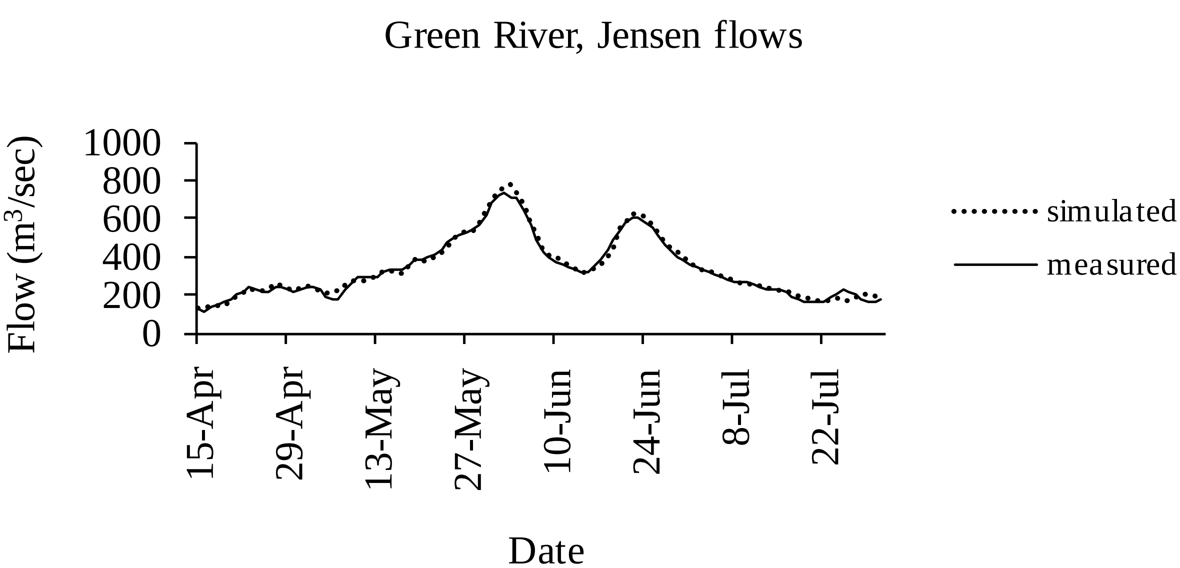


Figure 5. Flows of the Little Snake River, near Lily, Colorado (LSRLily, U. S. Gelogical Survey gauge # 09260000), the Yampa River, near Maybell, Colorado (YamMayb, gauge # 09251000), and the Green River near Greendale, Utah (GrnDale, gauge # 09234500) in 1951 (upper panel). Lower panel depicts measured Green River flows at Jensen, Utah (gauge # 09261000) compared to those simulated using a flow routing model.

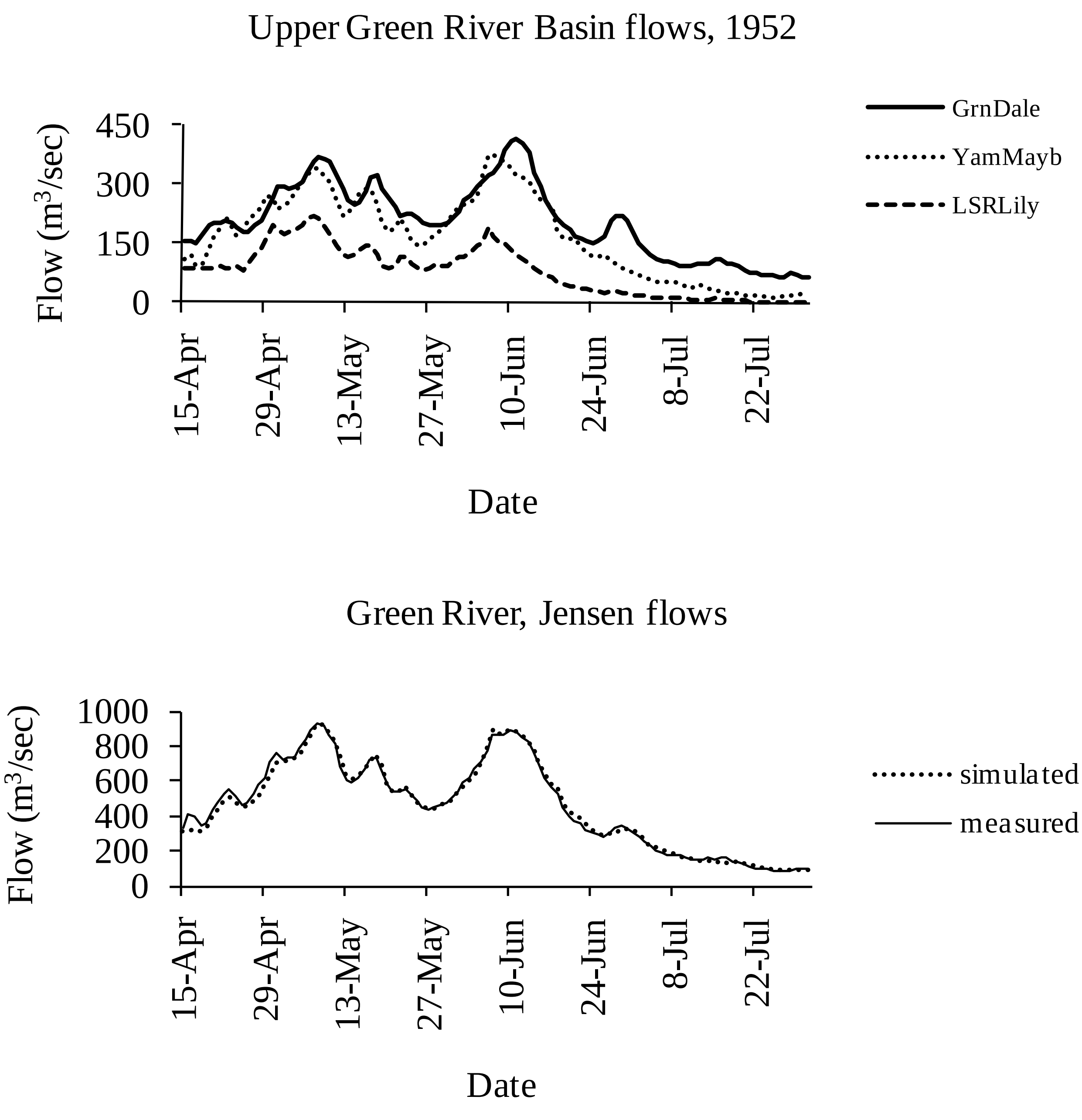


Figure 6. Flows of the Little Snake River, near Lily, Colorado (LSRLily, U. S. Gelogical Survey gauge # 09260000), the Yampa River, near Maybell, Colorado (YamMayb, gauge # 09251000), and the Green River near Greendale, Utah (GrnDale, gauge # 09234500) in 1952 (upper panel). Lower panel depicts measured Green River flows at Jensen, Utah (gauge # 09261000) compared to those simulated using a flow routing model.

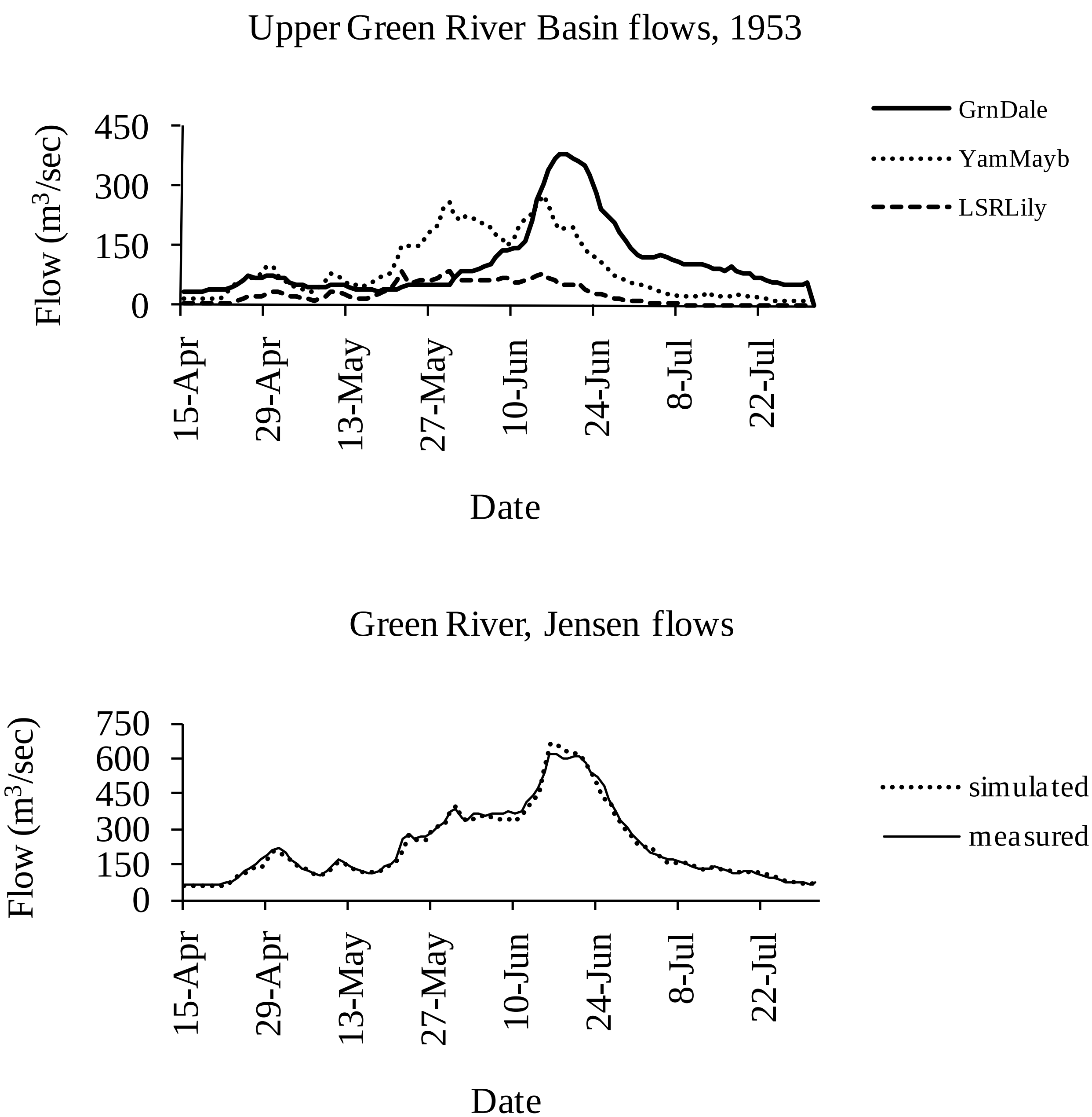
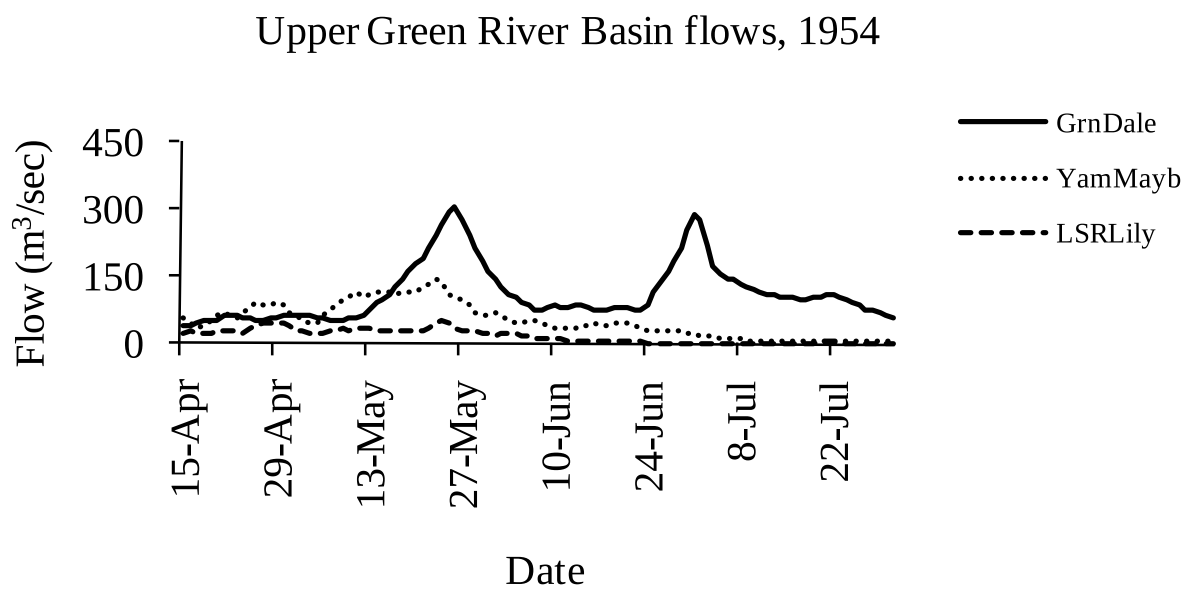


Figure 7. Flows of the Little Snake River, near Lily, Colorado (LSRLily, U. S. Gelogical Survey gauge # 09260000), the Yampa River, near Maybell, Colorado (YamMayb, gauge # 09251000), and the Green River near Greendale, Utah (GrnDale, gauge # 09234500) in 1953 (upper panel). Lower panel depicts measured Green River flows at Jensen, Utah (gauge # 09261000) compared to those simulated using a flow routing model.



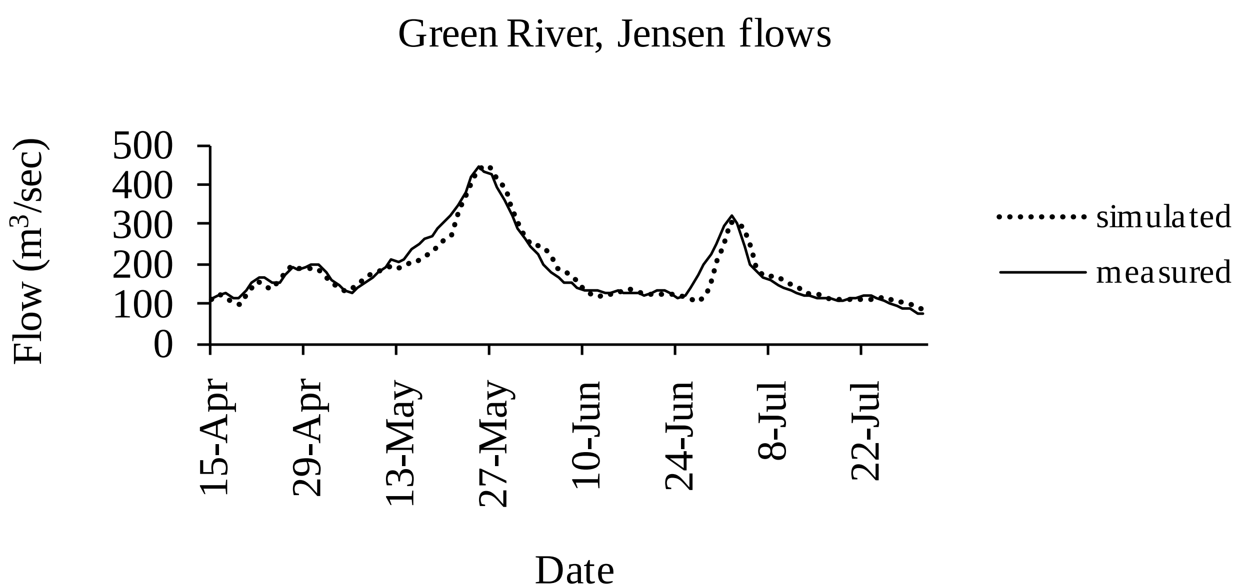
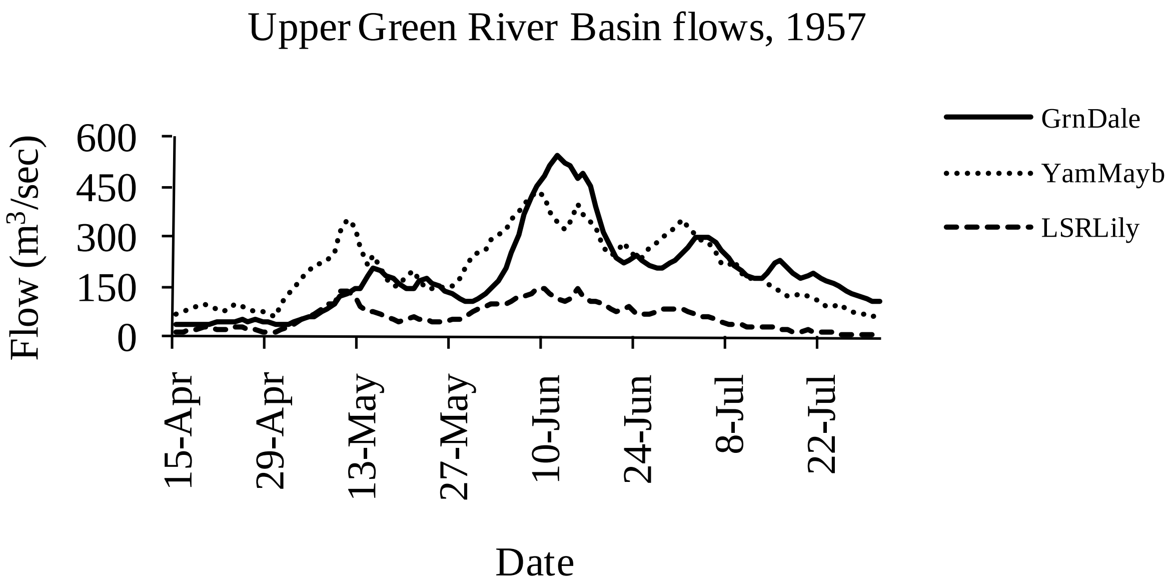


Figure 8. Flows of the Little Snake River, near Lily, Colorado (LSRLily, U. S. Gelogical Survey gauge # 09260000), the Yampa River, near Maybell, Colorado (YamMayb, gauge # 09251000), and the Green River near Greendale, Utah (GrnDale, gauge # 09234500) in 1954 (upper panel). Lower panel depicts measured Green River flows at Jensen, Utah (gauge # 09261000) compared to those simulated using a flow routing model.



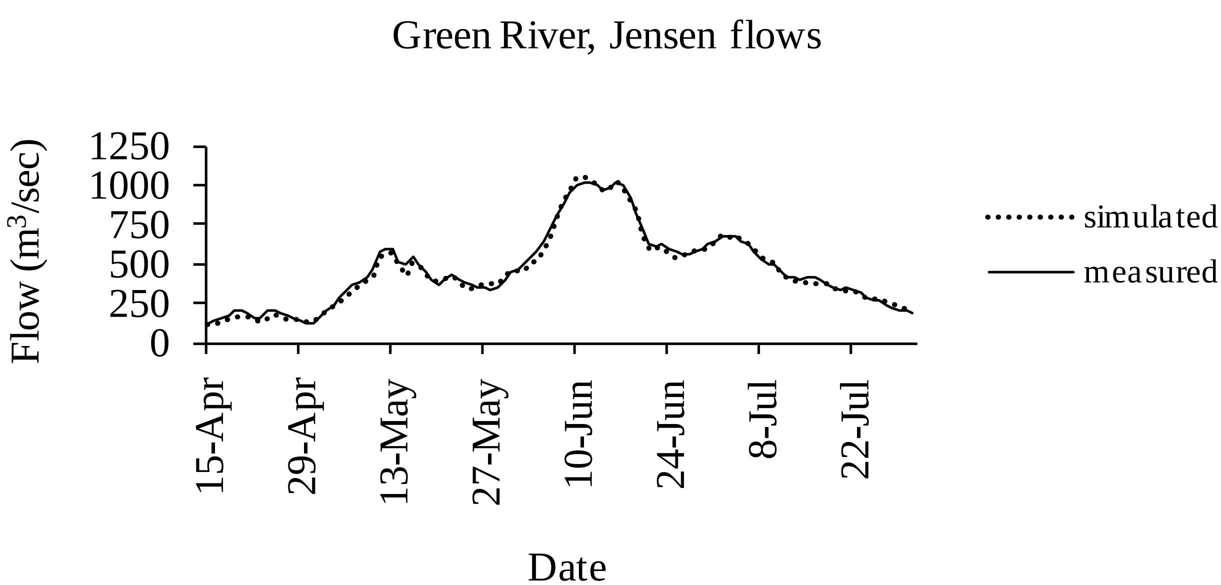
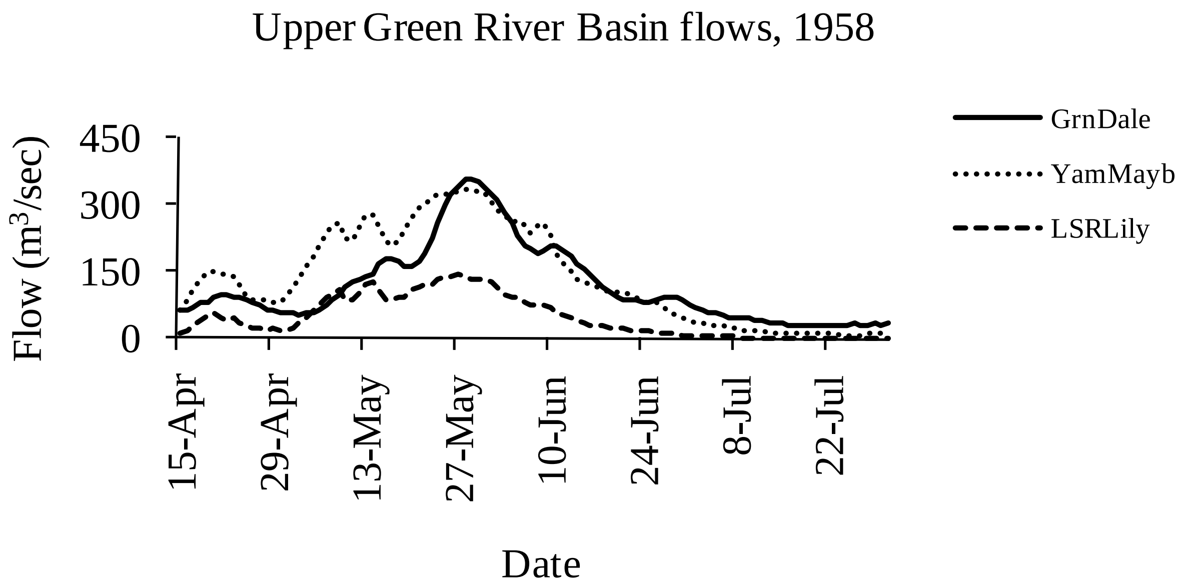


Figure 9. Flows of the Little Snake River, near Lily, Colorado (LSRLily, U. S. Gelogical Survey gauge # 09260000), the Yampa River, near Maybell, Colorado (YamMayb, gauge # 09251000), and the Green River near Greendale, Utah (GrnDale, gauge # 09234500) in 1957 (upper panel). Lower panel depicts measured Green River flows at Jensen, Utah (gauge # 09261000) compared to those simulated using a flow routing model.



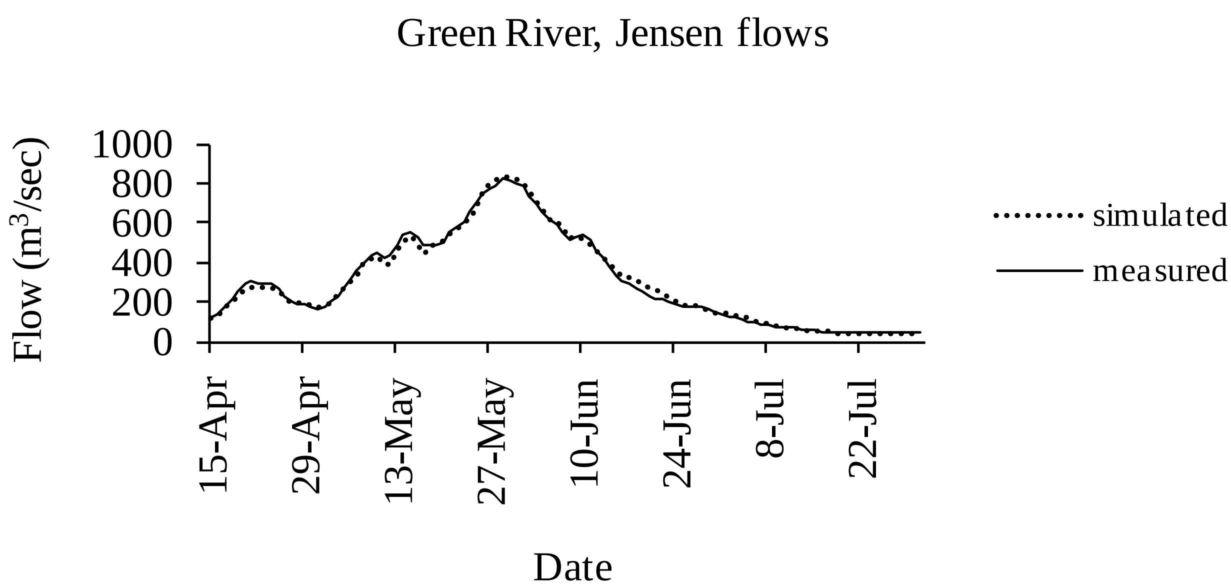


Figure 10. Flows of the Little Snake River, near Lily, Colorado (LSRLily, U. S. Gelogical Survey gauge # 09260000), the Yampa River, near Maybell, Colorado (YamMayb, gauge # 09251000), and the Green River near Greendale, Utah (GrnDale, gauge # 09234500) in 1958 (upper panel). Lower panel depicts measured Green River flows at Jensen, Utah (gauge # 09261000) compared to those simulated using a flow routing model.

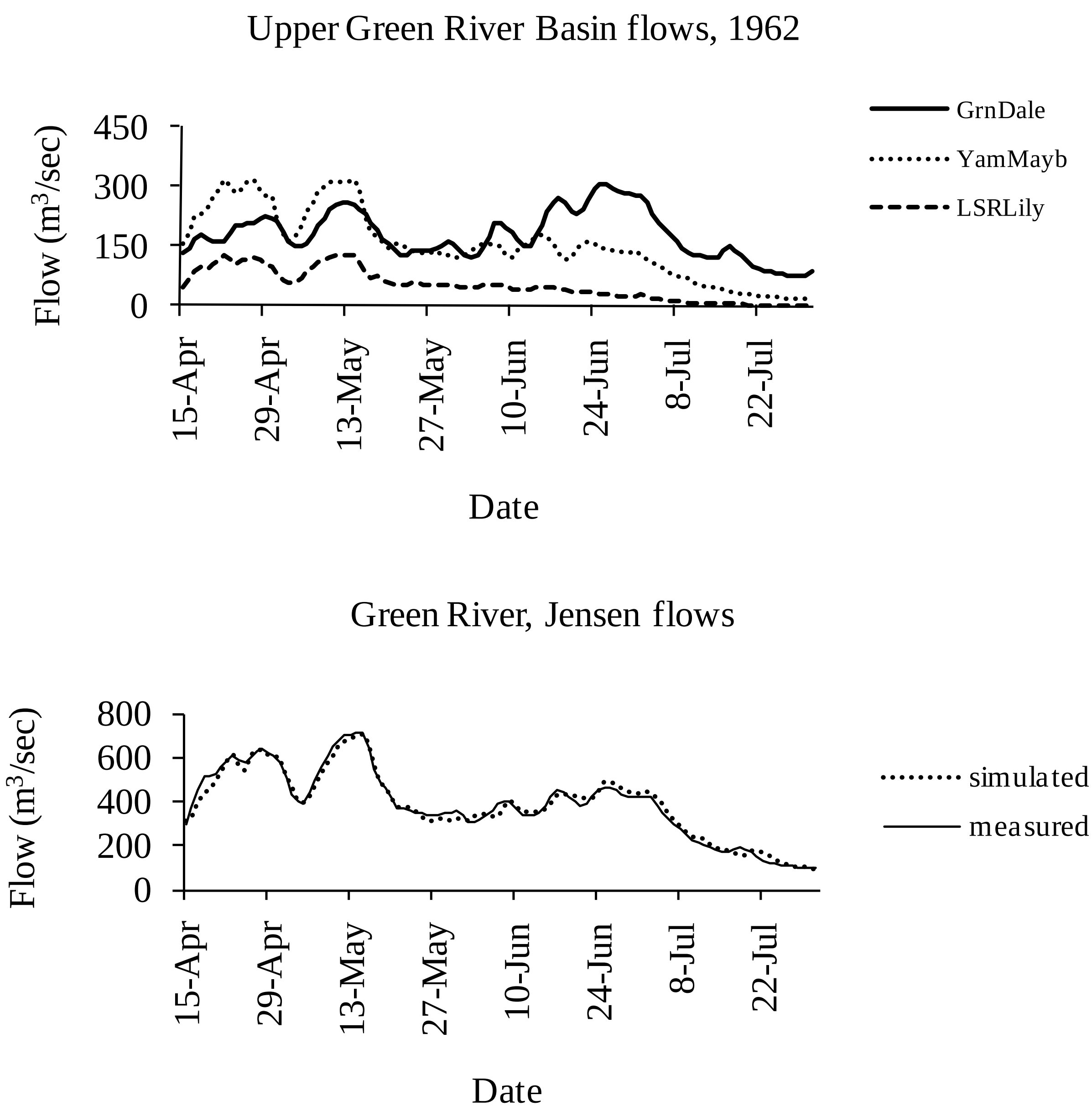


Figure 11. Flows of the Little Snake River, near Lily, Colorado (LSRLily, U. S. Gelogical Survey gauge # 09260000), the Yampa River, near Maybell, Colorado (YamMayb, gauge # 09251000), and the Green River near Greendale, Utah (GrnDale, gauge # 09234500) in 1962 (upper panel). Lower panel depicts measured Green River flows at Jensen, Utah (gauge # 09261000) compared to those simulated using a flow routing model.

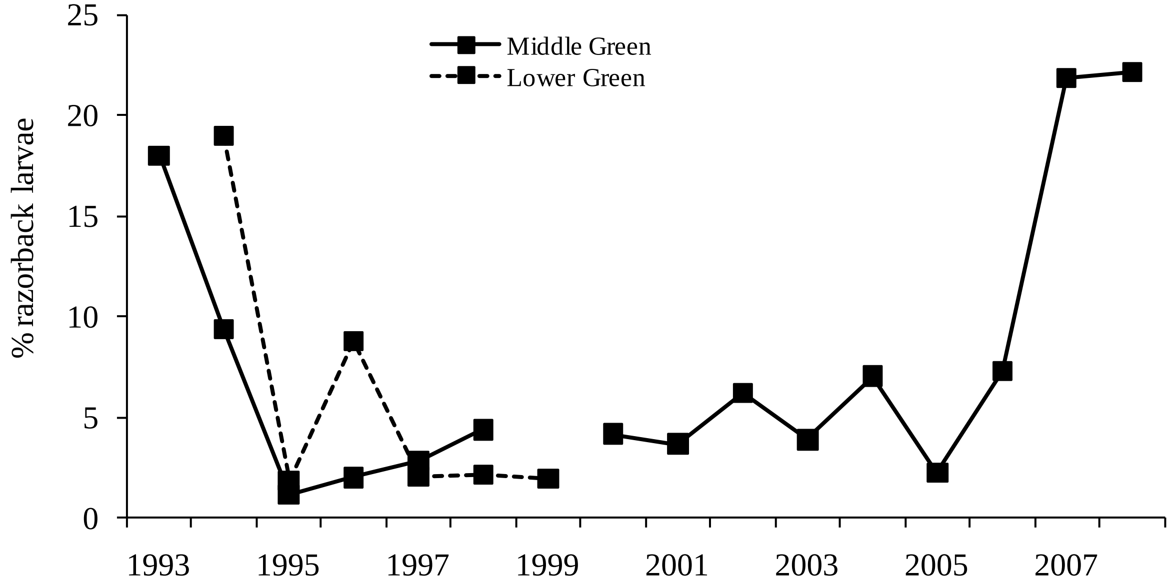


Figure 12. Percent wild razorback sucker larvae relative to total number of native catostomid larvae captured in light trap samples in the middle and lower Green River, Utah, 1993-2008.

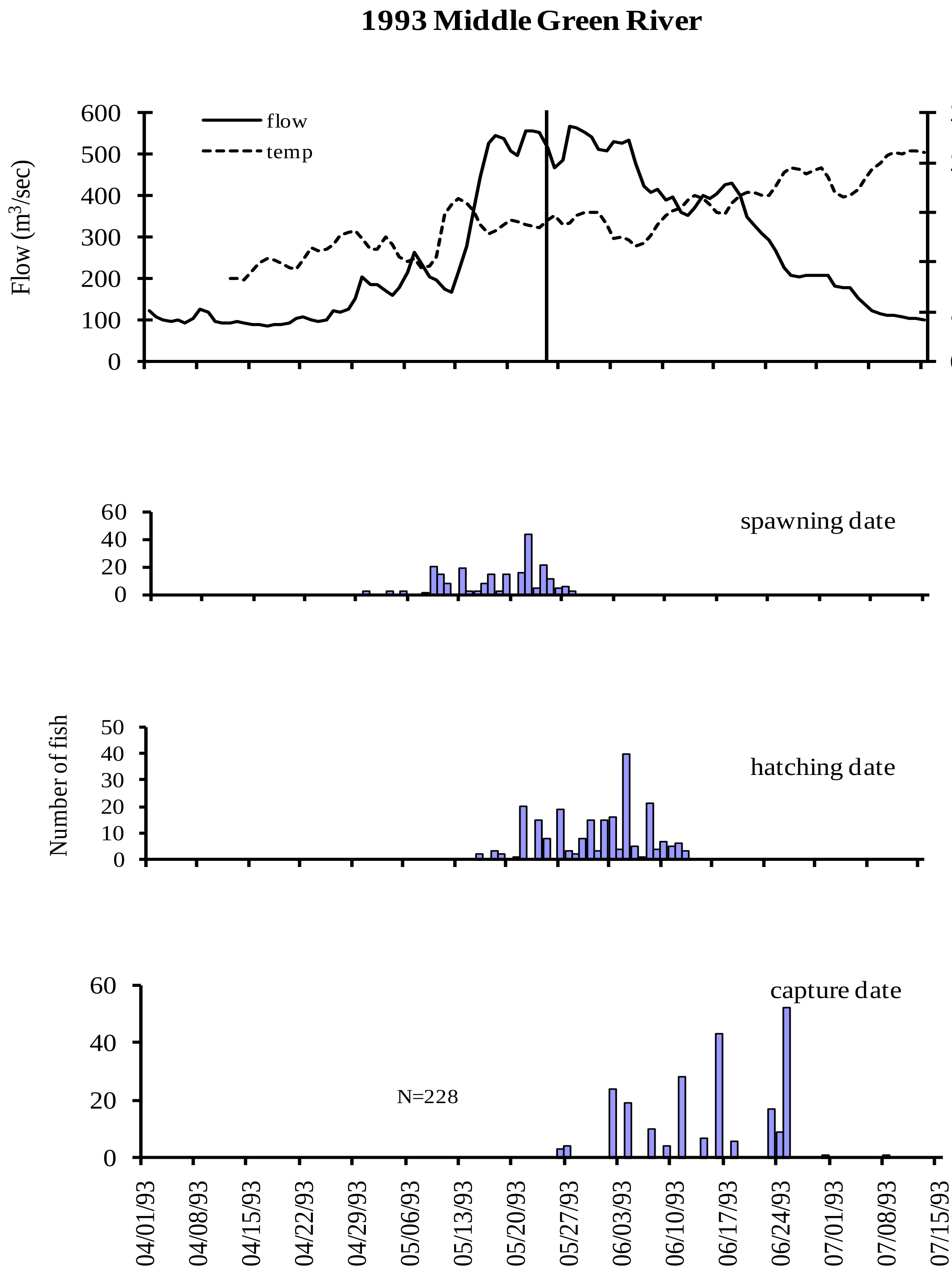


Figure 13. Capture and otolith-age-estimated hatching and spawning date distributions for razorback sucker larvae captured in light trap samples collected in the middle Green River, Utah, 1993. Flow and water temperatures of the Green River overlie distributions to show timing related to environmental factors. Vertical line in top panel indicates time of first presence of larvae.

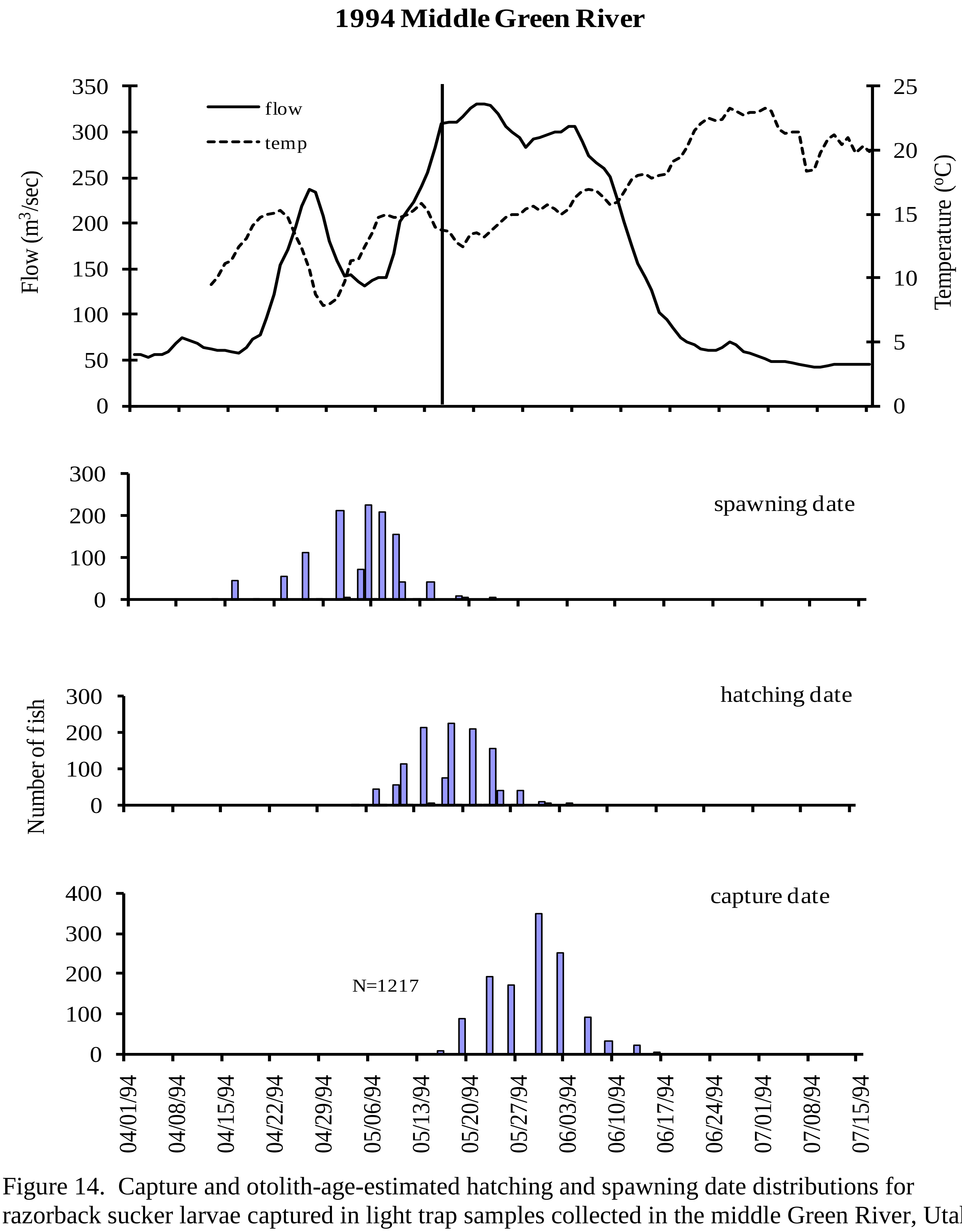


Figure 14. Capture and otolith-age-estimated hatching and spawning date distributions for razorback sucker larvae captured in light trap samples collected in the middle Green River, Utah, 1994. Flow and water temperatures of the Green River overlie distributions to show timing related to environmental factors. Vertical line in top panel indicates time of first presence of larvae.

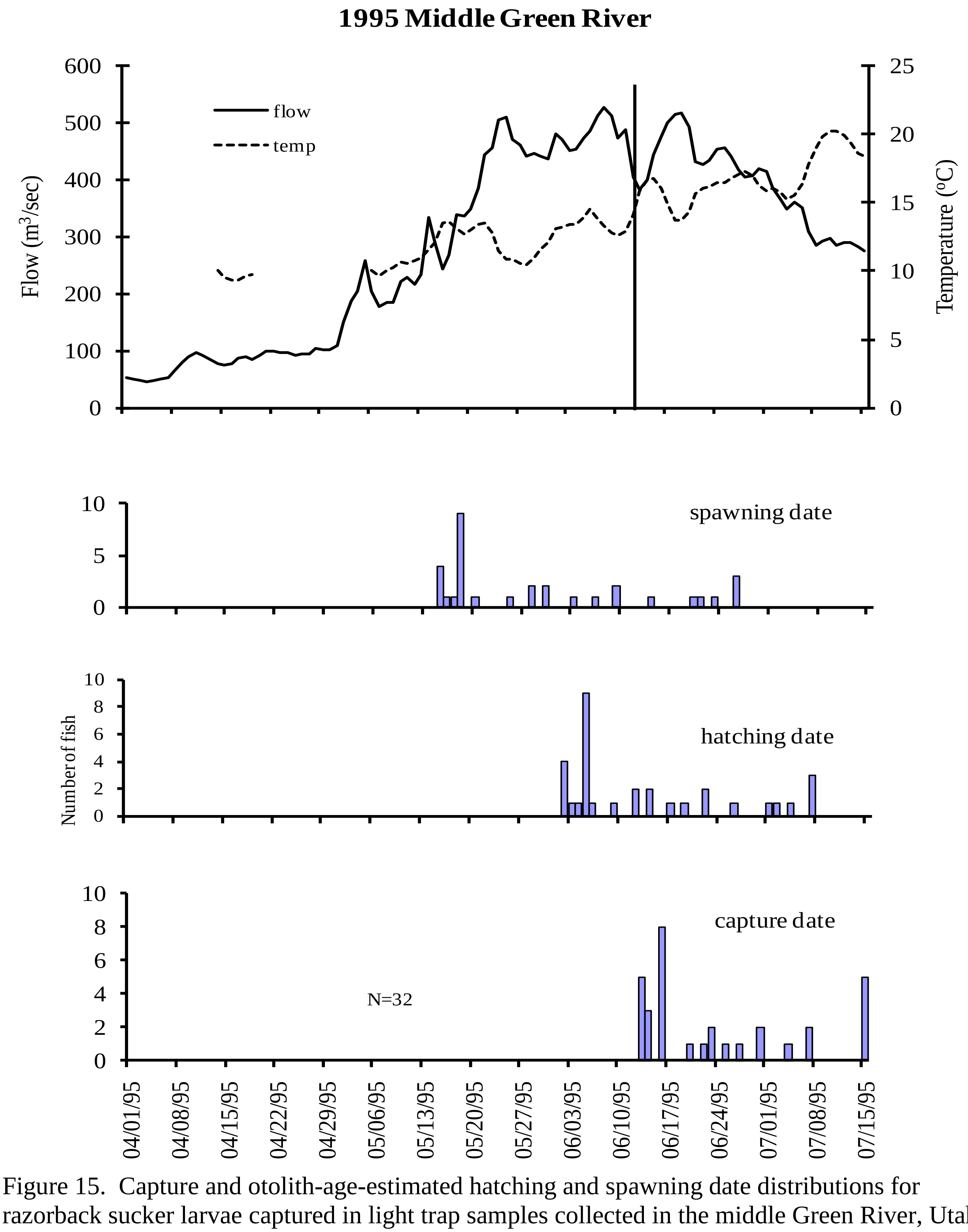


Figure 15. Capture and otolith-age-estimated hatching and spawning date distributions for razorback sucker larvae captured in light trap samples collected in the middle Green River, Utah, 1995. Flow and water temperatures of the Green River overlie distributions to show timing related to environmental factors. Vertical line in top panel indicates time of first presence of larvae.

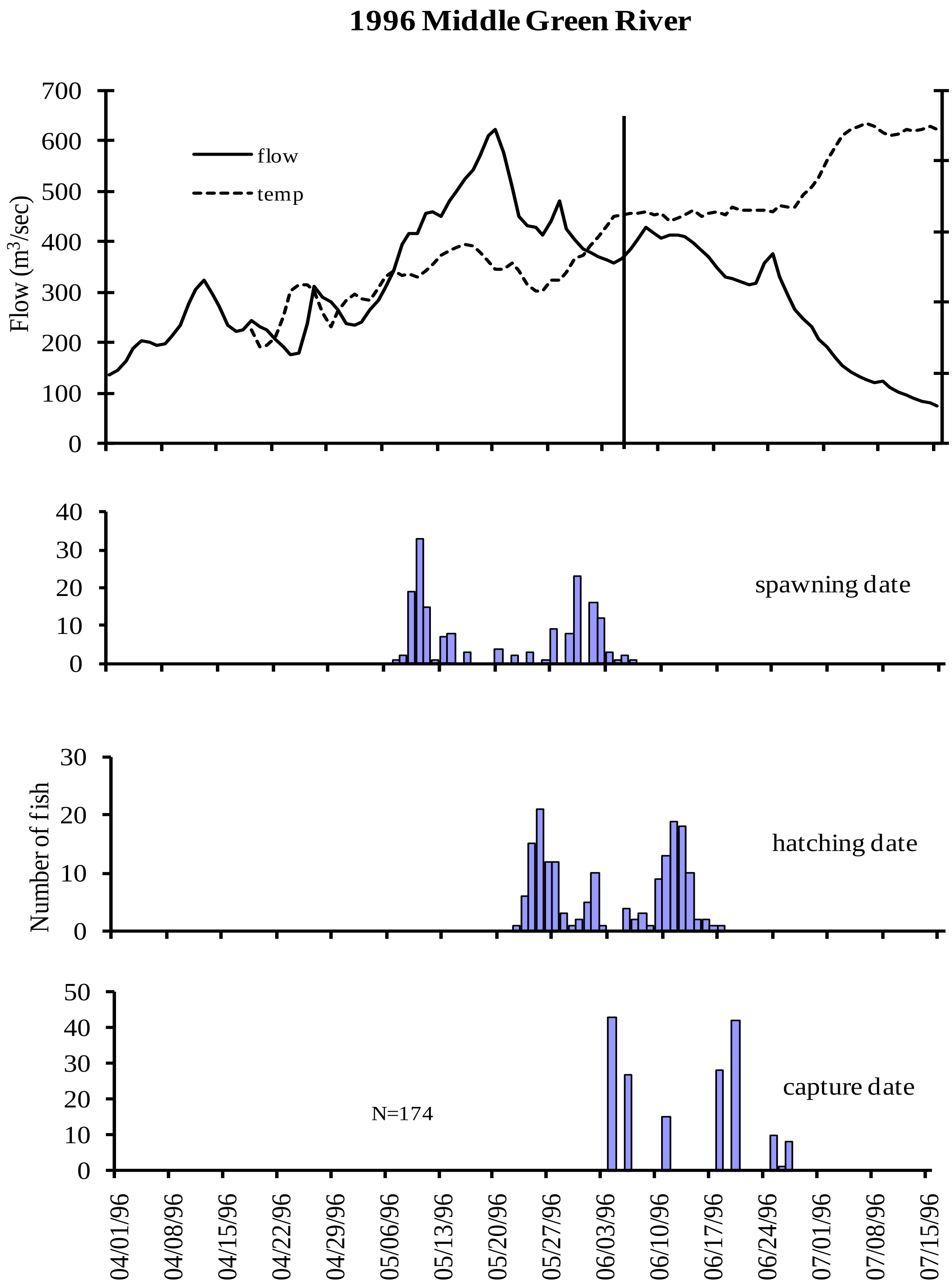


Figure16. Capture and otolith-age-estimated hatching and spawning date distributions for razorback sucker larvae captured in light trap samples collected in the middle Green River, Utah, 1996. Flow and water temperatures of the Green River overlie distributions to show timing related to environmental factors. Vertical line in top panel indicates time of first presence of larvae.

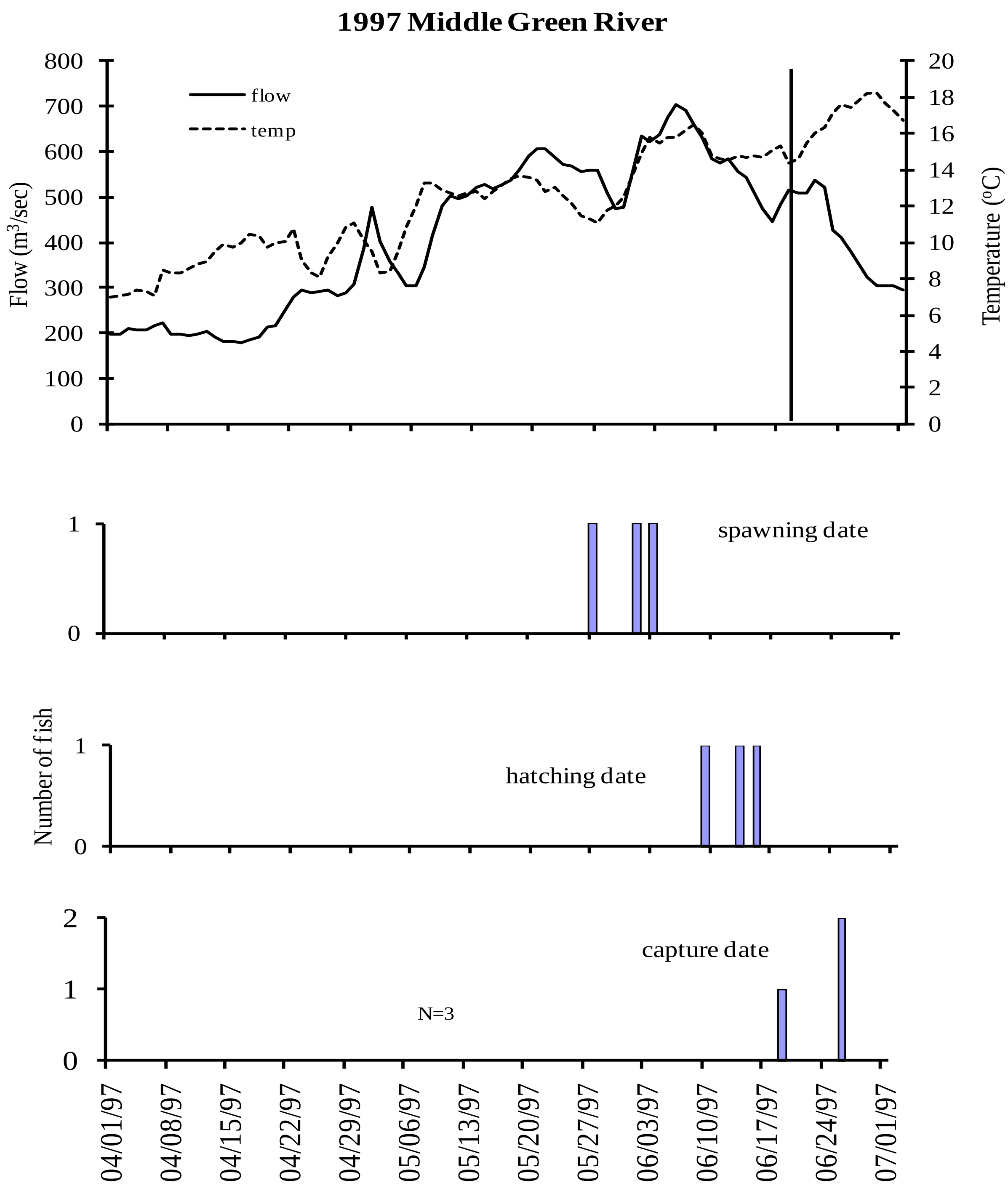


Figure 17. Capture and otolith-age-estimated hatching and spawning date distributions for razorback sucker larvae captured in light trap samples collected in the middle Green River, Utah, 1997. Flow and water temperatures of the Green River overlie distributions to show timing related to environmental factors. Vertical line in top panel indicates time of first presence of larvae.

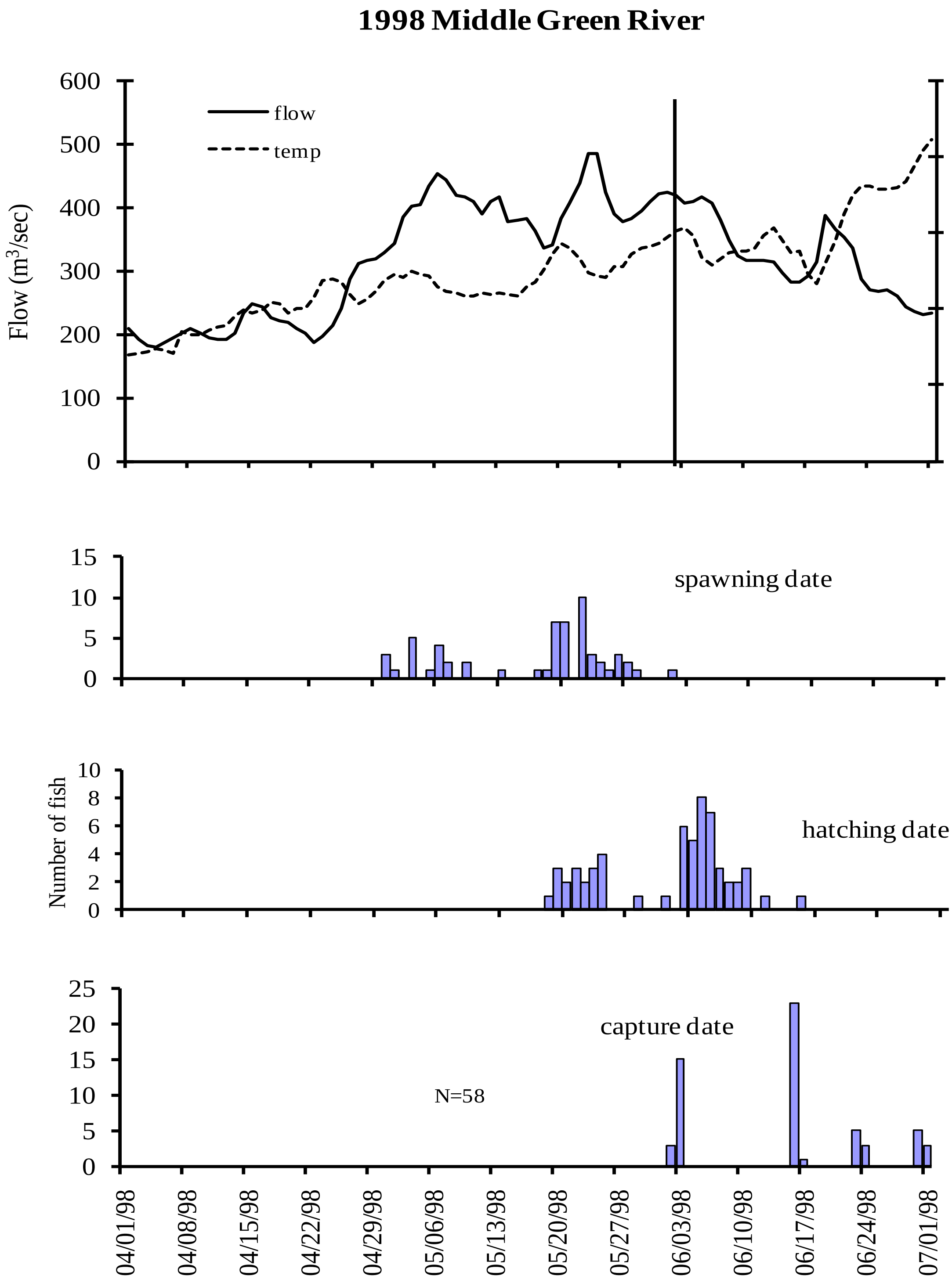


Figure 18. Capture and otolith-age-estimated hatching and spawning date distributions for razorback sucker larvae captured in light trap samples collected in the middle Green River, Utah, 1998. Flow and water temperatures of the Green River overlie distributions to show timing related to environmental factors. Vertical line in top panel indicates time of first presence of larvae.

1999 Middle Green River

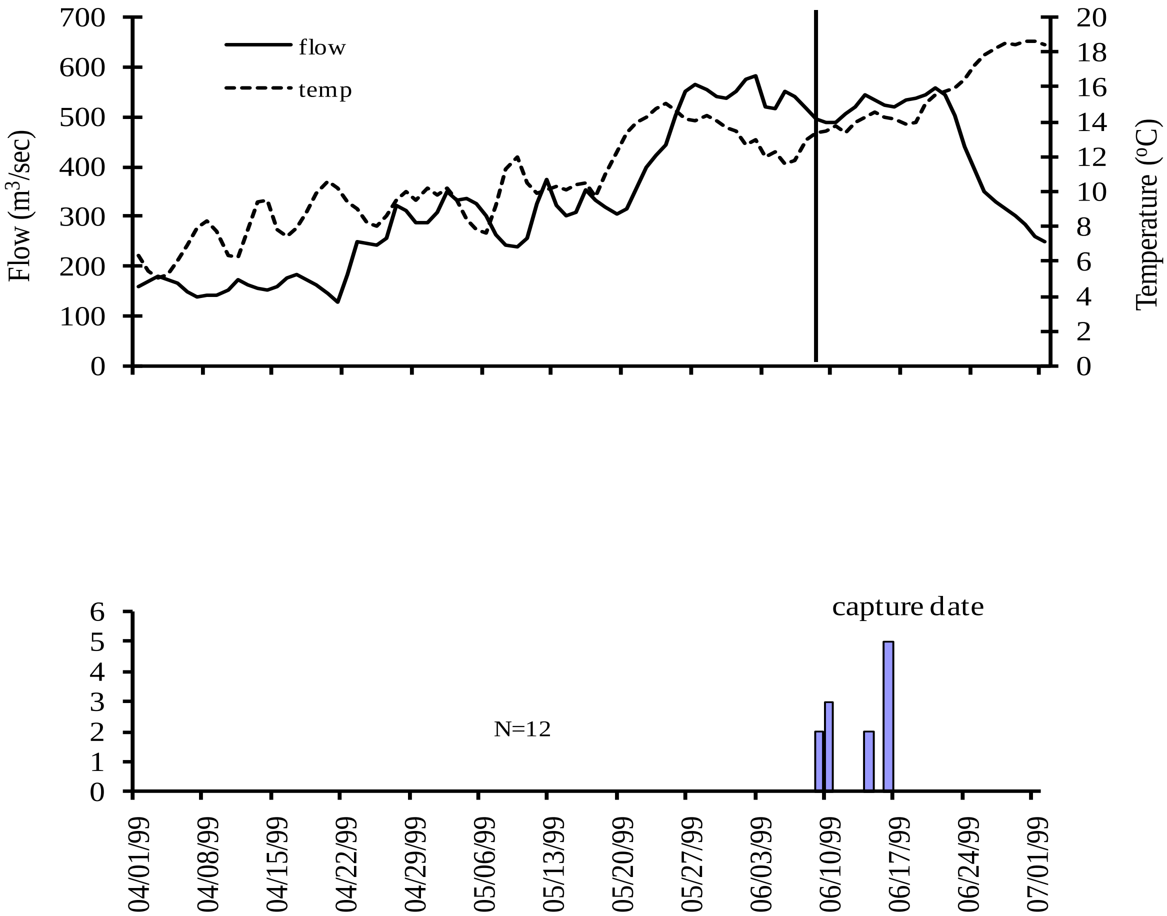


Figure 19. Capture and otolith-age-estimated hatching and spawning date distributions for razorback sucker larvae captured in light trap samples collected in the middle Green River, Utah, 1999. Flow and water temperatures of the Green River overlie distributions to show timing related to environmental factors. Only capture dates for larvae are shown because (12) all were taken to the hatchery for rearing for potential brood stock. Vertical line in top panel indicates time of first presence of larvae.

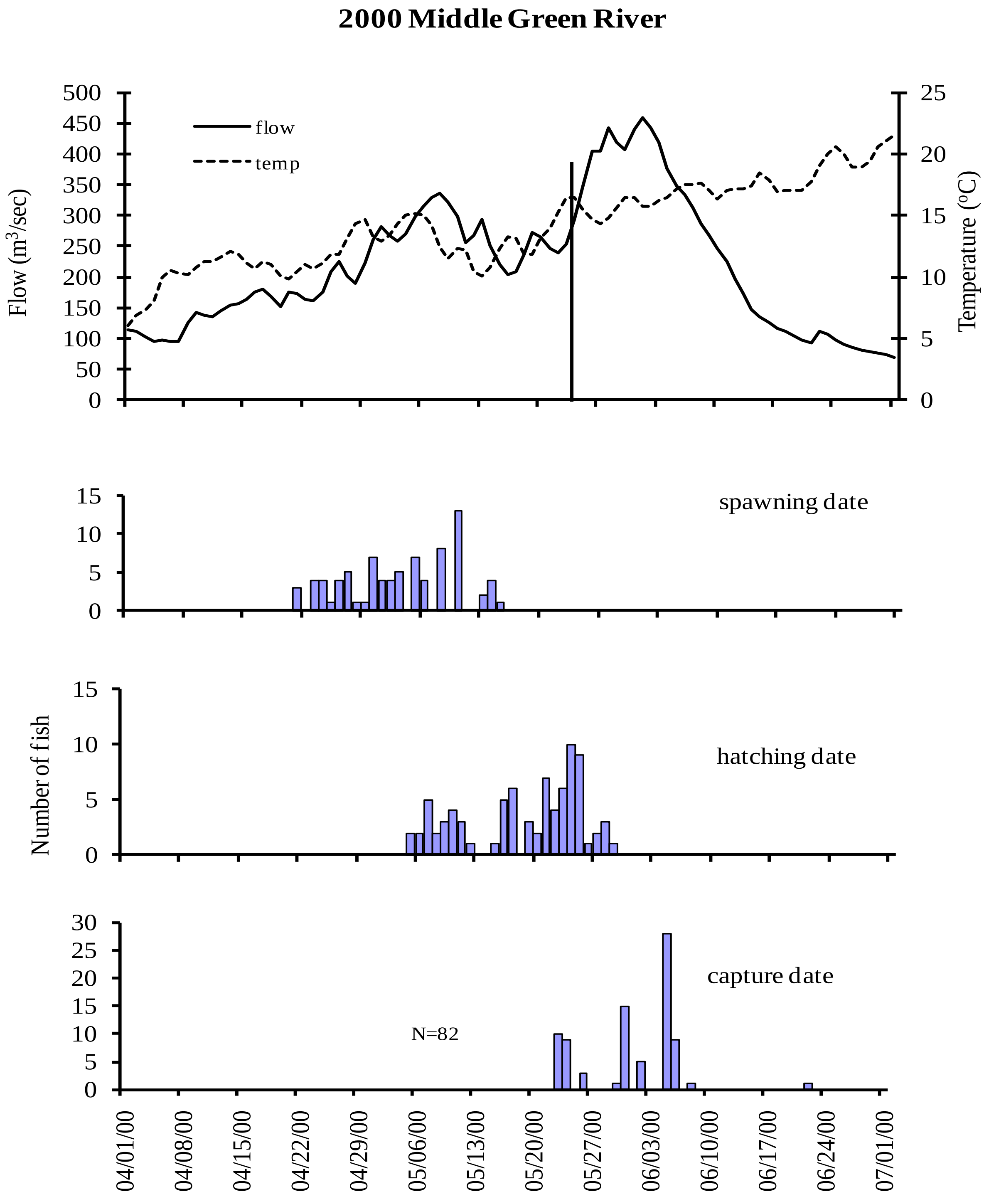


Figure 20. Capture and otolith-age-estimated hatching and spawning date distributions for razorback sucker larvae captured in light trap samples collected in the middle Green River, Utah, 2000. Flow and water temperatures of the Green River overlie distributions to show timing related to environmental factors. Vertical line in top panel indicates time of first presence of larvae.

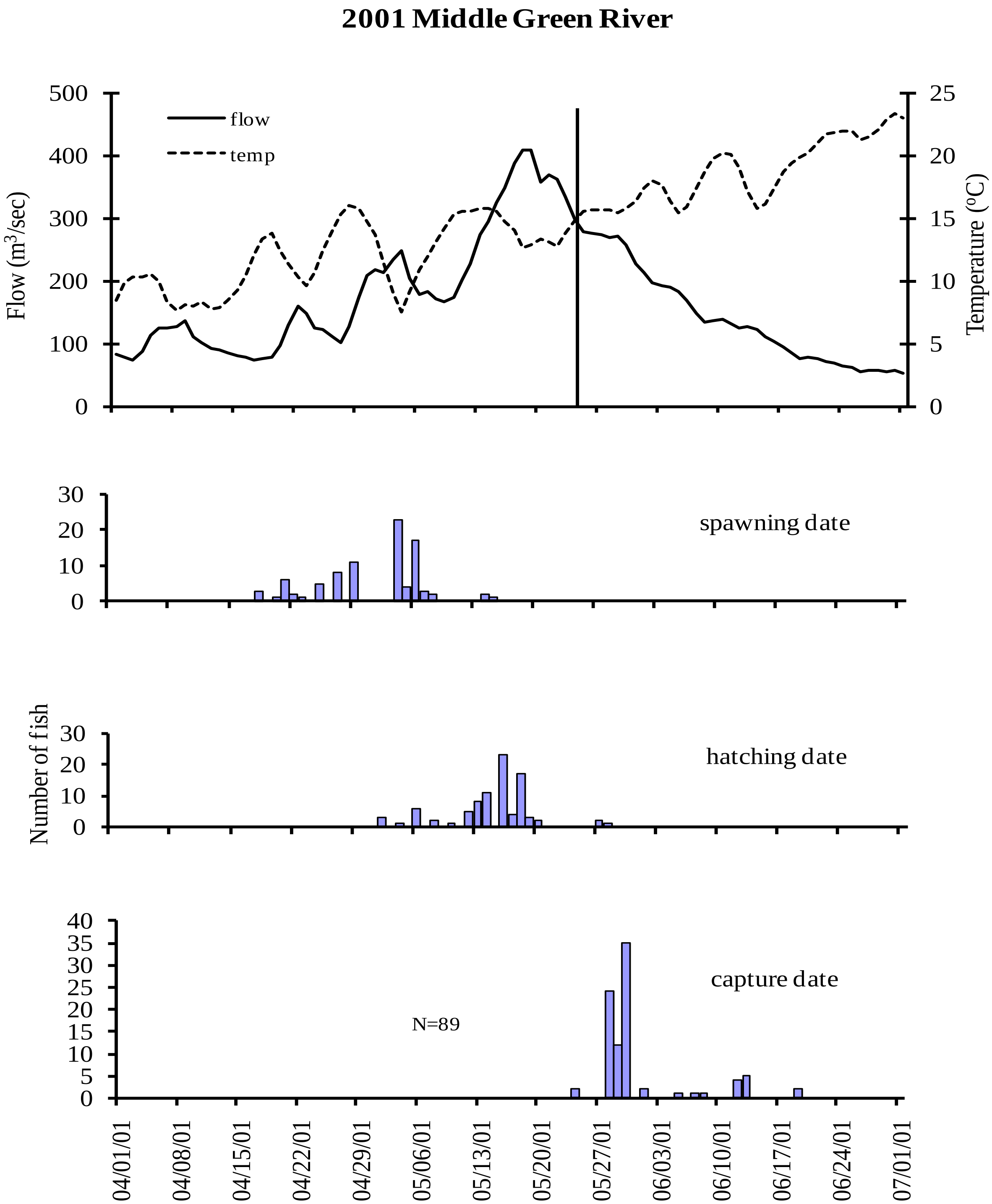


Figure 21. Capture and otolith-age-estimated hatching and spawning date distributions for razorback sucker larvae captured in light trap samples collected in the middle Green River, Utah, 2001. Flow and water temperatures of the Green River overlie distributions to show timing related to environmental factors. Vertical line in top panel indicates time of first presence of larvae.

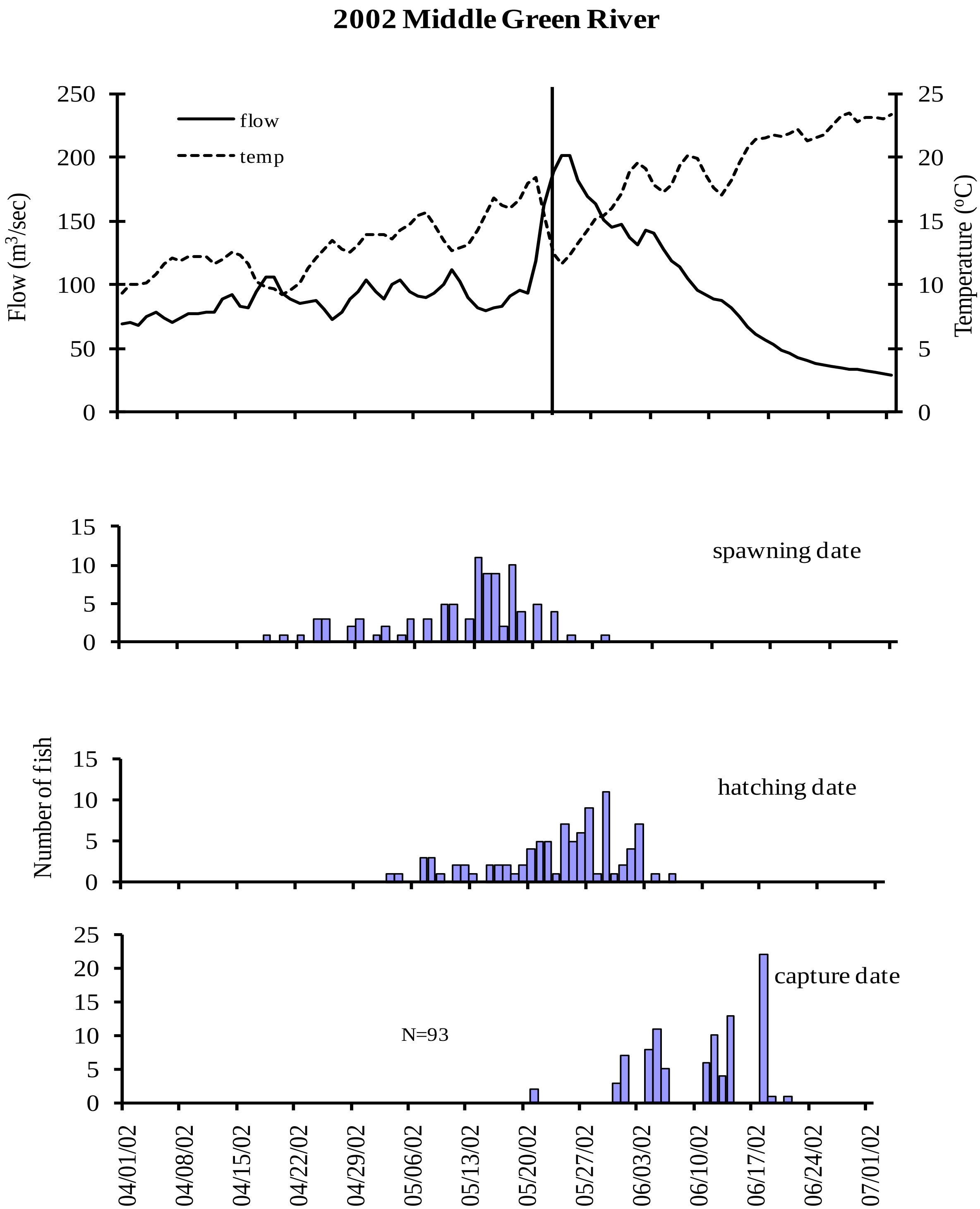


Figure 22. Capture and otolith-age-estimated hatching and spawning date distributions for razorback sucker larvae captured in light trap samples collected in the middle Green River, Utah, 2002. Flow and water temperatures of the Green River overlie distributions to show timing related to environmental factors. Vertical line in top panel indicates time of first presence of larvae.

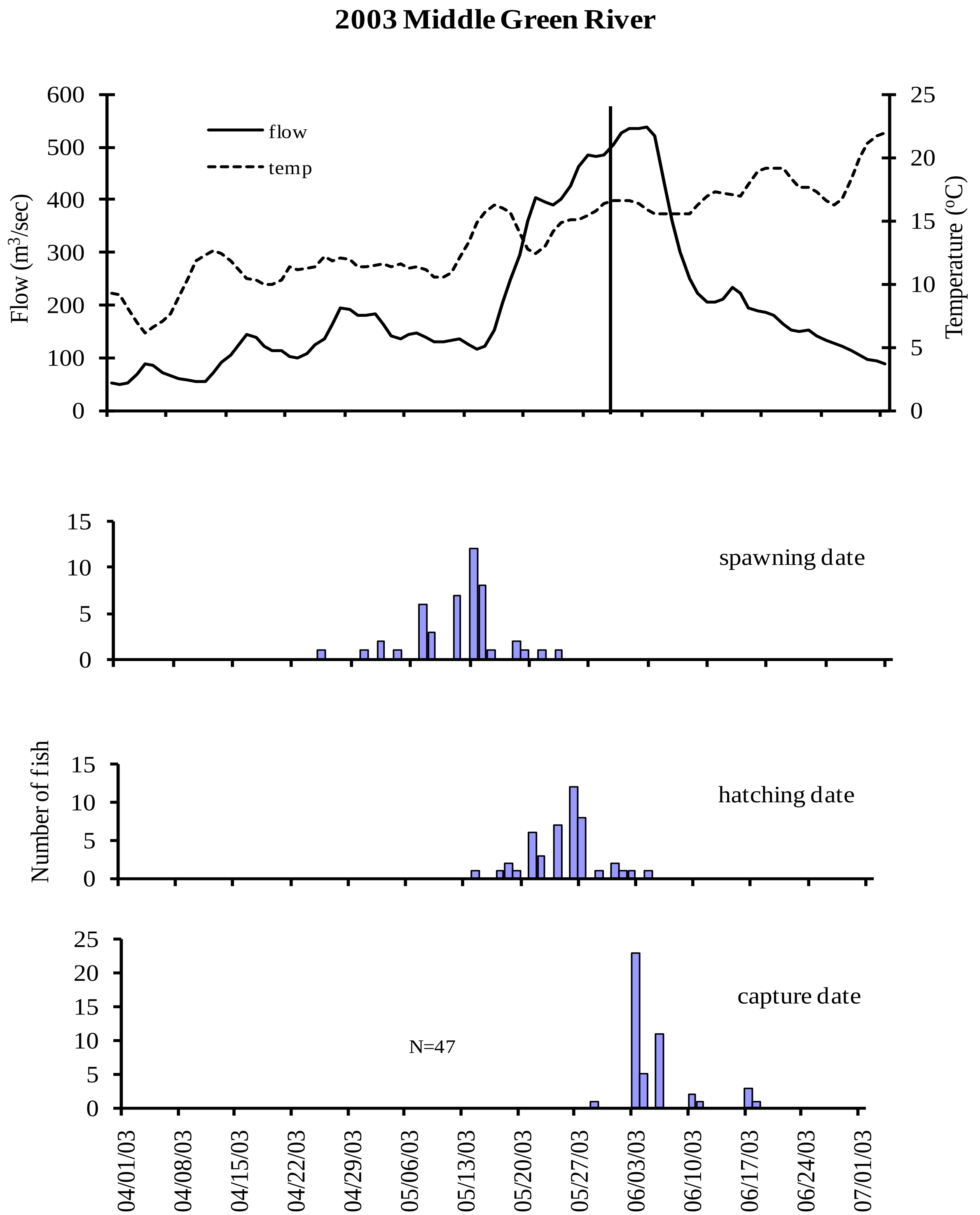


Figure 23. Capture and otolith-age-estimated hatching and spawning date distributions for razorback sucker larvae captured in light trap samples collected in the middle Green River, Utah, 2003. Flow and water temperatures of the Green River overlie distributions to show timing related to environmental factors. Vertical line in top panel indicates time of first presence of larvae.

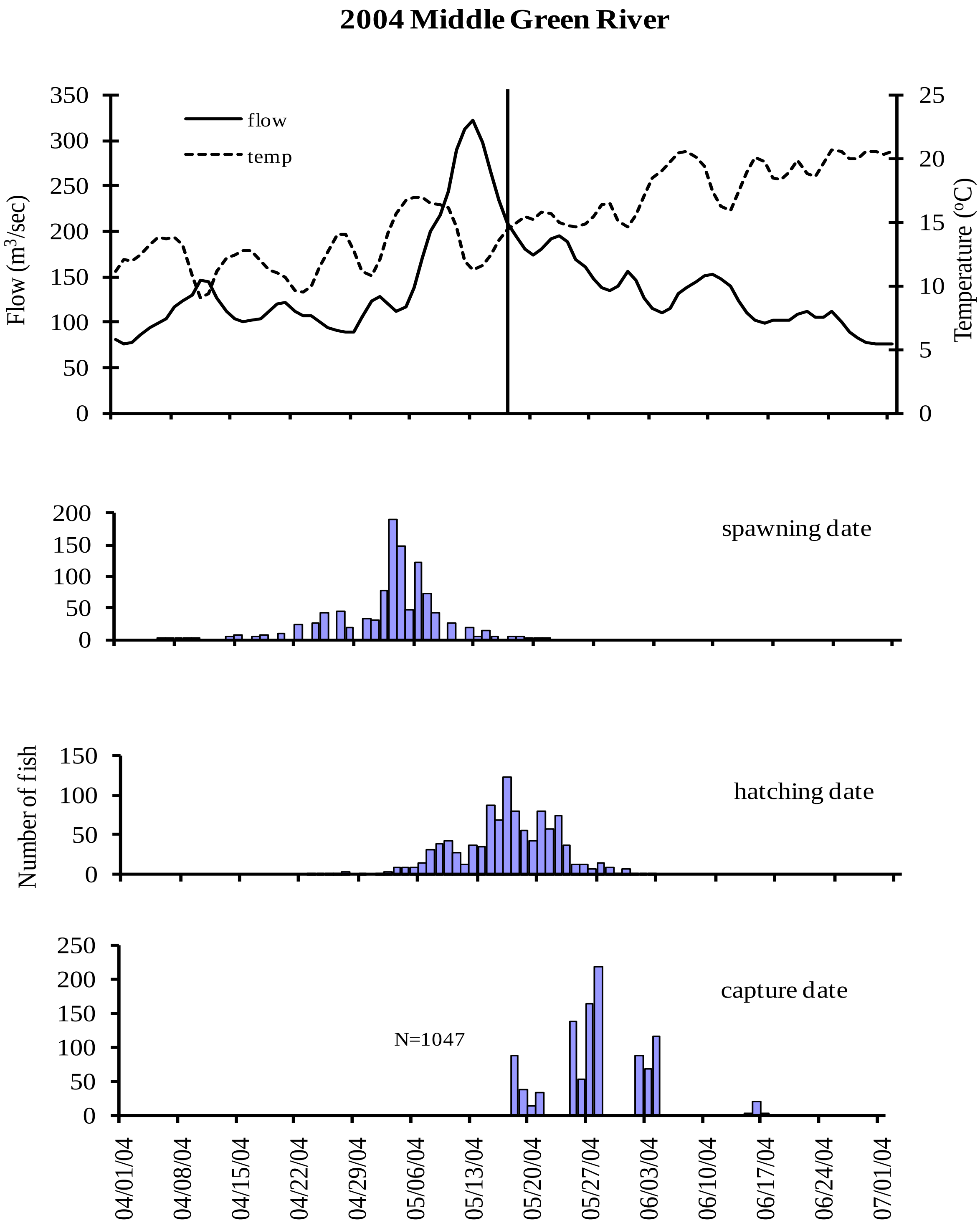


Figure 24. Capture and otolith-age-estimated hatching and spawning date distributions for razorback sucker larvae captured in light trap samples collected in the middle Green River, Utah, 2004. Flow and water temperatures of the Green River overlie distributions to show timing related to environmental factors. Vertical line in top panel indicates time of first presence of larvae.

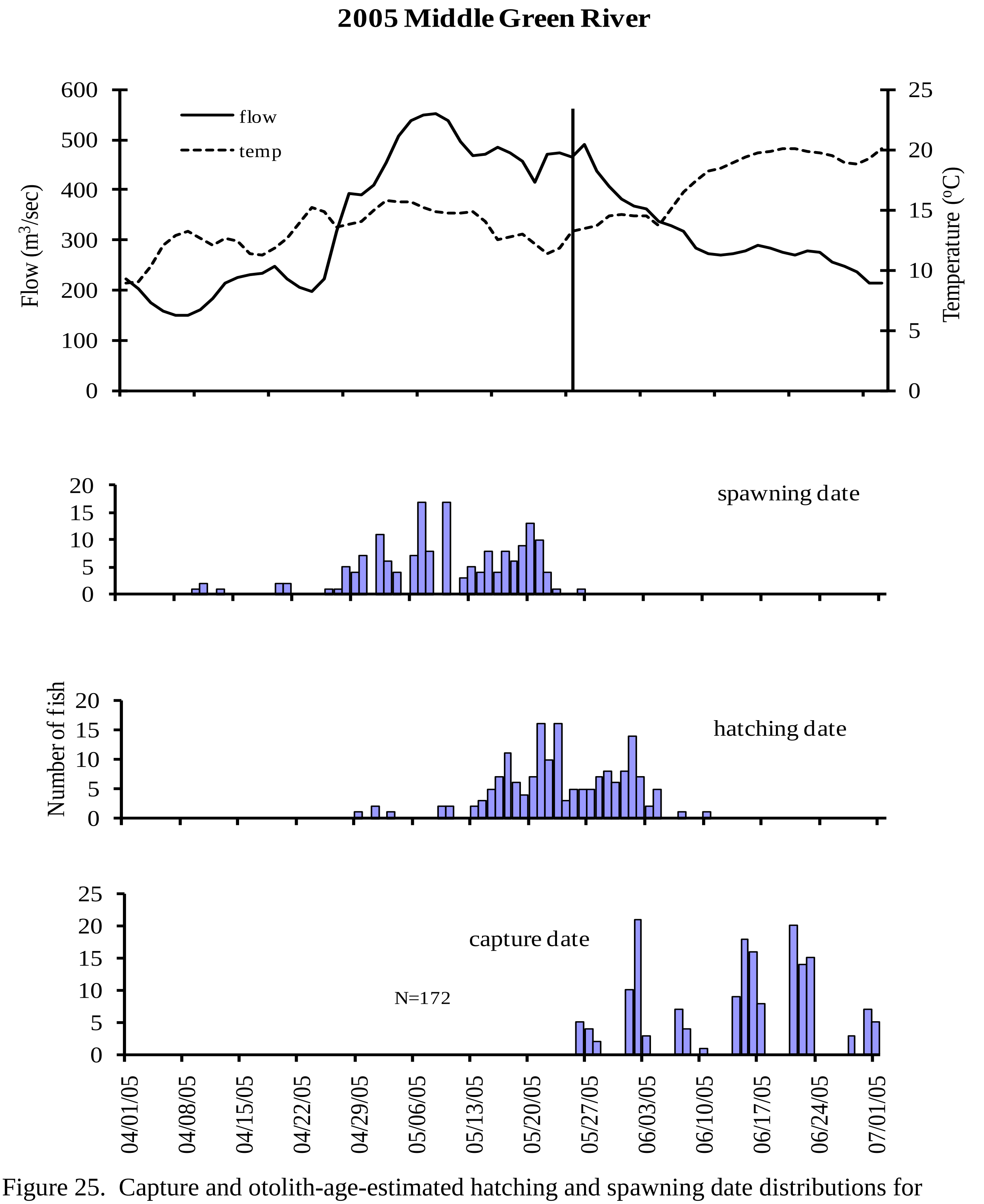


Figure 25. Capture and otolith-age-estimated hatching and spawning date distributions for razorback sucker larvae captured in light trap samples collected in the middle Green River, Utah, 2005. Flow and water temperatures of the Green River overlie distributions to show timing related to environmental factors. Vertical line in top panel indicates time of first presence of larvae.

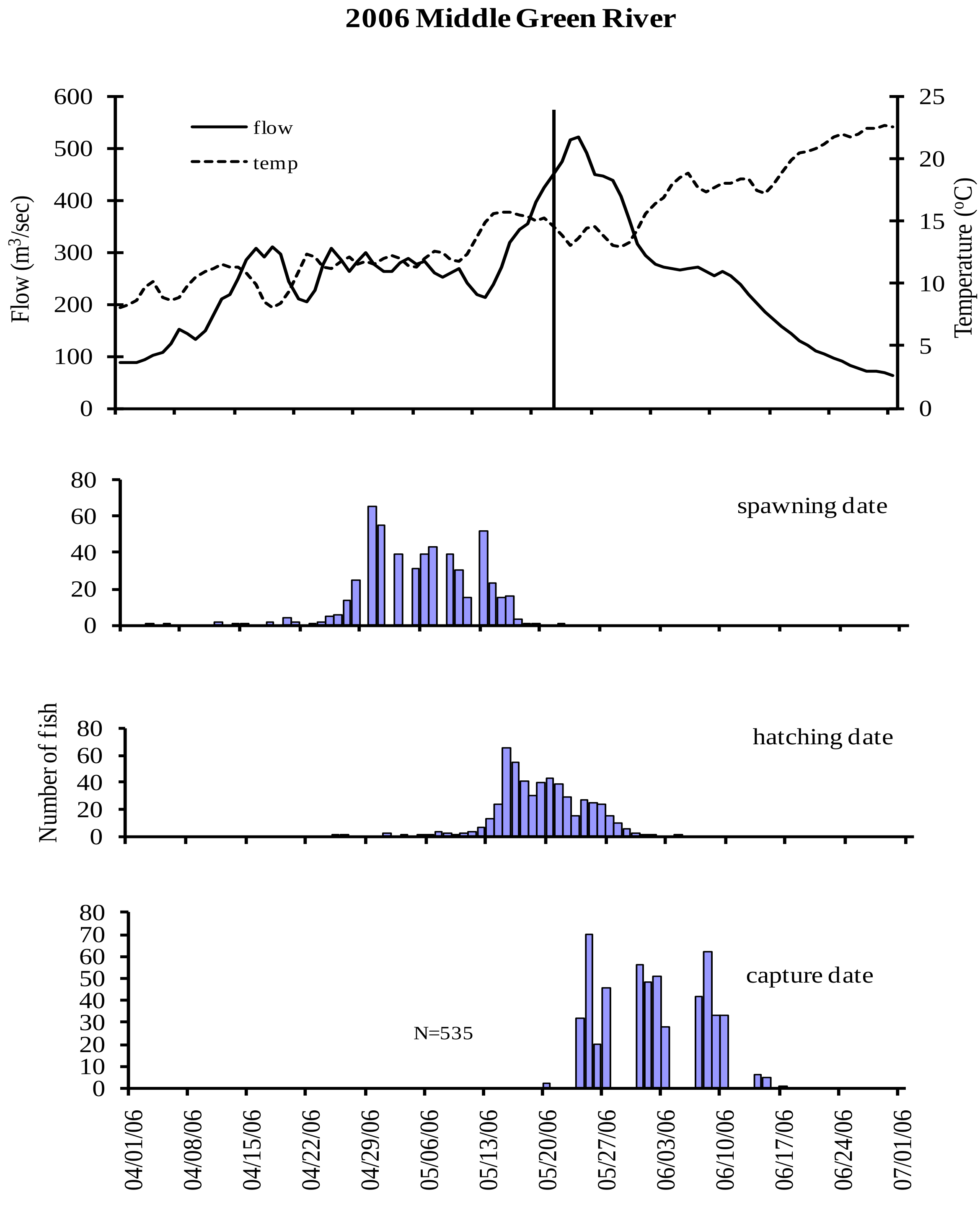


Figure 26. Capture and otolith-age-estimated hatching and spawning date distributions for razorback sucker larvae captured in light trap samples collected in the middle Green River, Utah, 2006. Flow and water temperatures of the Green River overlie distributions to show timing related to environmental factors. Vertical line in top panel indicates time of first presence of larvae.

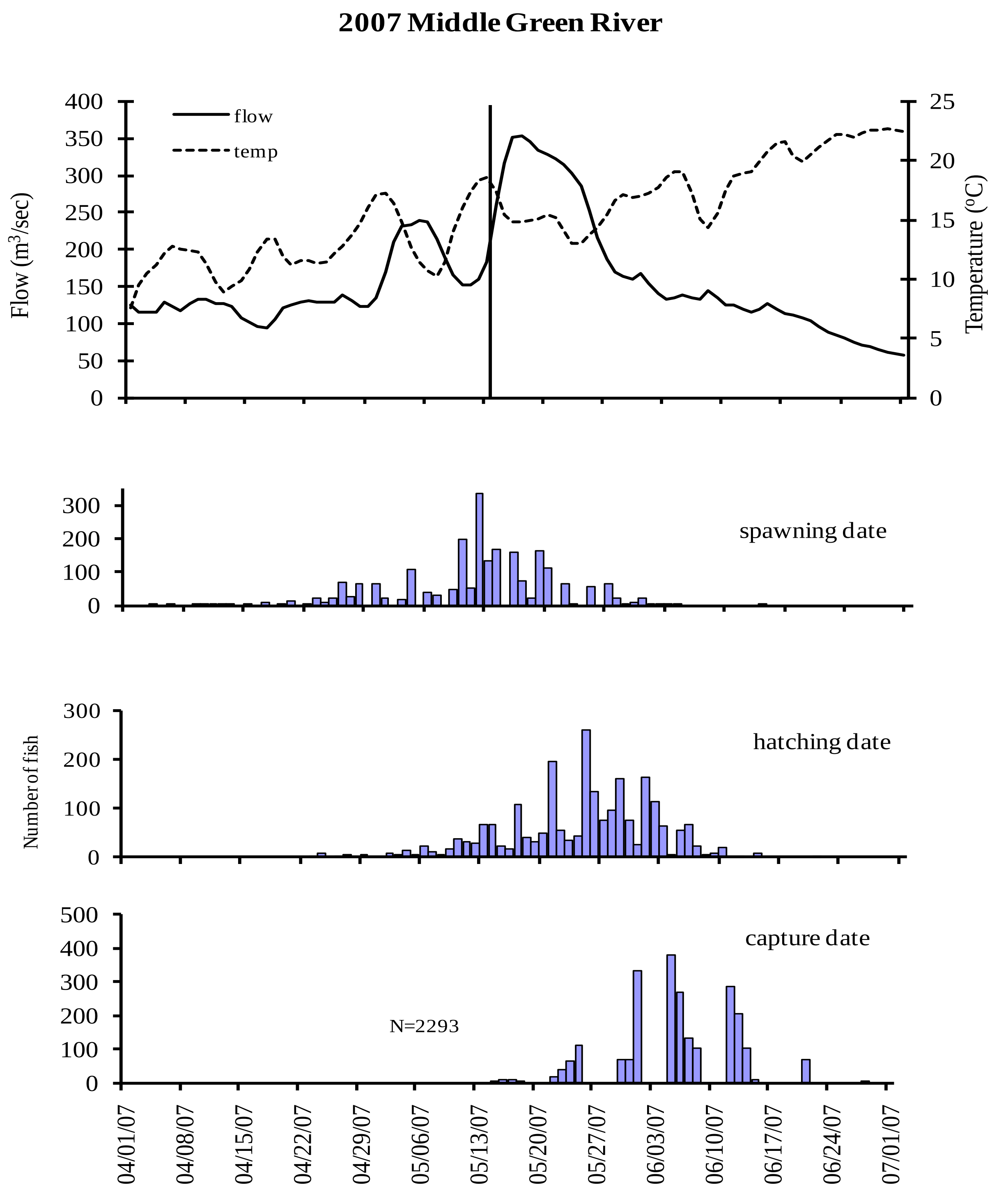


Figure 27. Capture and otolith-age-estimated hatching and spawning date distributions for razorback sucker larvae captured in light trap samples collected in the middle Green River, Utah, 2007. Flow and water temperatures of the Green River overlie distributions to show timing related to environmental factors. Vertical line in top panel indicates time of first presence of larvae.

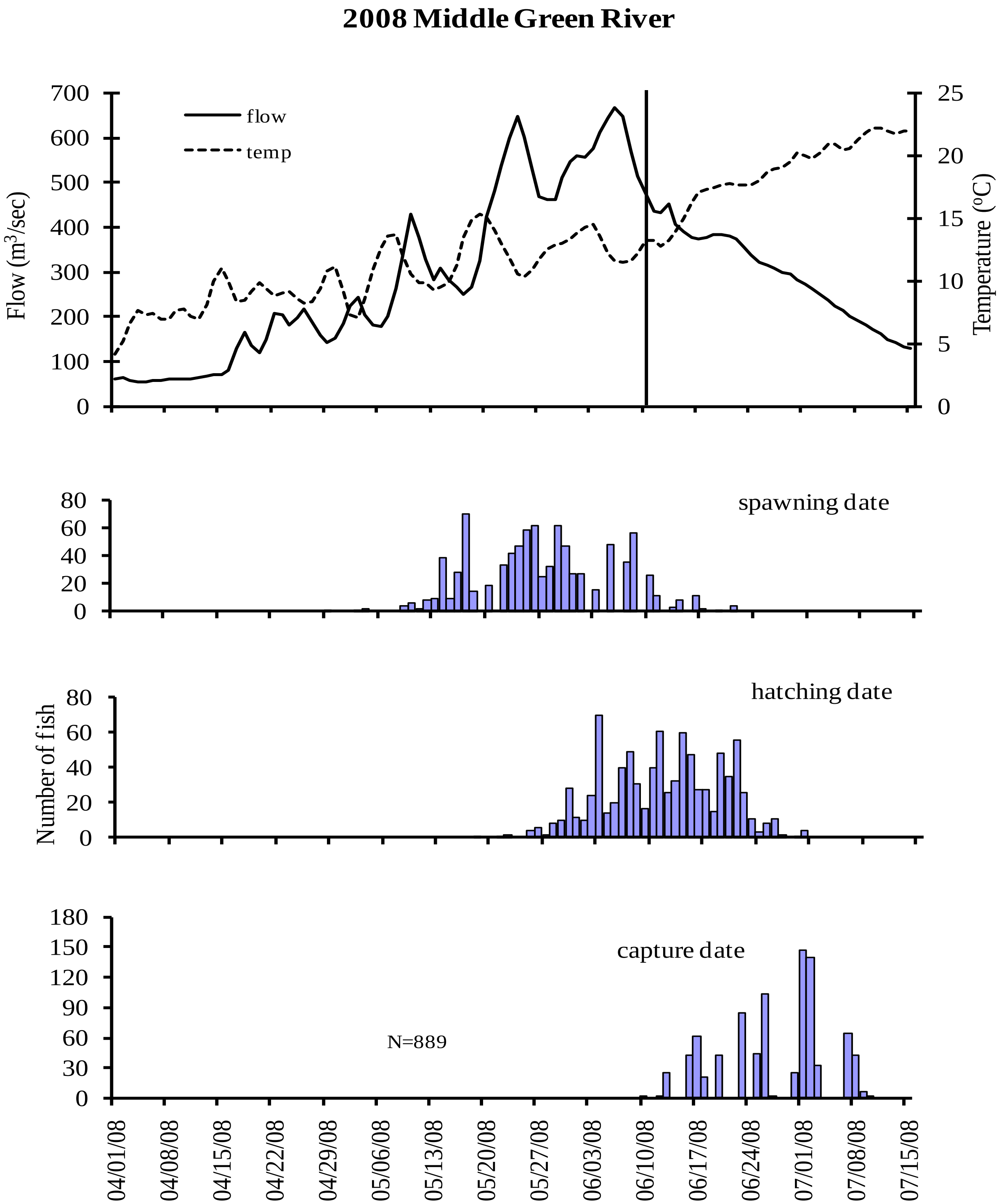


Figure 28. Capture and otolith-age-estimated hatching and spawning date distributions for razorback sucker larvae captured in light trap samples collected in the middle Green River, Utah, 2008. Flow and water temperatures of the Green River overlie distributions to show timing related to environmental factors. Vertical line in top panel indicates time of first presence of larvae.

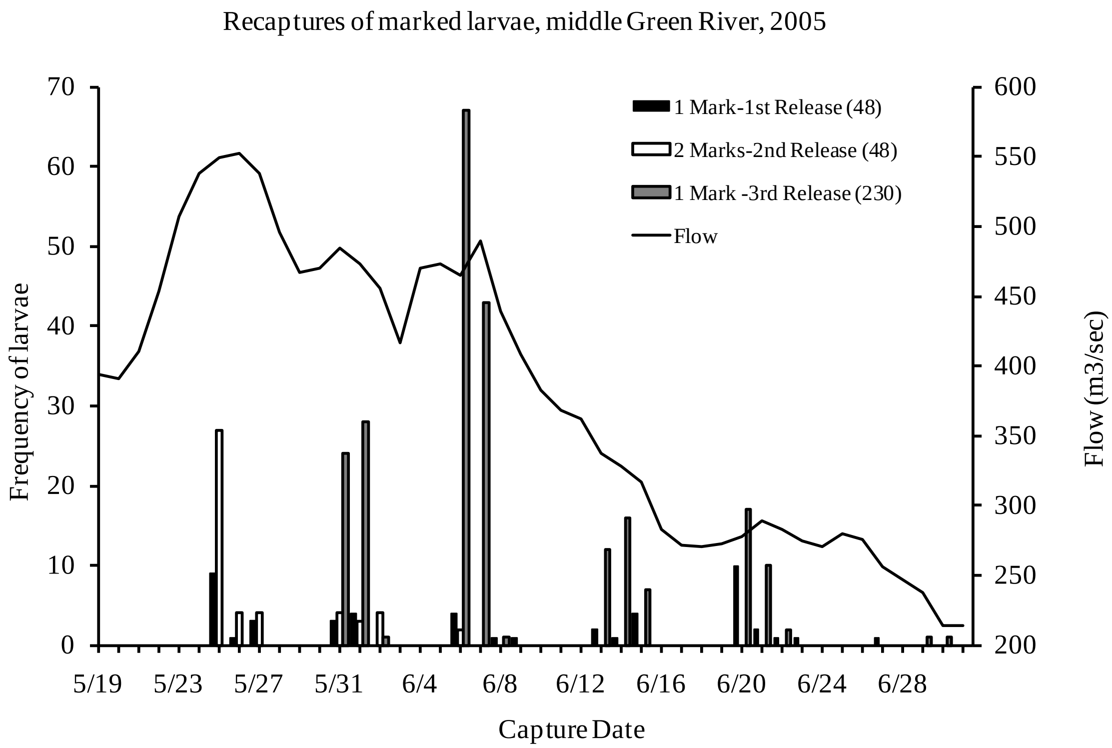
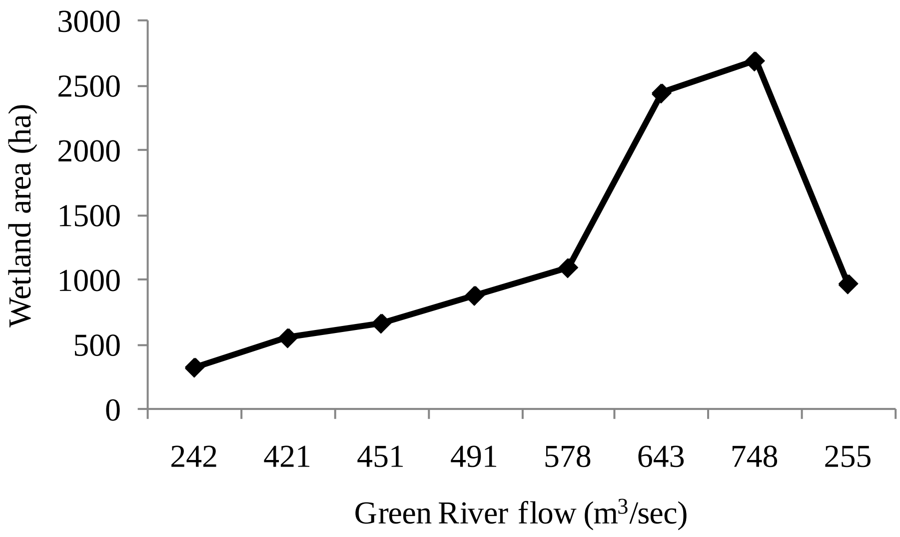


Figure 29. Timing and recapture frequency of marked razorback sucker larvae (n = 326 total) released in the middle Green River on 20 (n = 104,000 released), 24 (n = 94,500), and 31 May (n = 395,500), 2005 (releases 1-3 respectively).



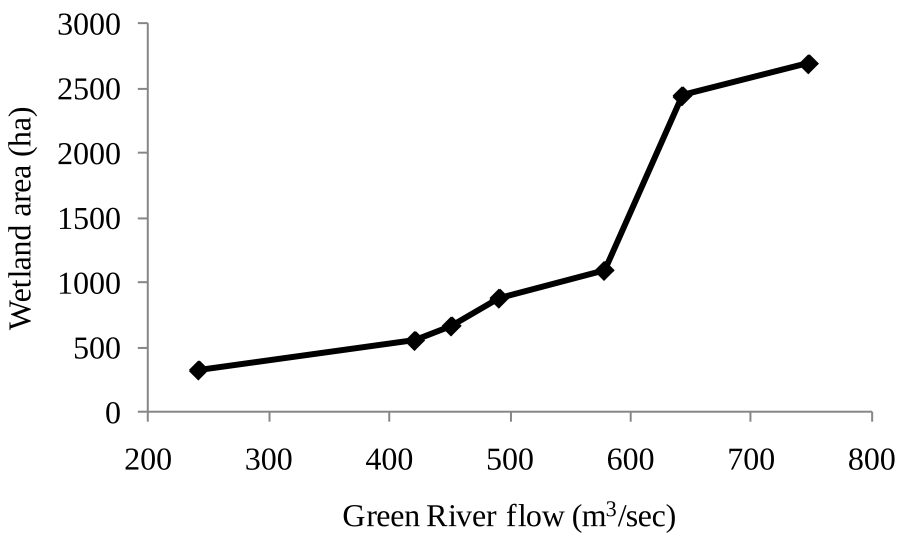


Figure 30. Relationship of area of 12 flood plain wetlands as a function of flow in the middle Green River, Utah. The upper graph depicts flow as a categorical variable to show the progression of wetland area in pre- and post-peak conditions. The lower panel shows the same data graphed as a continuous variable, except the post peak datum (255 m^3/sec) is excluded. Flow levels were estimated for a location near Ouray National Wildlife Refuge and were the sum of the Green River Gauge at Jensen and the Ashley Creek gauges in 2005 for the day prior to wetland surface area measurements to account for transit time. Inundation area data for the 12 depression-type wetlands (see Table 14 and Table 15 for specific details) comes from a variety of sources (Argonne unpublished rpt., FLO 1996, reports, Valdez and Nelson 2004, Heitmeyer and Fredrickson 2005; Hedrick et al. 2009).

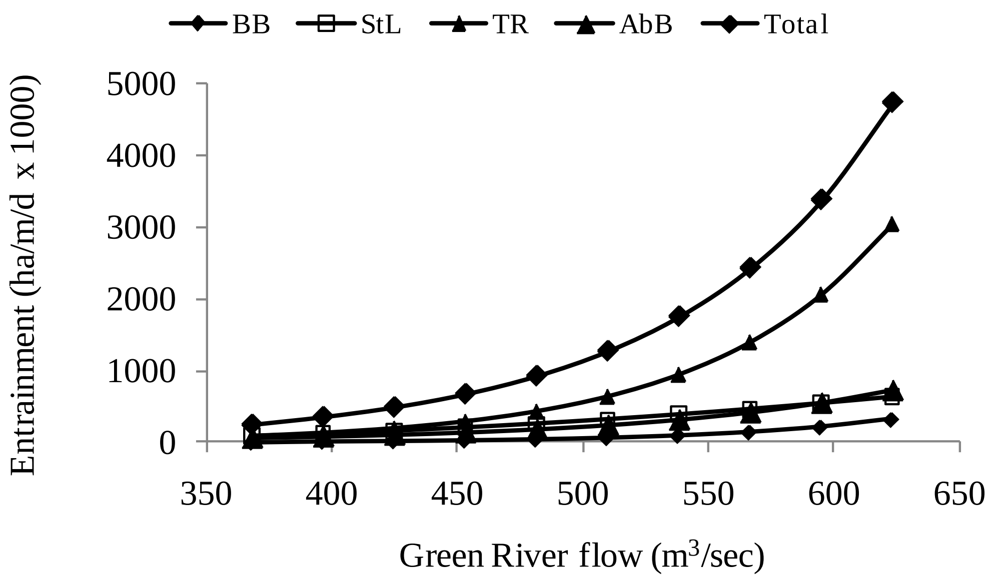


Figure 31. Comparison of simulated entrainment volume (ha/m x 1000) per day for Bonanza Bridge (BB), Stewart Lake (StL), Thunder Ranch (TR), and Above Brennan (AbB) flow-through floodplain wetlands and total flow entrained for all four as a function of Green River flow in the middle Green River Utah.

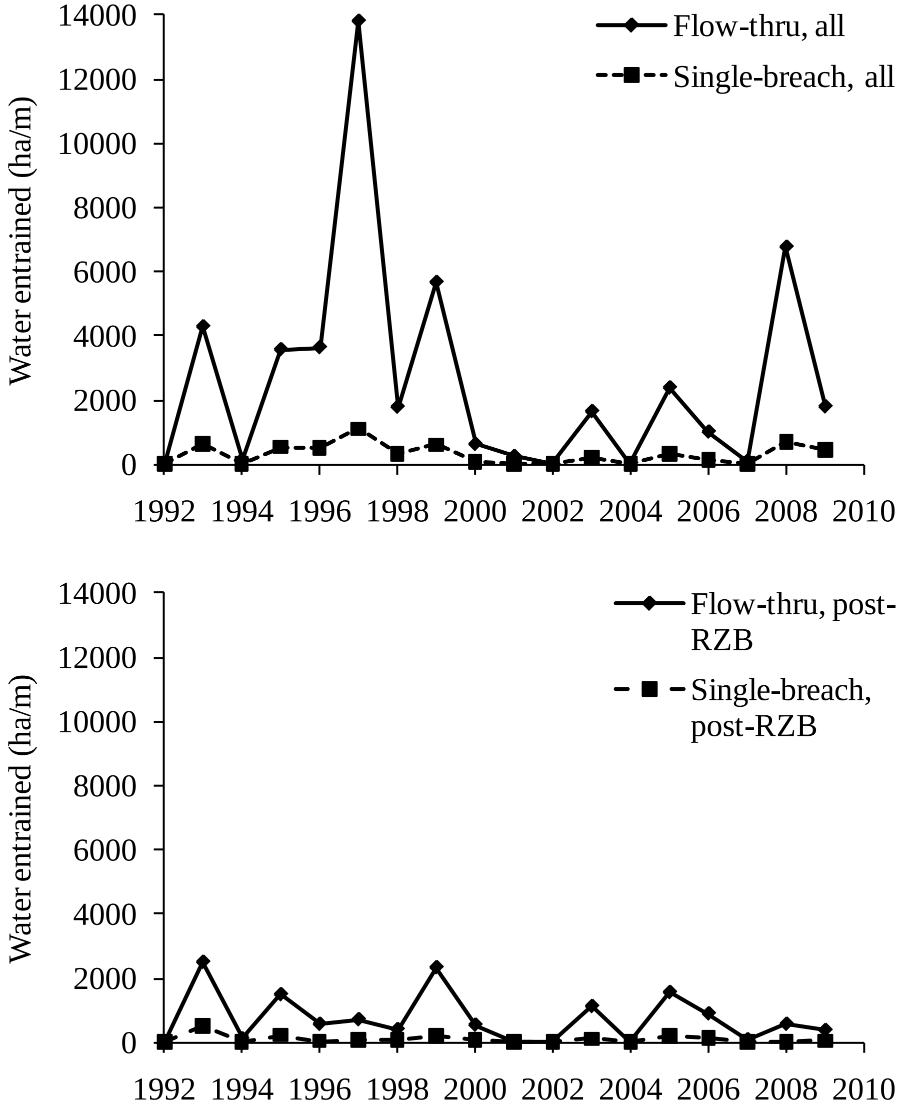


Figure 32. Estimated volume of water entrained (hectare/meters, the volume required to cover 1 hectare in 1 m of water) into flow-through wetlands (Thunder Ranch, Stewart Lake, Bonanza Bridge [in 2005], Above Brennan) compared to single-breach wetlands (Horseshoe Bend, The Stirrup, Baeser Bend, Johnson Bottom, Leota Wetlands complex [@494 m^3/sec], and Old Charley Wash) in the middle Green River, Utah, 1992-2009. The upper panel depicts higher entrainment volumes over the entire season when wetlands and the Green River are connected (upper panel) and substantially lower volumes for the period only after razorback sucker larvae were first detected in light trap samples (lower panel). Bonanza Bridge data in 2005 were for a slightly lower breach inundation level as was that for the Leota wetlands complex, each of which results in greater entrainment volumes.

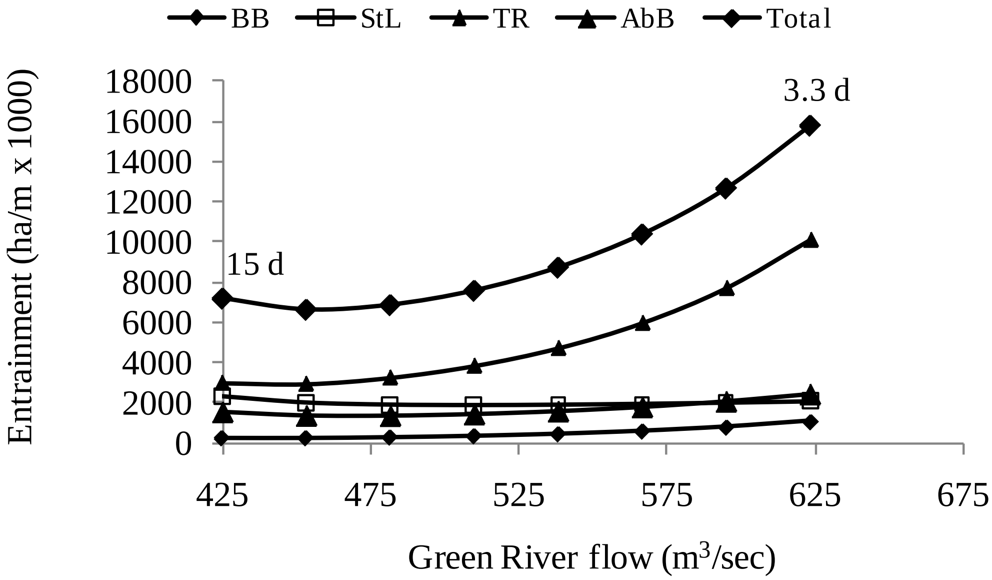


Figure 33. Estimated entrainment volume (ha/m x 1000) for Bonanza Bridge (BB), Stewart Lake (StL), Thunder Ranch (TR), and Above Brennan (AbB) flow-through floodplain wetlands and total flow entrained over periods of 3.3-15 days and the total for all four as a function of Green River flow in the middle Green River Utah. An identical volume of Green River flow (850 m^3/sec for one day) was divided by days in the period (below) and added to a base flow representing the inundation level of most wetlands (368 m^3/sec) at inundation. Flow entrainment proceeded for 15, 10, 7.5, 6, 5, 4.3, 3.75, and 3.3 d. With one exception, the comparison showed that more water was entrained at higher flow levels and less water is entrained at lower flows *per unit volume* of the Green River. Stewart Lake was the exception, and showed a slight decrease and then a slight increase at the highest flow level.

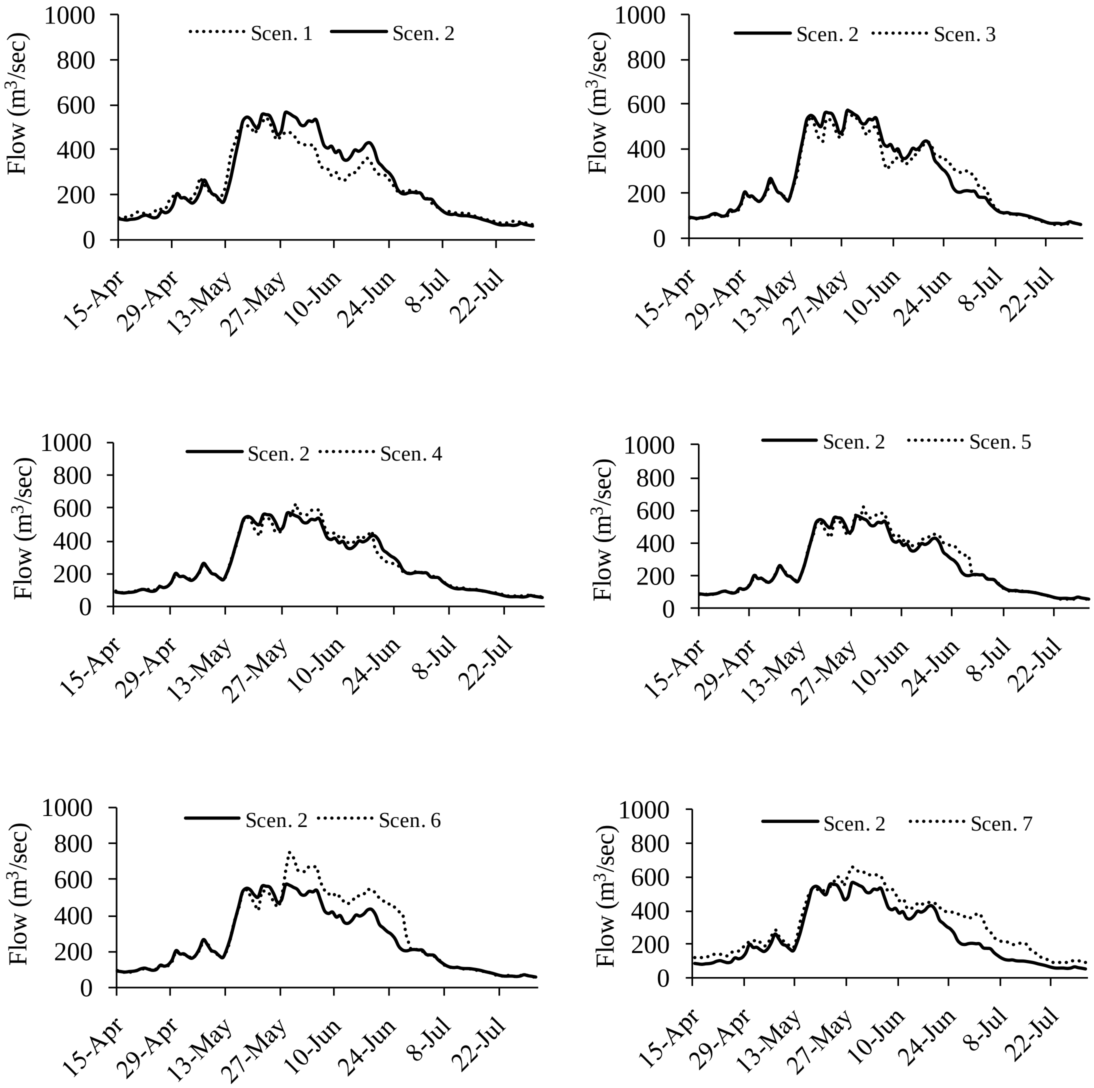


Figure 34. Simulated and actual flow patterns for the middle Green River near Jensen, Utah, in 1993. The solid black line in each graph is the actual pattern measured with release timing attempting to match Yampa River flow peaks. Simulated Flaming Gorge Dam flow scenarios included; (Scenario [Scen.] 1) a steady annual flow; (3) conditions as Scenario 2 with release timing matched to first appearance of razorback sucker larvae; (4) conditions as in Scenario 3 except that total release volume was compacted into half the release duration to achieve higher magnitude flows; (5) conditions as in Scenario 4 except duration extended twice as long (magnitudes retained, up to 30 days maximum, back to the duration used in scenarios 2 and 3); and (6) conditions as in Scenario 5 except flow magnitude in 11 of 18 wet years, including 1993, was increased to 244 m^3/sec (8,600 cfs). Scenario 7 is the unregulated flow pattern. The number of days that flows under each scenario exceeded thresholds of 368, 396, and 527 m^3/sec are in Table 19.

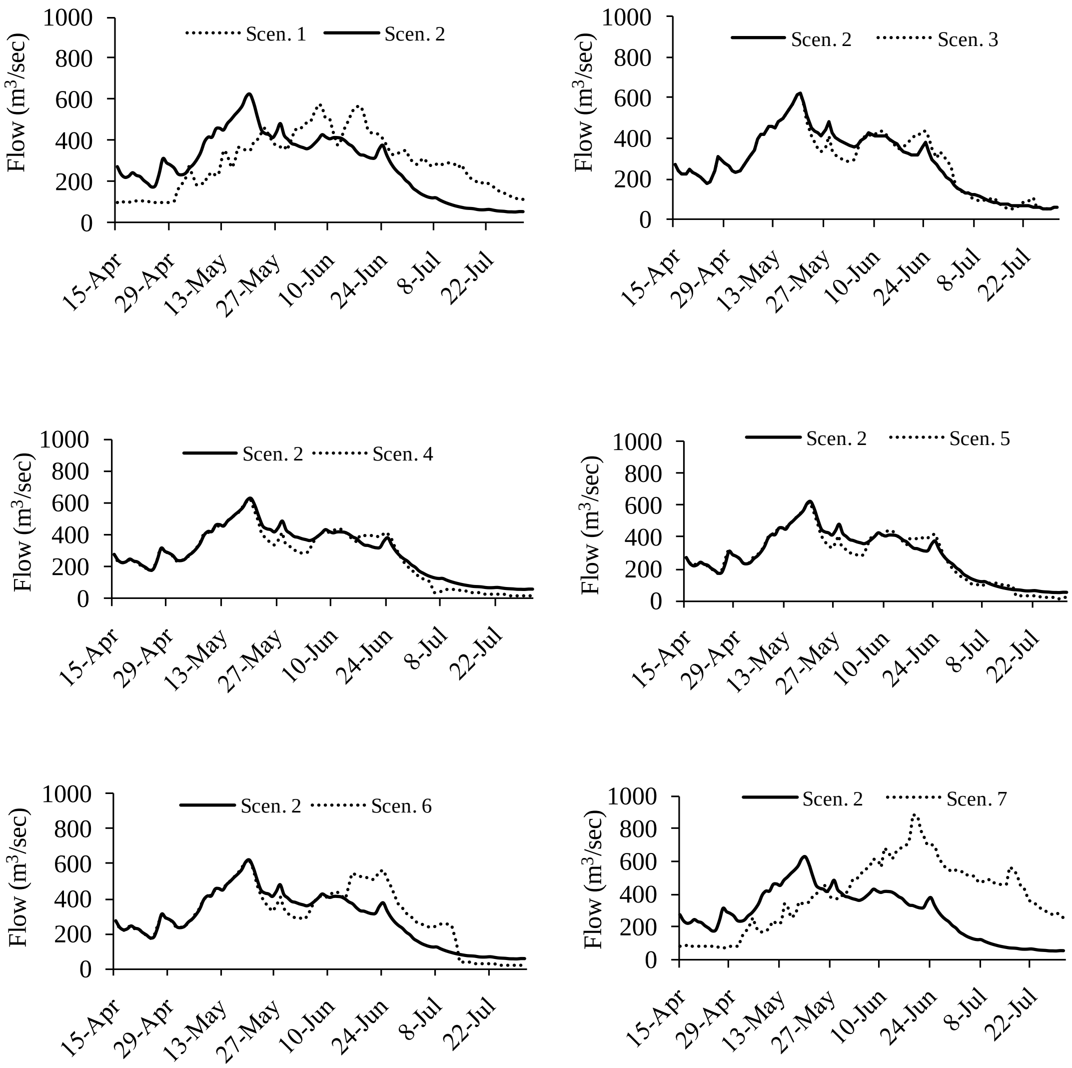


Figure 35. Simulated and actual flow patterns for the middle Green River near Jensen, Utah, in 1995. The solid black line in each graph is the actual pattern measured with release timing attempting to match Yampa River flow peaks. Simulated Flaming Gorge Dam flow scenarios included; (Scenario [Scen.] 1) a steady annual flow; (3) conditions as Scenario 2 with release timing matched to first appearance of razorback sucker larvae; (4) conditions as in Scenario 3 except that total release volume was compacted into half the release duration to achieve higher magnitude flows; (5) conditions as in Scenario 4 except duration extended twice as long (magnitudes retained, up to 30 days maximum, back to the duration used in scenarios 2 and 3); and (6) conditions as in Scenario 5 except flow magnitude in 11 of 18 wet years, including 1995, was increased to 244 m^3/sec (8,600 cfs). Scenario 7 is the unregulated flow pattern. The number of days that flows under each scenario exceeded thresholds of 368, 396, and 527 m^3/sec are in Table 19.

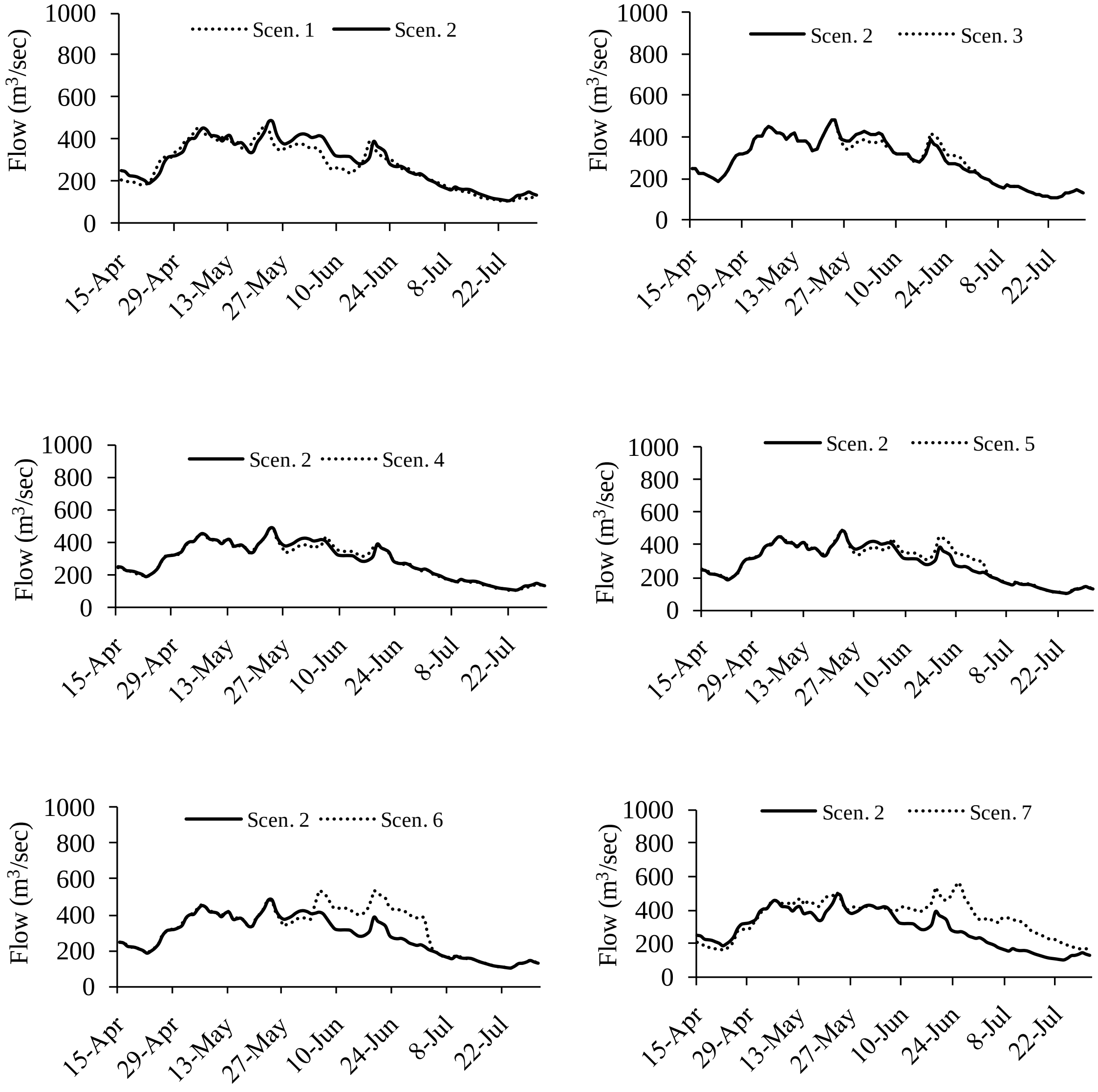


Figure 36. Simulated and actual flow patterns for the middle Green River near Jensen, Utah, in 1998. The solid black line in each graph is the actual pattern measured with release timing attempting to match Yampa River flow peaks. Simulated Flaming Gorge Dam flow scenarios included; (Scenario [Scen.] 1) a steady annual flow; (3) conditions as Scenario 2 with release timing matched to first appearance of razorback sucker larvae; (4) conditions as in Scenario 3 except that total release volume was compacted into half the release duration to achieve higher magnitude flows; (5) conditions as in Scenario 4 except duration extended twice as long (magnitudes retained, up to 30 days maximum, back to the duration used in scenarios 2 and 3); and (6) conditions as in Scenario 5 except flow magnitude in 11 of 18 wet years, including 1998, was increased to 244 m^3/sec (8,600 cfs). Scenario 7 is the unregulated flow pattern. The number of days that flows under each scenario exceeded thresholds of 368, 396, and 527 m^3/sec are in Table 19.

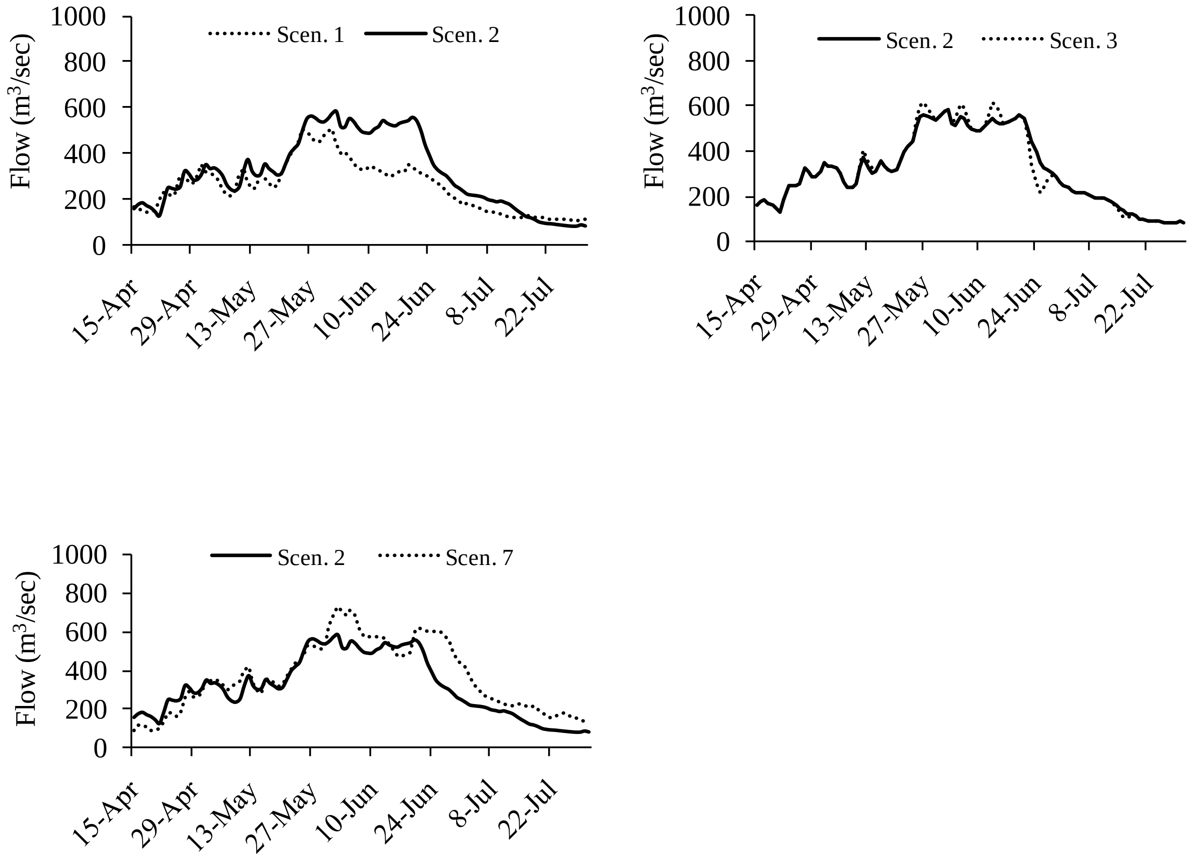


Figure 37. Simulated and actual flow patterns for the middle Green River near Jensen, Utah, in 1999. The solid black line in each graph is the actual pattern measured with release timing attempting to match Yampa River flow peaks. Simulated Flaming Gorge Dam flow scenarios included; (Scenario [Scen.] 1) a steady annual flow; (3) conditions as Scenario 2 with release timing matched to first appearance of razorback sucker larvae; Scenario 7 is the unregulated flow pattern. The number of days that flows under each scenario exceeded thresholds of 368. 396, and 527 m^3/sec are in Table 19. Scenarios 4, 5, and 6 were not simulated because flows were managed in the wet year 1999 for high conditions which maximized flood plain inundation.

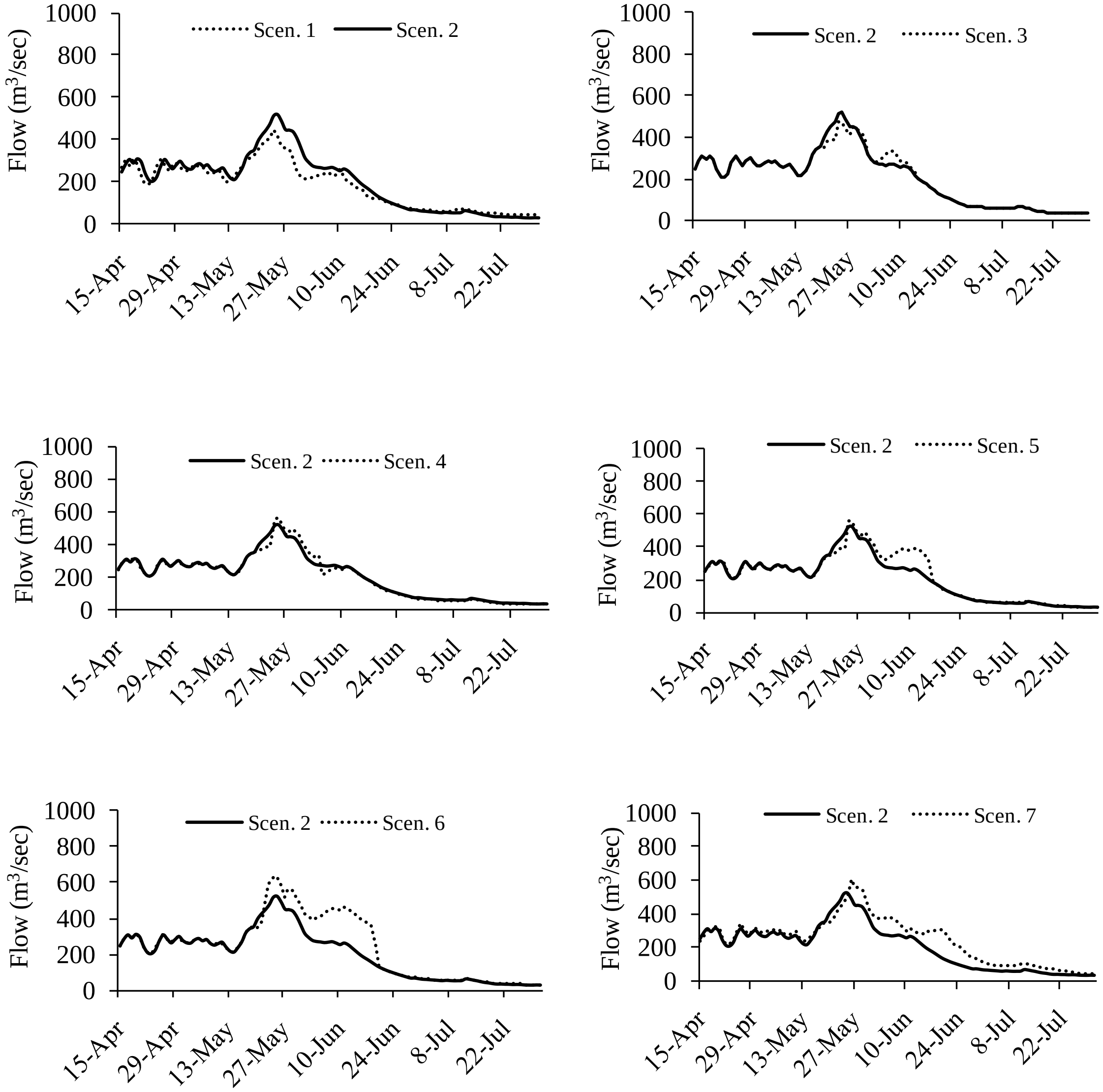


Figure 38. Simulated and actual flow patterns for the middle Green River near Jensen, Utah, in 2006. The solid black line in each graph is the actual pattern measured with release timing attempting to match Yampa River flow peaks. Simulated Flaming Gorge Dam flow scenarios included; (Scenario [Scen.] 1) a steady annual flow; (3) conditions as Scenario 2 with release timing matched to first appearance of razorback sucker larvae; (4) conditions as in Scenario 3 except that total release volume was compacted into half the release duration to achieve higher magnitude flows; (5) conditions as in Scenario 4 except duration extended twice as long (magnitudes retained, up to 30 days maximum, back to the duration used in scenarios 2 and 3); and (6) conditions as in Scenario 5 except flow magnitude in 11 of 18 wet years, including 2006, was increased to 244 m^3/sec (8,600 cfs). Scenario 7 is the unregulated flow pattern. The number of days that flows under each scenario exceeded thresholds of 368, 396, and 527 m^3/sec are in Table 19.

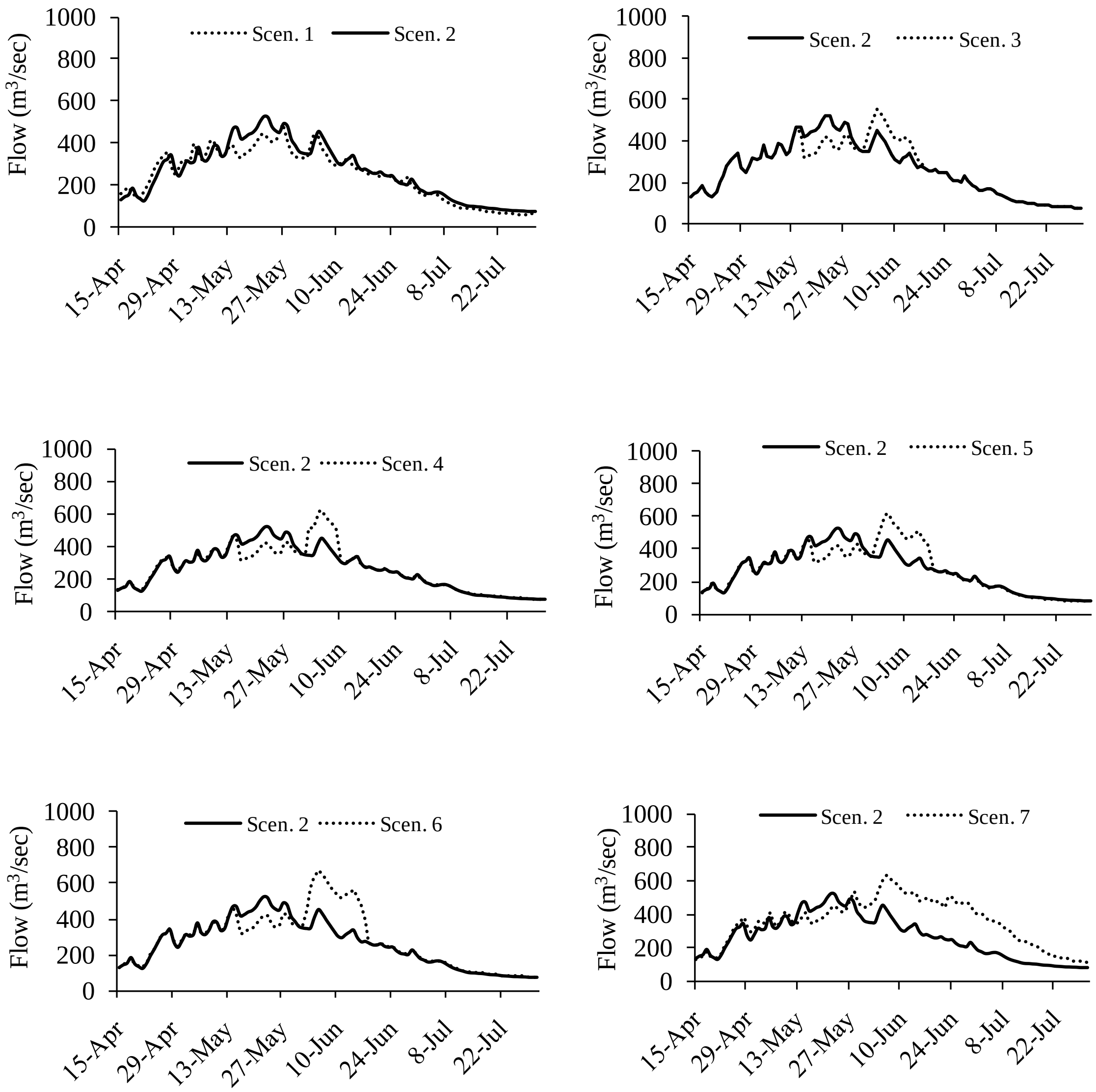


Figure 39. Simulated and actual flow patterns for the middle Green River near Jensen, Utah, in 2009. The solid black line in each graph is the actual pattern measured with release timing attempting to match Yampa River flow peaks. Simulated Flaming Gorge Dam flow scenarios included; (Scenario [Scen.] 1) a steady annual flow; (3) conditions as Scenario 2 with release timing matched to first appearance of razorback sucker larvae; (4) conditions as in Scenario 3 except that total release volume was compacted into half the release duration to achieve higher magnitude flows; (5) conditions as in Scenario 4 except duration extended twice as long (magnitudes retained, up to 30 days maximum, back to the duration used in scenarios 2 and 3); and (6) conditions as in Scenario 5 except flow magnitude in 11 of 18 wet years, including 2009, was increased to 244 m^3/sec (8,600 cfs). Scenario 7 is the unregulated flow pattern. The number of days that flows under each scenario exceeded thresholds of 368, 396, and 527 m^3/sec are in Table 19.

APPENDIX I

Fulfillment of information needs. Because of the length of the report and the complexity of the information reported, we thought it would be useful to summarize the information needs that were central to this project, and the types of data that were used to answer questions relation to each.

Information need 1. Flow and stage at which flood plains with levee breaches become sufficiently inundated to provide nursery habitat for razorback suckers. This aspect was adequately described with existing information and suggested initial inundation of levee breaches at flows ranging from 227 to 538 m^3/sec. Thus, the process of inundation of levee breaches occurs along a continuum of flows. Some information for individual wetlands was variable due to discrepancies with measured elevations and actual observations of inundation at various flow levels, or changes in breach levels due to sedimentation.

Only minimal inundation would occur under "Dry" and "Moderately Dry" hydrologic conditions, as described by Muth et al. (2000), with Stewart Lake achieving some level of connection at those flows. This could have a substantial contribution to razorback sucker recovery if recruitment limitations in Stewart Lake were overcome because in some low flow years abundance of razorback sucker larvae is very high (e.g., 1994, 2004). For example, if the 231 ha surface area Stewart Lake was filled with 1 m of water at a time when razorback sucker were as abundant as they were during drift net sampling on 28 May 2004 (0.054 wild larvae/m^3, from 2004 drift netting), nearly 125,000 larvae would be entrained (231 ha * 10,000 m^2/ha * 1 m depth * 0.054 larvae/m^3 =

124,700 larvae); number of larvae would be higher if the system was operated as a flow through wetland for longer time durations. Entrainment levels in this and other wetlands would be much higher, of course, if entrainment of even higher flows was timed with presence of razorback sucker larvae. In "Average" or wetter hydrologic conditions, all flood plain wetlands would be inundated, some in a substantial way, others not.

Information need 2. Frequency of flood plain inundation relative to the hydrologic cycle. This can now be easily described and modeled for individual flood plain wetlands based on knowledge of annual hydrology. Again, because of the range of breach elevations for the different wetlands, this process can best be described as a continuum. The frequency of inundation is important, because flood plain wetlands need to be connected to interact with the river and provide a recruitment environment for razorback sucker early life stages. However, at least as important is the duration of inundation and the amount of inflow, particularly when razorback sucker larvae are available for entrainment.

Information need 3. Area, depth, volume, and persistence of floodplain depression habitat after peak flows recede and relationship with peak flow magnitude. This aspect remains poorly known, because little post-runoff data was available to describe physical attributes of wetlands in summer and beyond. We do have observational data on some however, and know that several wetlands offer only poor summer, autumn, or overwinter habitat (e.g., Thunder Ranch) and survival of larvae entrained is sometimes low or non-existent. Stewart Lake has additional problems to overcome, including perhaps water levels and high selenium levels. Nearly all flood plain wetlands support large populations of non-native fishes if they have been connected to the river recently and many are not sufficiently deep to allow fishes to escape predation by birds.

Information need 4. Rates of sediment deposition and erosion in breaches and floodplains. This aspect remains poorly understood based on lack of relevant information. Sediment levels change through the runoff season, typically increasing on the ascending limb of the hydrograph and declining thereafter. Sediment transport rates also depend on particle size, with suspended and bedload being main contributors. We discussed bedload movement into breaches and effects of that on inundation levels observed at Bonanza Bridge in 2005 and 2006. Breach monitoring should be conducted to ascertain whether breach filling is a substantial problem in other areas as well. Such monitoring could also include a component that examined suspended sediment deposition in flood plain wetlands. This was a substantial enough an issue that Ouray Nation Wildlife Refuge will no longer manage wetlands as flow-through, but rather will allow wetlands only to backfill from downstream and reduce sediment impacts. This was described in more detail in Heitmeyer and Fredrickson (2005) and Hedrick et al. (2009).

Information need 5. Entrainment and retention of larvae in floodplain nursery habitats as a function of physical characteristics and timing of drift.

This was a main focus of the Results presented in this report. Entrainment of water (as a surrogate for larvae) was described under various flow levels and management schemes, both for total flow and also constrained to the period when razorback sucker larvae were available, for both flow-through wetlands as well as single breach types. Retention was discussed but no data was available to estimate total entrainment and net entrainment, which would account for transport of larvae through the wetland.

Only minimal data were available to describe actual densities of razorback sucker larvae in relation to flows. That derived from capture of wild larvae on 26 May 2004 during bead and fish releases to estimate downstream transport rates. We have derived a seasonal density distribution for that data that may be useful to estimate entrainment rates of larvae into flood plain wetlands, but we ran out of resources to finish that analysis. A density distribution that reflected some notion of reality would be useful to guide additional simulations that examine seasonal entrainment rates and durations of flow releases, and additional simulations that examine tradeoffs between longer, lower flow releases, or higher shorter ones. This is an upgrade to existing analyses because those assumed equal densities of larvae regardless of timing of flows, and the seasonal distribution would allow effects of intra-season density differences to be illuminated more fully.

We also found that the type of wetland, flow-through or single-breach, was among the biggest factors affecting potential entrainment of larvae. Flow-through wetlands, even though they were fewer in number and substantially smaller in area, entrained much more water than single-breach wetlands. Overall, the level of entrainment of water into all flood plain wetlands in most years was low.

Information need 6. Temporal relationships between drifting larvae and hydrology during the runoff period with a focus on the peak flow characteristics needed to entrain larvae. Again, this was a main focus of Results presented, linking presence of larvae in the system via analysis of capture and hatching periods, with flow characteristics of the system. A main finding of this analysis was that flow releases from Flaming Gorge Dam were often too early, well before Yampa River peaks, and well before razorback sucker larvae were available for entrainment. First appearance of razorback sucker larvae coincided with peak Yampa River flows in most years, and Green River flows were not sufficient to maintain high flow peaks and sustain connections with wetlands when most larvae were available. The flow year 2009 was a good example of this, as flow releases were declining from Flaming Gorge Dam before the first razorback sucker larvae were captured in the system. In contrast, in 1999, flow releases from Flaming Gorge Dam were managed to extend the flow peaks and duration of connections of the river and flood plain wetlands when razorback sucker larvae were present, demonstrating that the process is possible.

Information need 7. The area of terrace and depression floodplains inundated at different flows. Extensive analysis was provided that described the relationship of area of depression flood plain wetlands as a function of various flow levels. That relationship suggested that as flows increased, the area and volume of flood plain wetlands of all types, including depression wetlands, also increased. Effects of flows higher than those for which we had relevant data (upper end of “Average” and “Moderately Wet”) were unknown, but it can be reasonably surmised that wetland area is very high during such flows. Only limited data was available to describe that for terrace-type wetlands. We assume that as flow levels increase above about bankfull level(e.g., about 527 m^3/sec), area of terrace wetlands will increase dramatically. Terraces may function as important but temporary refuges for early life stages of fishes, including razorback sucker.

Information need 8. What is the optimal combination of flow magnitude and duration to maximize entrainment of razorback sucker larvae.

This was a main emphasis in Results, and showed that magnitude and duration were both important. In general, a larger quantity of water was entrained at higher Green River flow levels over a shorter duration than in a lower flow, longer duration scenario. This was so because flow-through wetland breach flows entrained larger quantities of water as river flow increases per unit volume. In other words, the relationship of flow entrainment through breaches increased at an exponential rather than a linear rate as Green River flow increased. Amount of flow entrainment in single-breach wetlands also increased as Green River flow increased, but we were not able to define the nature of the relationship (exponential increasing, linear, etc.).

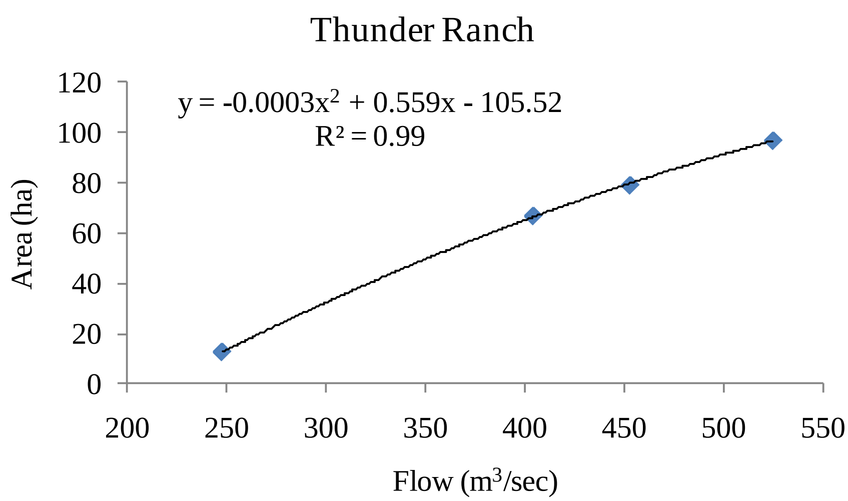
The most important factor determining the “optimal” flow magnitude and duration was to ensure that the period of wetland inflow matched with the period of availability of razorback sucker larvae. In some years (e.g. 1997), substantial volumes of water flowed into wetlands. However, because the period of inflow overlapped with only a limited amount of time when razorback sucker larvae were present, the effectiveness of those large inflows to potentially influence recruitment and recovery of razorback suckers was low. In contrast, flows into flood plain wetlands were moderately high but overlapped more substantially with the period when razorback sucker larvae were available and potentially resulted in higher entrainment. Apparently present flow patterns and presence of larvae are not sufficiently overlapped, as recruitment of fish in the wild remains low or non-existent.

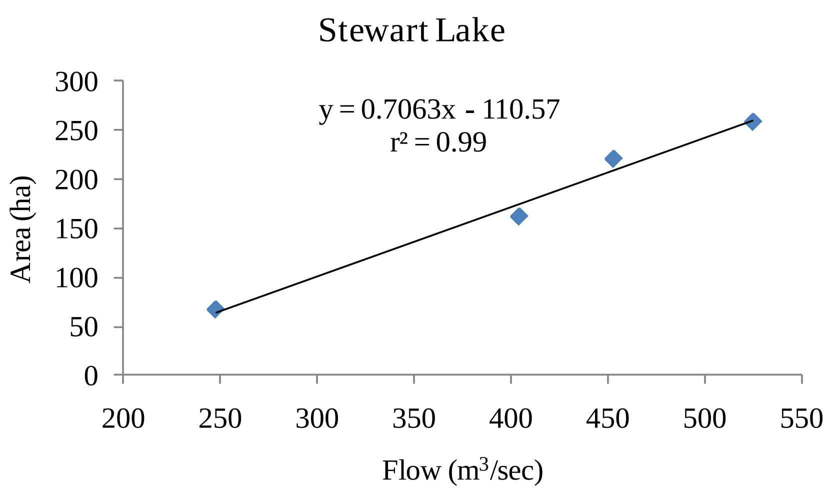
Forecasting the most “optimal” flow magnitude and duration would be aided by a realistic density distribution over time for razorback sucker larvae in the Green River. We showed that having the period wetland availability and larvae availability overlap as much as possible offered the best potential entrainment. Overlapping the timing of peak abundance of larvae with maximal flow entrainment into the flood plain would truly optimize the relationship. This is a challenge because the timing of first appearance of larvae occurs as much as 2-3 weeks before timing of peak abundance, based on light trap captures.

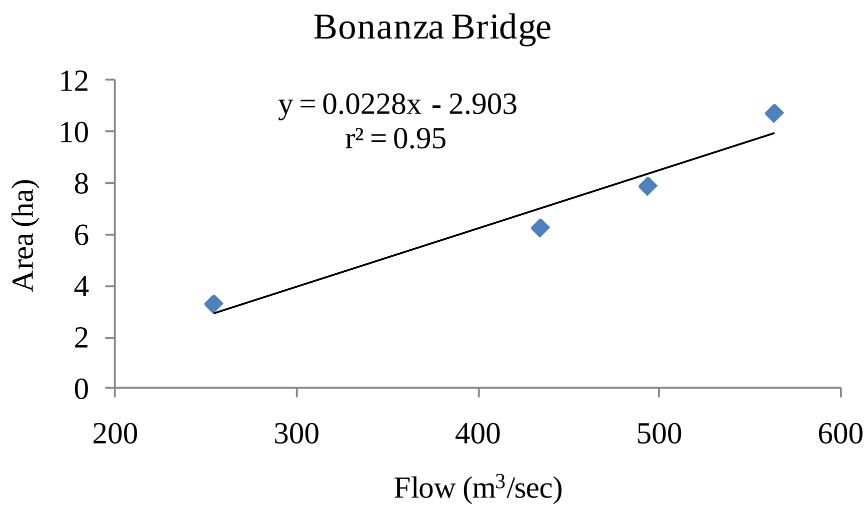
Ensuring overlap of habitat availability and highest abundance of razorback sucker larvae would require large alteration of flow release schedules and much higher water volumes from Flaming Gorge Dam. Demonstrating those tradeoffs was the essence of flow simulation scenarios that examined the number of inundation days of wetlands at various flow levels relative to seven different flow schedules. Those flow simulations, that used scenarios ranging from flat flow releases through an unregulated scenario, showed that to increase overlap of habitat availability and presence of razorback sucker larvae, flow releases needed to be of higher magnitude and for a longer duration. The unregulated scenario produced the highest overlap of habitat availability and presence of razorback sucker larvae in most years. A key question that remains, is how much more overlap is required to effect recovery of razorback sucker in the middle Green River.

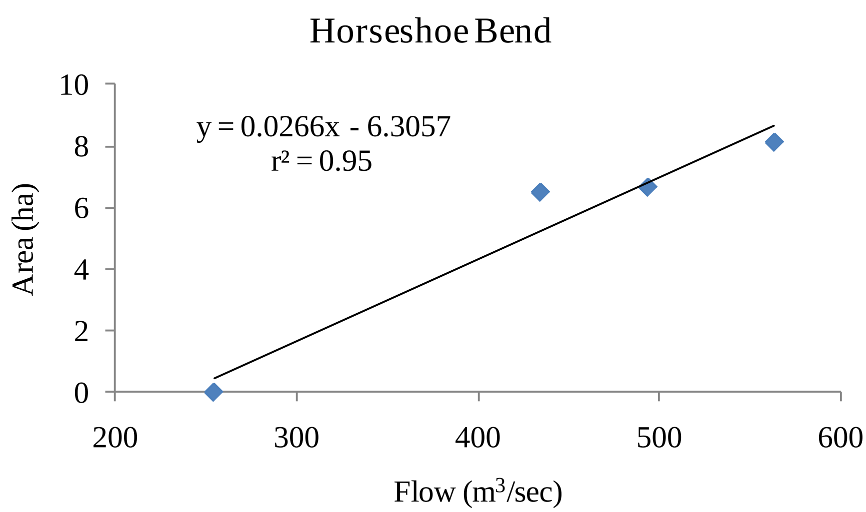
APPENDIX II

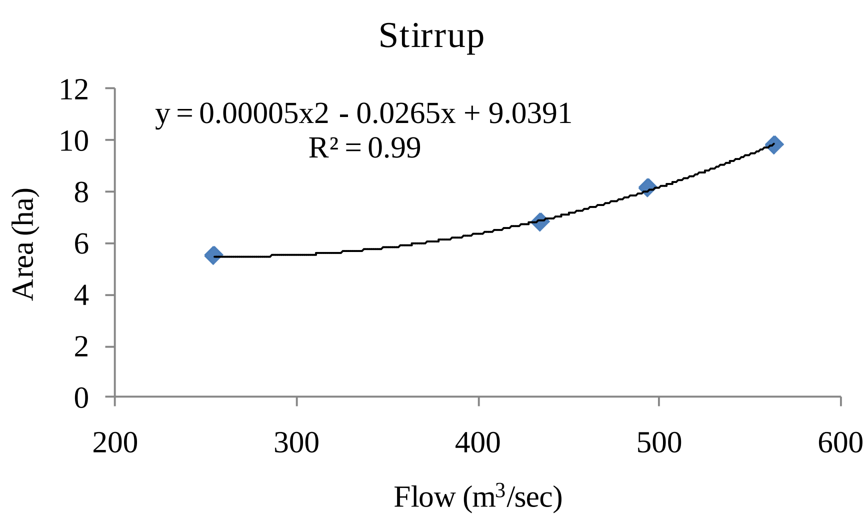
Regression functions to estimate flood plain area for several wetlands at various Green River flow levels (adjusted for inputs from Ashley Creek). Estimates of area were reported in the unpublished aerial photography report (Argonne National Laboratory 2006). Estimates of Green River flows were those from the Jensen gauge for the specific day aerial photography was collected for wetlands upstream of Ashley Creek; estimates of Green River flows for wetlands downstream of Ashley Creek on the day aerial photography was collected were flows from the Jensen and Ashley Creek gauges the day prior to account for travel time to the Ouray National Wildlife Refuge area of the river where most of those wetlands were located.

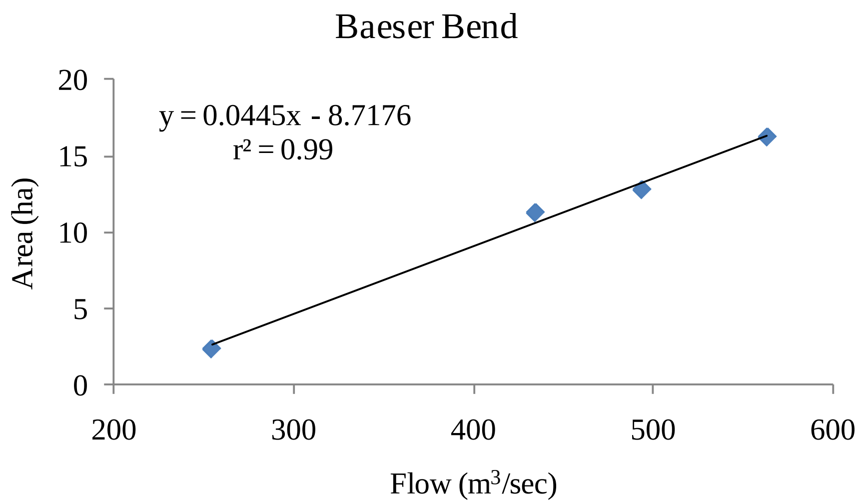


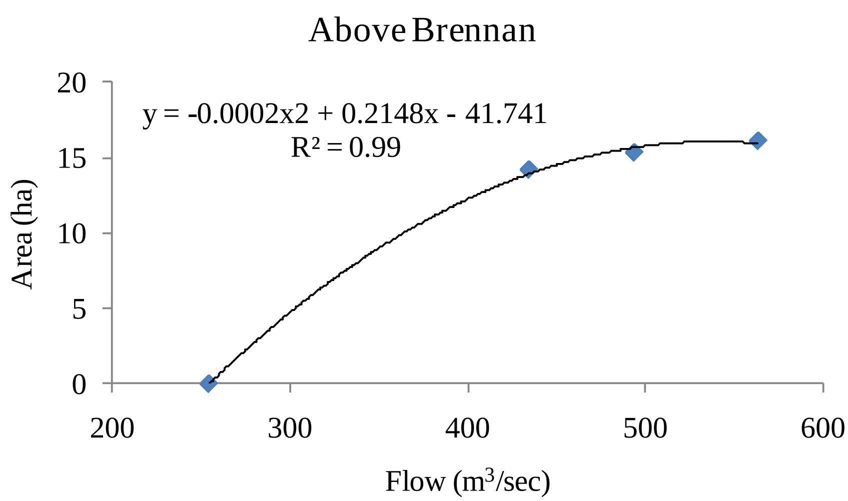


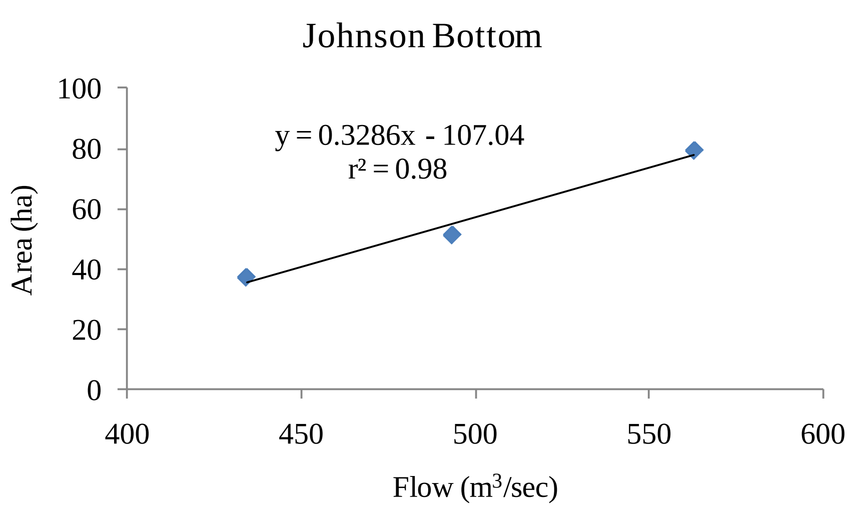

Bonanza Bridge
y = 0.0228x - 2.903
r² = 0.95
Area (ha)
Flow (m3/sec)
0
2
4
6
8
10
12
200
300
400
500
600

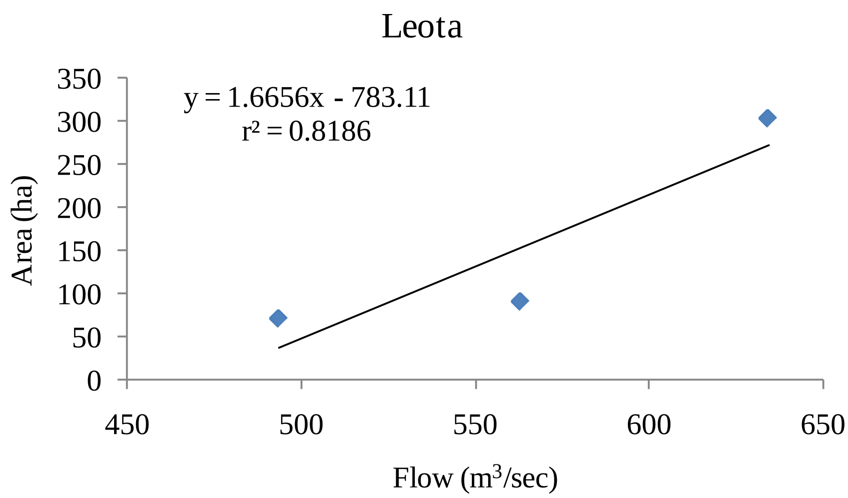

Horseshoe Bend
y = 0.0266x - 6.3057
r² = 0.95
Area (ha)
Flow (m3/sec)
0
2
4
6
8
10
200
300
400
500
600

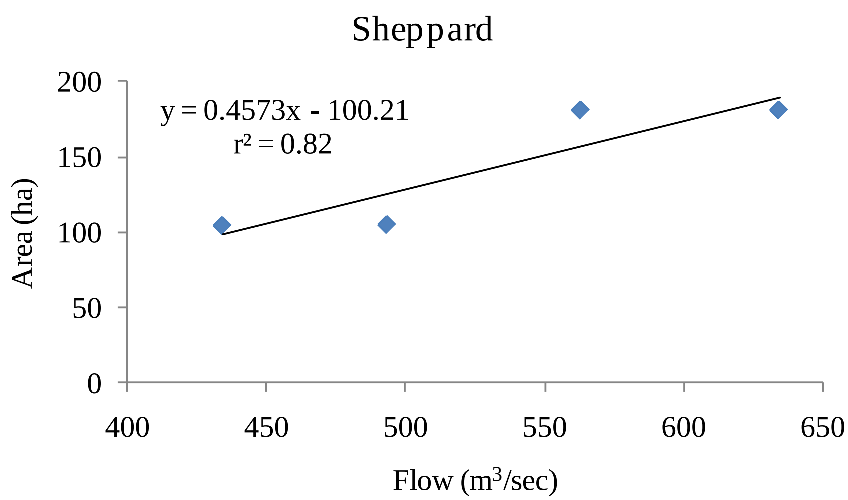

Stirrup
y = 0.00005x2 - 0.0265x + 9.0391
R² = 0.99
Area (ha)
Flow (m3/sec)
0
2
4
6
8
10
12
200
300
400
500
600

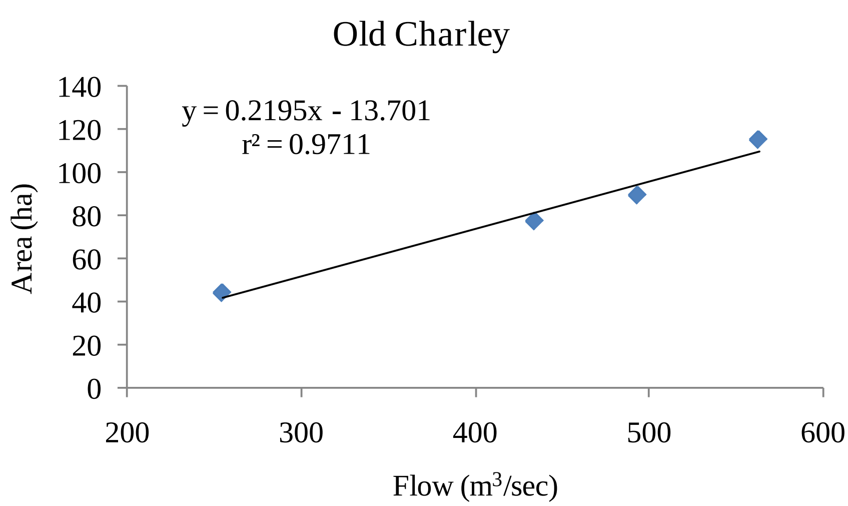

Baeser Bend
y = 0.0445x - 8.7176
r² = 0.99
Area (ha)
Flow (m3/sec)
0
5
10
15
20
200
300
400
500
600


Above Brennan
y = -0.0002x2 + 0.2148x - 41.741
R² = 0.99
Area (ha)
Flow (m3/sec)
0
5
10
15
20
200
300
400
500
600


Johnson Bottom
y = 0.3286x - 107.04
r² = 0.98
Area (ha)
Flow (m3/sec)
0
20
40
60
80
100
400
450
500
550
600


Leota
y = 1.6656x - 783.11
r² = 0.8186
Area (ha)
350
300
250
200
150
100
50
0
450
500
550
600
650
Flow (m3/sec)

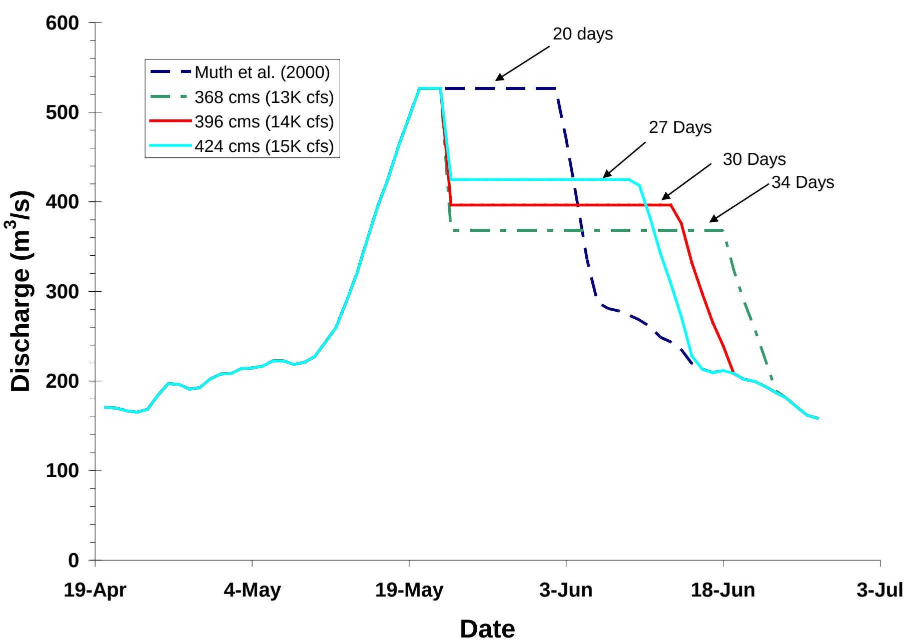

Sheppard
y = 0.4573x - 100.21
r² = 0.82
Area (ha)
200
150
100
50
0
400
450
500
550
600
650
Flow (m3/sec)


Old Charley
y = 0.2195x - 13.701
r² = 0.9711
Area (ha)
140
120
100
80
60
40
20
0
200
300
400
500
600
Flow (m3/sec)

APPENDIX III

This section evaluates the flow recommendations presented in Hayse et al. (2005) to provide flood plain wetland habitat in the middle Green River, Utah. This was already done, in part, in the original report and presented in Table 15 (also tables 16 and 17 in part), and figures 30, 31, and particularly 33, where tradeoffs of flow stage and duration were specifically explored. Expanded analysis was undertaken to satisfy a peer reviewer request.

The essence of the Hayse et al. (2005) flow recommendations was, in average years, to provide a peak flow of 527 m^3/sec (18,600 cfs) consistent with Muth et al. (2000), but for a shorter duration of 3 days instead of the 14 days as suggested in flow recommendations. The water "saved" over the 11 days at the 527 m^3/sec level was then reallocated and delivered to the middle Green River in three flow scenarios at levels of 368, 396, and 425 m^3/sec (13,000, 14,000, and 15,000 cfs) but of a volume equal to the amount released from Flaming Gorge Dam over the period 20 April to 27 June. Thus, the amount of water delivered was identical in all four scenarios because flows at the lower levels were of longer duration than for higher flow levels. The main idea of modified flows compared to those detailed in Muth et al. (2000) was that high flows would be delivered to accomplish river channel maintenance but for a shorter time and then lower flows would be delivered, presumably by altering releases from Flaming Gorge Reservoir, to extend the duration of flows connecting the Green River to flood plain wetlands to allow for colonization by razorback sucker larvae. Their hypothetical flow recommendations are depicted below (from Hayse et al. 2005).



The numbers of days depicted above each scenario reflected the combined total days of peak flows at 527 m^3/sec (14 days per the flow recommendations at 527 m^3/sec, 3 days at that level in all others), four days to ramp flows up to 527 m^3/sec, and then two days of downramp. Thus, in the original scenario outlined in Muth et al. (2000) there would be 14 days at 527 m^3/sec and 6 additional days of up-ramp or down-ramp flows (20 total).

The numbers of connection days (connection at 13,000 cfs or higher) for other lower flow scenarios were 34, 30, and 27 days for modified peak flows levels of 368, 396, and 425 m^3/sec (13,000, 14,000, and 15,000 cfs), which includes 3 days at 527 m^3/sec (Hayse et al. 2005).

We used those flow levels and durations to estimate the number of days of connections at each flood plain wetland, based on the various connection levels (Breach flow, Table below). In other words, for each Green River flow level (below) we counted the number of days of connections of each wetland, which are different because of different breach inundation levels. The days at baseline number was the number of days at the modified peak flow, except for the 527 m^3/sec flow, where the six days reflected ramping days up or down. The total number of days at 527 m^3/sec and baseline do not necessarily sum to the number of connection days (usually more) because some connections were possible at flows lower than the flow scenarios used.

	Breach	Green River flow level (m3/sec			
Wetland	flow (m3/s)	368	396	425	527
Flow-through					
Thunder Ranch	340	35	31	29	21
Stewart Lake	227	43	40	37	36
Bonanza Bridge	396	6	6	25	19
Above Brennan	334	35	31	29	22
total flow-through		119	108	120	98
Single-breach					
Horseshoe Bend	404	6	6	25	18
The Stirrup	368	34	30	27	20
Baeser Bend	337	35	31	29	21
Johnson Bottom	368	34	30	27	20
Leota wetlands complex	431	5	5	5	17
Wyasket Lake	526	3	3	3	14
Sheppard Bottom	525	3	3	3	14
Old Charley Wash	368	34	30	27	20
total single-breach		154	138	146	144
total, all wetlands		273	246	266	242
days @ 527 m3/sec		3	3	3	14
days @ baseline		31	27	24	6*

The number of flow connection days of the Green River to flow-through wetlands was slightly lower (about 20%, n = 98 days) at 527 m^3/sec compared to other lowers modified peak flow scenarios. The number of flow connection days of the Green River to single-breach wetlands was similar across all flow scenarios. The relationship of the number of flow connection days at single breach wetlands was slightly different than for flow through wetlands under the various scenarios because many single breach ones did not connect until relatively higher flow levels. Thus, some connections at lower flows were for only 3 or 5 days when flows were 527 m^3/sec while others were for longer durations. The number of connection days at the Stirrup, Johnson Bottom, and Old Charley Wash wetlands when flows were 368 m^3/sec was likely substantially overestimated because connections just first occurred at those levels and substantial filling was unlikely. Nevertheless the total connections days for all wetlands were relatively similar across all flow levels, in part because only at the highest level did Leota and Wyasket Lake wetlands connect for a substantial (e.g., > 3 days) period. Those wetlands are important because of their large size.

We then evaluated entrainment rates of water at various flow levels for both flow through and single breach wetlands. Estimates of entrainment volumes (hectare/meters of water, 1 m of water over a hectare of surface area) for flow-through wetlands were straightforward because we know the levels of breach inundation and specific flow rates into flood plain wetlands at various Green River flows, which when multiplied by the appropriate durations, yielded volume.

Single breach wetland entrainment rates were slightly more complicated and were estimated in two parts. The first volume of water was that entrained when flow achieved the peak of 527 m^3/sec, which occurred for varying times under all scenarios. To estimate that volume the area of wetlands was estimated at that flow level (e.g. Appendix II) from regression relationships. The difference between river stage just prior to inundation at various breach heights and at 527 m^3/sec was calculated from Figure 4; for example, a wetland with a breach that floods at 368 m^3/sec was estimated to have a stage increase of 0.46 m at 527 m^3/sec based on the stage-flow relationship. That stage increase was multiplied by surface area to achieve volume; we assumed the wetland was nearly full prior to achieving breach inundation. That is almost never the case but alternative scenarios would require detailed knowledge of the amount of wetland inundation prior to filling (varies by year and time of year) and detailed bathymetric knowledge of wetlands. Thus, initial filling volumes are underestimated.

A second part of the filling and volume estimation scenario was to estimate effects of daily stage fluctuations on water transfer into (and out of) single breach wetlands. This level of fluctuation was assumed to be 0.2 m/day and was multiplied by wetland area (either at the 527 level for the initial peak, and for the lower peak flow levels, re-estimated for the smaller area) and the appropriate number of days (3 at peak for the three lower flow scenarios, and the balance at the other levels (21 to 28 days), 14 for 527 m^3/sec) to estimate the volume of water exchanged over the period of connection. This scenario assumes the area of the wetland was at the modified peak flow level when flows were on the descending limb except for the highest flow scenario, where wetland area was assumed to be equivalent to that at 425 m^3/sec level to reduce calculation time. The result was that entrainment levels at the highest flow level were slightly underestimated. The average stage fluctuation in floodplain wetlands in the spring during snowmelt runoff estimated from 1992-2009 was about 2 m, so a level of 0.2 m/day was deemed appropriate.

The table below details findings for flow volumes into flow through and single breach wetlands. In general, flow volumes in flow through wetlands were about 2.5X the amount at Green River flows of 527 m^3/sec compared to 368 m^3/sec, in spite of much longer connection periods at the lower flow. This is because inflow rates increased in an exponential fashion at higher flows (e.g., Figure 3). Flow volumes into the four flow through wetlands were also about 90% of the total flow volumes into all flood plain wetlands (e.g., tables 16 and 17, figure 32).

Flow volumes into single breach wetlands were relatively low but also increased with Green River flow level and were > 2X the amount at Green River flows of 527 m^3/sec compared to 368 m^3/sec. The main difference between entrainment volume at 425 m^3/sec compared to 527 m^3/sec was continuous connection of larger flood plain wetlands such as Leota and Wyasket. The relatively low volumes at lower flow levels (Horseshoe @ 368 m^3/sec and 396 m^3/sec) were because water entrainment occurred only during the 3-day high flow event at 527 m^3/sec and when flows dropped, the river and flood plain connection ceased. The increases at the higher flow volumes were due to the daily water fluctuations which also fill (and drain) single breach wetlands.

Our conclusions from this analysis were that even though days of connection for flow through wetlands were slightly higher at the lower levels of modified flows as portrayed by Hayse et al. (2005), the limited flow entrainment volumes substantially offset those advantages because water entrainment rates were 2.5X as high at the flow recommended by Muth et al. (2000) compared to that at 368 m^3/sec.

For single breach wetlands, the number of connection days to the river was similar across the range of flows. However, the lower entrainment volumes at lower flows (56% less at 368 m^3/sec compared to 527 m^3/sec) and the lack or limited connection of large and important wetlands such as Leota were viewed as detrimental and would not be as beneficial as fewer days of connection at higher flows. A main requirement to ensure the viability of the shorter duration of connecting flows was to have flows and wetlands available when razorback sucker larvae were available for entrainment; e.g., emphasis on appropriate timing of flow increases from Flaming Gorge Dam.

Wetland	Breach flow (m^3/s)	Green River flow level (m^3/sec) 368	396	425	527
Flow-through					
Thunder Ranch	340	4936	6745	7558	13111
Stewart Lake	227	3033	4518	4912	6173
Bonanza Bridge	396	357	633	713	1297
Above Brennan	334	2124	3073	3316	4689
ha/m total, flow-through		10450	14971	16499	25270
Single-breach					
Horseshoe Bend	404	8	8	32	31
The Stirrup	368	29	44	42	37
Baeser Bend	337	64	64	65	59
Johnson Bottom	368	113	194	226	249
Leota wetlands complex	431	85	85	85	302
Wyasket Lake	526	220	220	220	645
Sheppard Bottom	525	0	0	0	0
Old Charley Wash	368	319	506	493	421
ha/m total, single-breach		838	1122	1163	1743
ha/m, all wetlands		11288	16093	17662	27013
days @ 527 m3/sec		3	3	3	14
Other days		31	27	24	6
% difference		-58	-40	-35	0

We also plotted the flow patterns required from Flaming Gorge Dam to meet the scenarios outlined in Hayse et al. (2005); those are just below. In all scenarios, 3 or more days of flows > 8600 cfs (full powerplant, plus bypass tubes, plus spillway flow) from Flaming Gorge Dam are required to meet the peak of 18,600 cfs in the middle Green River, and for sustained flows of 18,600 for 14 days, 11 such days are required. That is so because the flow regime and peak flow level chosen for the Yampa River was quite low (criteria for selection of the flow were not reported), peaking at 10,360 cfs and maintaining at a 10,000 cfs level or greater for only 3 days. Interestingly, the numbers of days requiring flows > powerplant capacity (but < spillway level of > 8,600) for the 18,600, 13,000, 14,000, and 15,000 cfs scenarios were 20, 17, 18, and 26 days, respectively. The Yampa River flow regime used in this scenario was of a relatively low flow level and duration scenario, and actual peak flow in the 1992-2009 period were lower only in 1992, 1994, 2001, 2002, 2004, and 2007. Thus, this scenario seems unrealistic because the likelihood of using bypass flows exceeding powerplant capacity, much less use of spillway flows, seems unlikely in such a dry hydrologic condition.

Finally, the flow patterns from Flaming Gorge Dam are highly unnatural, not befitting the basic paradigm of the “Natural Flow Regime” (Poff et al. 1997) and embraced when the flow recommendations were developed (Muth et al. (2000). Flow are unnatural because high releases are required initially to obtain the high peak of 18,600 but are then much reduced when flows of the Yampa River peak. Releases are then increased again to levels well in excess of powerplant capacity to maintain wetland-river connections. The extreme fluctuations are needed to “save" water to meet the requirement of equal volumes of water released in each scenario when the Yampa Peaks in order to extend the flow durations at the lower peak levels of 13,000, 14,000, and 15,000 cfs levels. This operational scenario is not in keeping with a natural flow paradigm and also seems unlikely to be embraced by operators, given the complexity of the manipulations required and that the magnitude and pattern of flows are distant from those recommended in Muth et al. (2000).